Spectrum Management for Radio Astronomy

Proceedings of the IUCAF Summer School

Held at Green Bank, West Virginia, June 9-14, 2002

Edited by B. M. Lewis & D. T. Emerson

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[†] The IUCAF acronym is formed from the Inter-Union Committee on the Allocation of Frequencies, which, as the original name of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Research, is well known at the ITU and so has been retained.

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Spectrum Managers need to reach agreements. A first step for radio astronomers is to reach agreement among themselves, which is often facilitated by meeting after ITU sessions in Geneva at the Lord Jim.

Editors’ Forward

Tom Gergely has served the passive users of the radio spectrum for many years from his post at the National Science Foundation, which gives him perspective. He has seen at first hand the escalating demand for access to radio spectrum over the years, as well as the increasing effort that must be applied at the ITU for astronomers to hold on to their bands. Moreover, as the years have naturally taken their toll on the folk who undertook this task, new recruits are needed, and these need help to come up to speed. Hence the idea for a Summer School, which Tom tirelessly pushed, and for which he provided the first agenda. We have also to acknowledge the help we received from the staff of NRAO, both to mount the Summer School, and to publish these proceedings. In particular the participants thank Becky Warner for smoothing their path at Green Bank. Finally we appreciate the financial support from NSF and URSI that allowed the school to happen.

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Introduction to the Summer School

Tomas Gergely

National Science Foundation

I believe, that the idea of a Summer School in Spectrum Management for Radio Astronomers first came up in a conversation I had with Jim Cohen, during one of the long walks back to our hotel from one of a number of excellent restaurants we visited in May 2000, during the World Radiocommunications Conference held in Istanbul. After the WRC, Jim went on sabbatical, I believe, and got busy with other things. Soon after that Darrel became Chairman of IUCAF, and the idea was discussed further over a beer or two at a Geneva restaurant during a WP 7D meeting, (a pretty standard way of doing business by the WP 7D crowd), and here we are today!

There appeared to be at least two good reasons to hold such a school. The first was that the most experienced radio astronomers active in spectrum management had either just retired, or were then about to do so. Thus Dick Thompson, who we are lucky to have here as one of our lecturers, had officially retired the previous year. And I had attended the first in a long series of Boris Doubinsky retirement parties (which I believe are still going on) in Istanbul, while John Whiteoak, who chaired WP 7D for many years, retired shortly after the WRC. Others are likely to follow within a decade or so, so an infusion of younger people into spectrum management from the radio astronomy side is highly desirable. Secondly, the few newcomers to this activity had little previous exposure to spectrum issues, and even less to the language, structure, and culture of the International Telecommunication

Fig. 1: The GBT, which is located in the National Radio Quiet Zone.

Union (ITU). Defending radio astronomy interests in spectrum fora is never easy, and to be thrown into the middle of a WRC is not a very pleasant way to learn about how to do it, as some present here can surely tell!

Well, there are few ways to entice people into spectrum management! Few teenagers are smart enough to decide early on that they want to go into spectrum management when they grow up. Even among technical people not too many are aware of what the activity is about, and most scientists are turned off when you begin an explanation. Important, maybe! But boooooring In fact, most of those in spectrum management, be they astronomers, engineers, or lawyers, drift into it accidentally, and then decide to stay. So, we thought that there had to be a better way, and hopefully this Summer School is going to turn out to be one of those better ways!

And while we are at it, I thought I'd give you a definition of Spectrum Management. When I happened to drift into this activity, I was given the office occupied by the previous incumbents. As usual, there was lots of junk left on the walls, a definition of spectrum management among them. It is the best that I ever found, and I kept it! Here it is:

> **"Radio Frequency Management Is Done by Experts Who Meld Years of Experience With a Curious Blend of Regulation, Electronics, Politics and Not a Little Bit of Larceny. They Justify Requirements, Horse-trade, Coerce, Bluff and Gamble With an Intuition That Cannot Be Taught Other Than by Long Experience."**
>
> **Vice Admiral Jon L. Boyes**
> **U.S. Navy**

Well, he certainly did have it right!

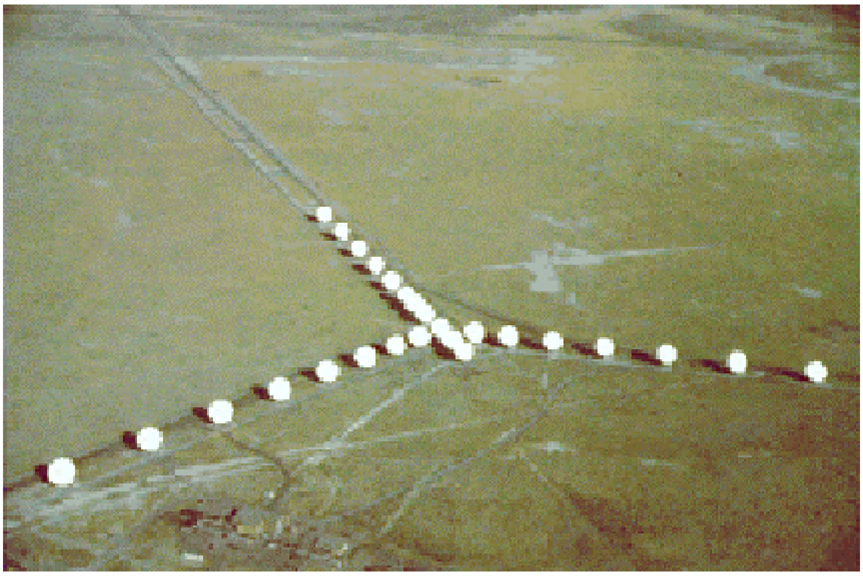

Fig. 2: The VLA consists of 27 antennas arranged in a huge Y pattern, up to 36 km (22 miles) across. Each antenna is 25 meters (81 feet) in diameter; their output is combined electronically to give the resolution of an antenna 36 km (22 miles) across, with the sensitivity of a dish 130 meters (422 feet) in diameter. At the highest observing frequency (43 GHz) this gives a resolution of 0.04 arc seconds, which is sufficient to see a golf ball held by a friend 150 km (100 miles) away. The dishes can be moved along a track, which allows the telescope to perform the radio equivalent of a zoom lens.

I was told that some of you may have never seen a radio telescope or array, and so here are some pictures to introduce you to them, before you get a chance to visit the GBT in person. Pictures of many more can be seen near the entrance to this building.

Fig. 3: The Arecibo telescope is a 305 m (1000 feet) diameter spherical reflector, 167 feet deep, and covers an area of about twenty acres. The surface is made of almost 40,000 perforated aluminum panels, each measuring about 3 feet by 6 feet, supported by a network of steel cables strung across the underlying karst sinkhole.

Fig. 4: Some radio telescopes. From top left-to-right: (a) The Parkes telescope, Australia; (b) The IRAM mm-wave telescope, Granada, Spain; (c) The Westerbork array, the Netherlands; (d) The Nobeyama interferometer, Japan.

Finally, I made an attempt to summarize the worldwide investment in radio telescopes made during the 1990s together with that expected to be made in this decade. I am sure that I omitted some, but as an approximation it will do. The worldwide investment in radio telescopes during these two decades is expected to run to roughly one billion dollars, although the real figure is likely to end up being higher.

USA

GREEN BANK TELESCOPE (GBT)	NRAO	$ 85 M
ARECIBO (UPGRADE)	NAIC	$ 22 M
SUBMILLIMETER WAVELENGTH ARRAY (SWA)	SAO	$ 62 M
EVLA (Phase I)	NRAO	$ 50 M
ALMA (US Contrb.)	NRAO	$330 M
LARGE MILLIMETER TELESCOPE (LMT)	U Mass	$ 43 M
CARMA	U. Calif- CALTECH	$ 15 M
ALLEN TELESCOPE ARRAY (ATA)	Berkeley-Private	$ 25 M
SKA (Development)	Consortium	$ 1.5 M
Total		$633.5 M

Non-USA

ALMA	EUROPE	$330 M
LMT	MEXICO	$ 43 M
GMRT	INDIA	~ $ 50 M?
SARDINIA	ITALY	~ $ 60 M?

Our ultimate objective is to protect this investment for science and make sure that radio astronomers continue to have access to the spectrum, so that we can continue to learn about the Universe!

Thank you, and have a very enjoyable week!

CONCEPTUAL BACKGROUND TO RADIO

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1 Introduction

There are three types of electrical wires that one sees strung out over the countryside. They are:

1. Power lines. They have rather high voltages and currents that go up and down at 60 Hz. They go on and on and on with terrible monotony. But it is clear what they are conveying. It is power, and one can trace them from a power station to the final customer. We won't have much to say about them.

2. Telephone lines. These too can be traced from one place to another and they too carry power but not very much. What is interesting is that the voltages and currents are not monotonous. Instead they fluctuate. They fluctuate in a way that is predictable in its general character but which is quite unpredictable in detail. We shall try and understand what they are conveying.

3. Antennae. These carry high frequency voltages and currents that also may only be predictable in a general way but these wires don't go anywhere. They just stop in midair. We shall try and understand them as well.

Both telephones and antennae are in a sense the concern of, and are overseen by, the International Telecommunications Union: the ITU. It is through the coordinating work of the ITU that it is possible to make international telephones calls, have the Internet, and operate radio stations without mutual interference.

The ITU is one of the oldest international organizations. It was set up by the International Telegraph Conference held in Paris in 1865, convened by Emperor Napoleon III. Initially it was called the International Telegraphic Union at a time when there were already nearly a million kilometres of telegraph lines installed, but they couldn't cross international borders because of conflicting technical and operational standards. The ITU was set up before the invention of the telephone, before the invention of radio, and before the very word *telecommunication* was coined. Though Russia and Turkey and most of the European countries were represented, I regret to say that neither the USA nor the UK were in at the beginning.

The ITU became a *Specialized Agency* of the United Nations (UN) in 1947. But it has always held the UN somewhat at arm's length, firstly because the UN's predecessor organization, *The League of Nations* had collapsed, and also because there have been Member States of the ITU which have not been members of the UN. I have it by word of mouth in private conversation with the former Secretary-General of the ITU, Pekka Tarjanne, that the ITU does not receive instructions from, or report to, any higher body within the UN system of organizations. So it defines its own terms of reference.

We are going to hear a good deal this week about the ITU and its Recommendations and its Radio Regulations (RRs). Radio waves are no respecters of territorial sovereignty, but cross national borders, and can cause interference in other countries. It is the prime purpose of the ITU-R, the radio branch of the ITU, to manage the use of the Radio Spectrum in such a way that the various applications of radio can coexist and operate without causing mutual interference. We shall be learning how it addresses this mission, to what extent it is effective, and to what extent it is failing in this primary task.

It must never be forgotten that the ITU sees itself primarily as concerned with telecommunications. It is not primarily an international Spectrum Management organization, though in the absence of any other such body it has taken on that role. It views the electromagnetic spectrum as provided by nature for telecommunications and it rather grudgingly concedes that it has other uses, such as remote sensing. Radio Astronomy is a recognized *Radio Service,* one of about 40, but it is only recognized on the basis that it is a sort of "pretend" radio communication service. Most of our troubles stem from this pretence.

2 Information and its measure

The unpredictable fluctuating voltages on those telephone lines and on those antennae carry *information,* or at least they have the potential to do so. When English first acquired the word *inform* (via Old French *enfourmer)* it was used simply to mean to "give form or shape to". So one could inform a lump of clay. However it evolved from its primary notion of "shaping" and acquired the figurative meaning of "forming an idea of something" to "telling or instructing people about something". So *information* is strictly what shapes ideas in the mind, and *information technology,* about which we hear a lot, has the rather sinister meaning of being the technology for shaping ideas in people's minds.

I want to start by sketching out the rudiments of *Information Theory,* the theory of shaping ideas in people's minds. Claude Shannon, who was working for the great Bell Telephone Company, asked himself what is it that all their telephone lines were conveying. He knew it was information of course, the chatter on the wires certainly shaped ideas in minds, but he wanted to give a precise measure to it. He decided that a message conveys information to the extent that it is "News", that a message conveys information according to its surprise value.

A highly probable message tells us little and thus conveys little information: if the voice on the radio says "It will be sunny today with temperatures in the mid 70's", we are not astonished, we haven't learned much, indeed we might have guessed it. So very little information has been conveyed.

On the other hand if the voice says "The President has been shot", we sit up and take notice because it is an unlikely announcement. So more information has been conveyed. But alas it is the sort of thing that befalls presidents.

However if the voice were to say: "The Martians landed this morning near Soccoro, New Mexico", we would be very astonished indeed. That is so unlikely that it really is NEWS, and a substantial amount of information has been conveyed.

We see that the amount of information is not related to the number of words or symbols, but must be some function of the probability of the message.

Suppose message A has probability p_a and conveys information I_a, and message B has probability p_b and conveys information I_b

Then, as it seems reasonable to suppose that information should be additive, so that receipt of both messages conveys information $I_a + I_b$, we look for a function $f(p)$ such that

$$f\left(p_a\right) + f\left(p_b\right) = f\left(p_a \times p_b\right) \qquad (1),$$

since the joint probability of two independent events is the product of their individual probabilities. We don't have to look far. The function with this property is the logarithm. So Shannon defined the information I of a message of probability p as:

$$I = -\log_2(p) \qquad (2).$$

The minus sign is there because $p < 1$ and the log of a number <1 is negative. The unit of information is the bit. Thus a message of probability 1 % conveys 6.644 bits. In this context one is not restricted to an integer number of bits.

At this point I should point out that Shannon was not the sole inventor of *Information Theory*. The same shape formed in the mind of V.A. Kotelnikov in Russia.

Suppose in some communication system there are N possible messages with probabilities p_n. [In the early days of the ITU when the cables only conveyed telegrams, there was a set of four books containing all the 1.9 million words officially recognized by the ITU and those were the only words one was allowed to send!] Then the nth message conveys $-\log_2\left(p_n\right)$ bits when it is sent. But it is sent with average frequency (in the statistical sense) p_n. So in the long run that particular message conveys information $-p_n \log_2\left(p_n\right)$, (our 1 % message conveys on average 0.06644 bits per message), and the mean information rate of the system is

$$\mathrm{H} = -\sum_{n=1}^{n=N} p_n \log_2\left(p_n\right) \text{ bits per message} \qquad (3).$$

Notice that this is only a function of the message probability distribution. The larger N is, the smaller the p_n's become, and the bigger H (which is not upper case h but upper case Greek eta) becomes. H is in fact the Entropy of the message probability distribution. Two examples are shown in Fig. 1. The irregular probability distribution has entropy of 2.76 bits and the Gaussian 4.04 bits. In both cases the horizontal axis has no significance and the same result is obtained whatever the order in which the individual ordinates are plotted.

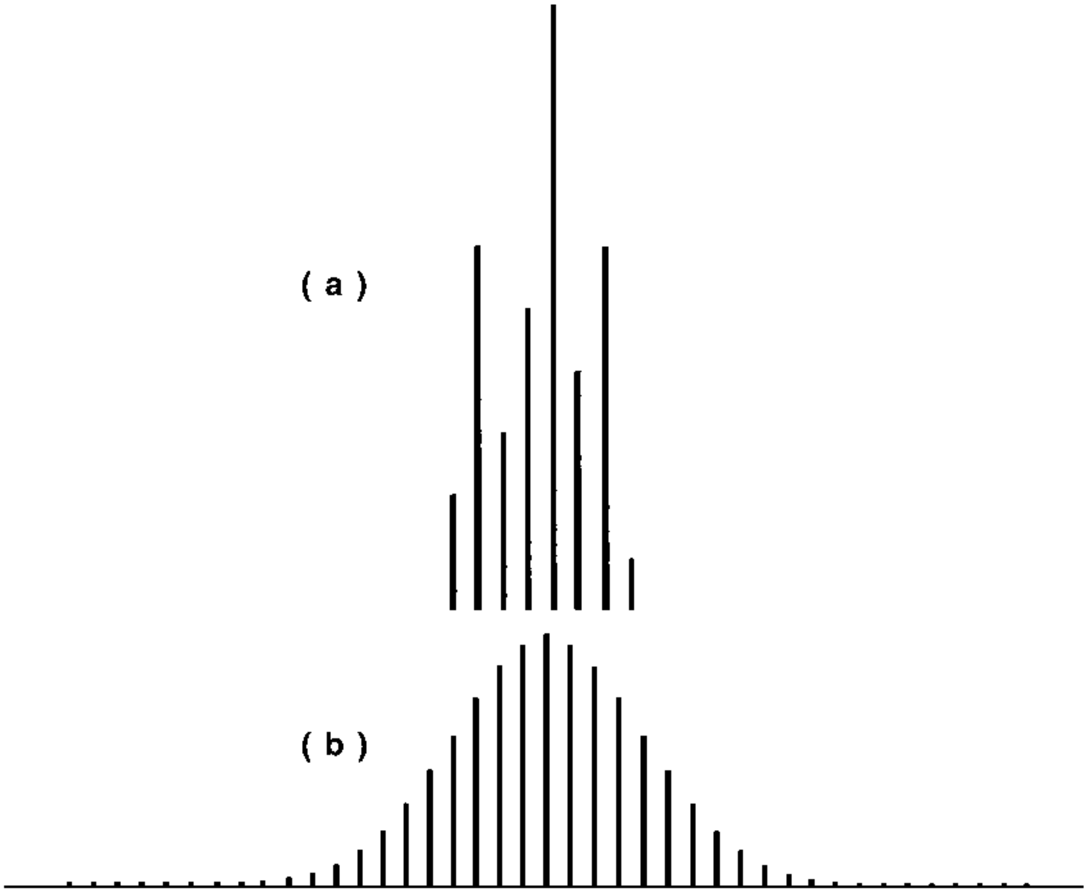

Fig. 1: Two message probability distributions; (a) has entropy 2.76 bits; (b) has entropy 4.04 bits.

I won't develop this further but I do want to impress on you that if the function of a communication system is to convey information, then it must emit unpredictable signals. The more unpredictable they are, the more information is **potentially** conveyed. That doesn't mean that all unpredictable signals contain a lot of information. They may be garbage or noise. But a wholly predictable signal, as on our 60 Hz power line, conveys no information.

An unpredictable message must start at some instant of time. It can have no precursor. That means that the signal symbols or fundamental elements in the coding and modulation system must start from absolutely zero at some instant of time. The waveforms must therefore be discontinuous at some instant.

3 Physical properties of signals

3.1 Degrees of freedom

All the electrical signals with which we have to deal can be viewed on an oscilloscope and seen as wiggly lines of various forms. They are continuous functions of time. Since they can take myriad forms one might at first think that to describe an arbitrary signal would require the specification of an infinite number of parameters. However it is not so. One may see this as follows. Imagine that you record on a length of magnetic tape your favourite piece of music. Then join the two ends of the tape to make an endless loop and then play it. What you will hear is an endless repetition of your piece. You may get fed up with it because after a time it no longer has surprise value. Be that as it may, the audio signal has become a periodic function with repeat time T.

The signal can be represented as a Fourier series of the form

$$v(t) = \sum_{n=1}^{n=N} \mathrm{A}_n \cos\left(2\pi\, n\, t / T\right) + \mathrm{B}_n \sin\left(2\pi\, n\, t / T\right) \qquad (4),$$

where the fundamental frequency is $1/T$, and the highest frequency N/T may be determined by your hearing. We call this upper limit the *bandwidth B* of the signal. It is measured in Hz

$$B = N/T \qquad (5).$$

Now we notice that for each harmonic there is an A coefficient and a B coefficient, so the total number of coefficients that have to be written down to completely describe the signal is *2N.* Thus far from needing an infinite number of parameters to describe a continuous signal we see that a signal of *bandwidth B* and of *duration T* can be completely described by *2BT* independent parameters.

A signal of bandwidth *B* and of duration *T* is said to possess *2BT degrees of freedom*. The degrees of freedom may be enumerated, as we have done, in frequency space, or equally well in time. Thus a signal of *bandwidth B* possesses *2B* degrees of freedom per unit time and is completely described if only its values at intervals of 1/(*2B*) are recorded. Given these regularly spaced values, the complete continuously varying original can be recovered. This result is due to Shannon and is called *Shannon's Sampling Theorem,* though the attribution is frequently dropped. *2B* is frequently described as the Nyquist sampling rate for a signal of bandwidth *B*.

The concept of the degrees of freedom of a signal is analogous to the concept of the mechanical degrees of freedom of, for instance, a molecule in a gas. In fact it is more than an analogy, they are the same. So, just as each degree of freedom of a molecule has, on average, energy kT/2, where k is Boltzmann's constant ($1.38\text{x}10^{-23}$ Joule per degree Kelvin) and T is now the absolute temperature (in degrees Kelvin), so the average energy of a thermally generated electrical signal is kT/2 per degree of freedom. Since for bandwidth *B* these come in the time domain at *2B* per second, the mean available noise power of a thermal signal of bandwidth *B* is kT*B* Joule/sec. This is the so-called Johnson noise.

Though the values given to the various degrees of freedom are independent, the values follow a definite distribution law. Johnson noise viewed in the time domain follows a *Gaussian amplitude probability distribution.* If such noise is sampled at the Nyquist rate and a histogram of the values plotted, it will be found to tend to a Gaussian. Likewise artificial band-limited Gaussian noise may be generated by choosing numbers at random from a source following a Gaussian distribution and using them to construct a continuous signal.

3.2 Reconstruction

A short length of artificial band-limited Gaussian noise is shown in Fig. 2. The sample values were drawn from a source of random numbers following the Gaussian amplitude probability distribution also shown. The smooth curve that passes through all the sample values was constructed by convolution with the *Queen of Functions,* the sinc function:

$$\operatorname{sinc}(x) = \frac{\sin(\pi x)}{\pi x} \qquad (6).$$

This has value 1 at t = 0 and value 0 for all integer $x \neq 0$. We set $x = 2B$t. Then since the interval between the samples is 1/Nyquist rate = $1/(2B)$, it means that the sinc

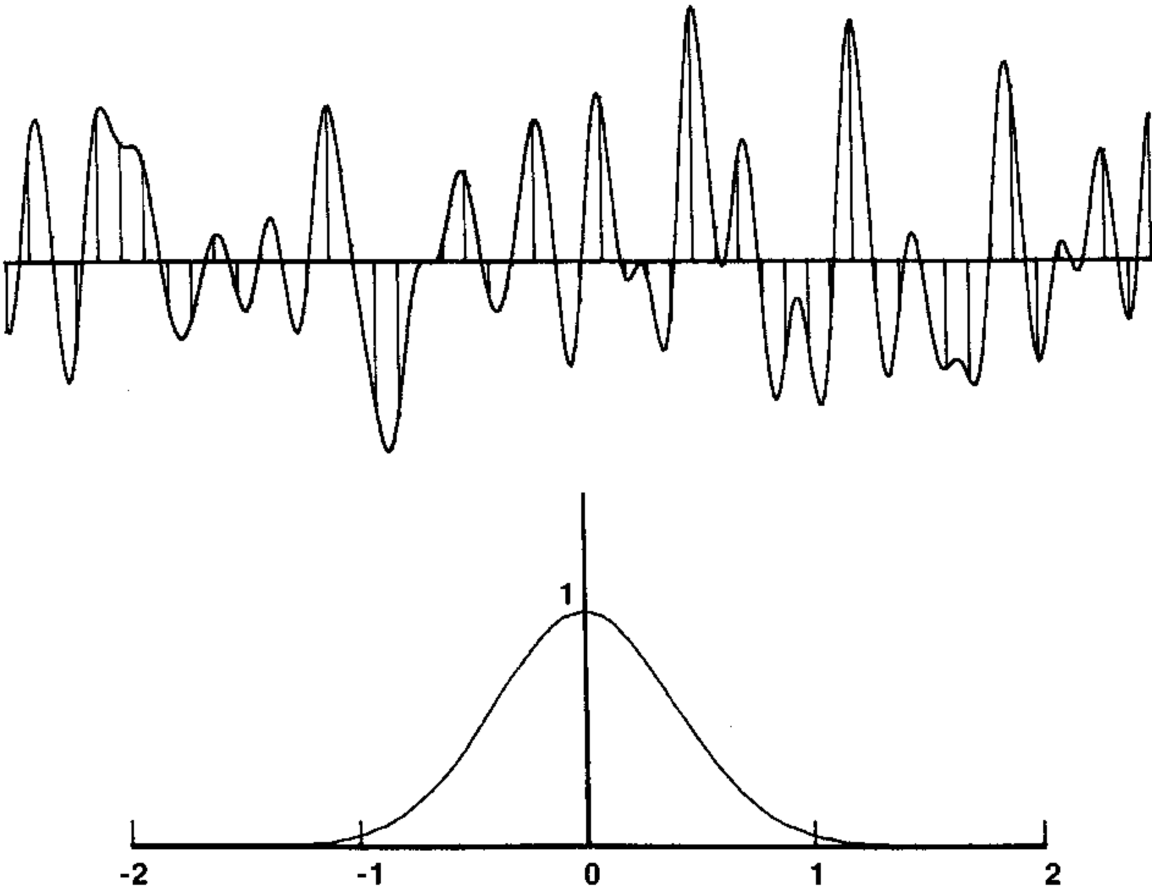

Fig. 2: Sample of band-limited Gaussian noise constructed from the samples shown. These were selected at random from the Gaussian amplitude probability distribution shown below.

function whose peak coincides with one sample has value zero at the positions of every other sample. This convolution amounts to erecting a sinc function at every sample and adding them together, so

$$v(\mathrm{t}) = \sum\nolimits_{all\ m} D_m \,\mathrm{sinc}\left(2\,B\,\mathrm{t} - \mathrm{m}\right) \qquad (7),$$

where D_m is the m$^{\mathrm{th}}$ sample.

This same construction allows a continuous band-limited signal to be reconstructed exactly from its equispaced sample values, provided the sampling rate exceeds or is at least equal to the Nyquist rate.

3.3 Thermal Gaussian noise

Thermal Gaussian noise is all-pervading. The mean power k$\mathrm{T}B$ is the *available power* at the terminals or port of any lossy, that is to say dissipative, electrical circuit. Obviously if the terminals aren't connected to a load the power doesn't flow. So k$\mathrm{T}B$ is the maximum power that would flow if the terminals were connected to a matched load. The temperature T is the temperature of the lossy element. If the lossy element is an identifiable resistor, then T is its physical temperature as measured by a thermometer in contact with it.

Of particular interest to us are the terminals of an antenna. This is a lossy structure in so far as the power fed in by a transmitter doesn't come back. An antenna has a *radiation resistance* and it too manifests thermal Gaussian noise. If one imagines an antenna as enclosed in a huge box with the walls at temperature T then, in equilibrium, the box will be filled with Black-Body radiation characteristic of that temperature. The antenna couples to the field and makes power k$\mathrm{T}B$ available at its terminals. With a narrow-beam antenna, ideally, the antenna temperature is the temperature of the surface at which the beam is directed.

4 Shannon's Channel Capacity Theorem

We have seen how the apparently infinitely parametered variation of a continuous band-limited signal has in fact only a finite number of degrees of freedom. This is well known. Less well known is that a continuous band-limited signal has a finite potential for conveying information. Shannon was able to show that in the presence of additive Gaussian noise of mean power N (Watts), a communication channel of bandwidth B (Hz) can convey information at the rate R *without any error* according to

$$R = B \log_2 \left(I + P\,/\,N\right) \text{ bits /sec} \qquad (8).$$

Here P is the signal power. This is *Shannon's Channel Capacity Theorem*. I make no attempt at a potted derivation of this very profound result. It is in several regards analogous to the Second Law of Thermodynamics. It defines the limit of the possible. The proof is a non-constructive "existence proof", so it is not known how to construct a system that achieves this limiting rate of transmission. What is known is that the signal will have the appearance and characteristics of Gaussian noise.

Just as one can use the Second Law of Thermodynamics to define a Carnot efficiency against which the efficiency of a real steam engine can be compared, so the limit defined by the Channel Capacity Theorem allows one to see how efficient a real communication system is in comparison with the theoretical limit. This ability should be a part of every Spectrum Manager's mental tool kit.

Denoting the Signal to Noise ratio $P / N = x$ we can write:

$$R = B \log_2 (1 + x) = B \ln (1 + x) / \ln (2) \qquad (9),$$

the latter form being more convenient. We shall study two cases of particular interest.

4.1 The Bandwidth limited case

This is the case where one has an allocated band and one must stick to it. B is fixed, so the noise power $N = \mathrm{k}\mathrm{T}B$ defined in §3.1 is fixed and proportional to bandwidth.

Since $\ln (1 + x) \approx x$ for small x, the information rate at low signal-to-noise ratio is proportional to signal power. So

$$R = B\, x / \ln (2) \qquad (10),$$

and what one wants, channel capacity, is proportional to what one has to pay for, which is signal power. That seems natural and good.

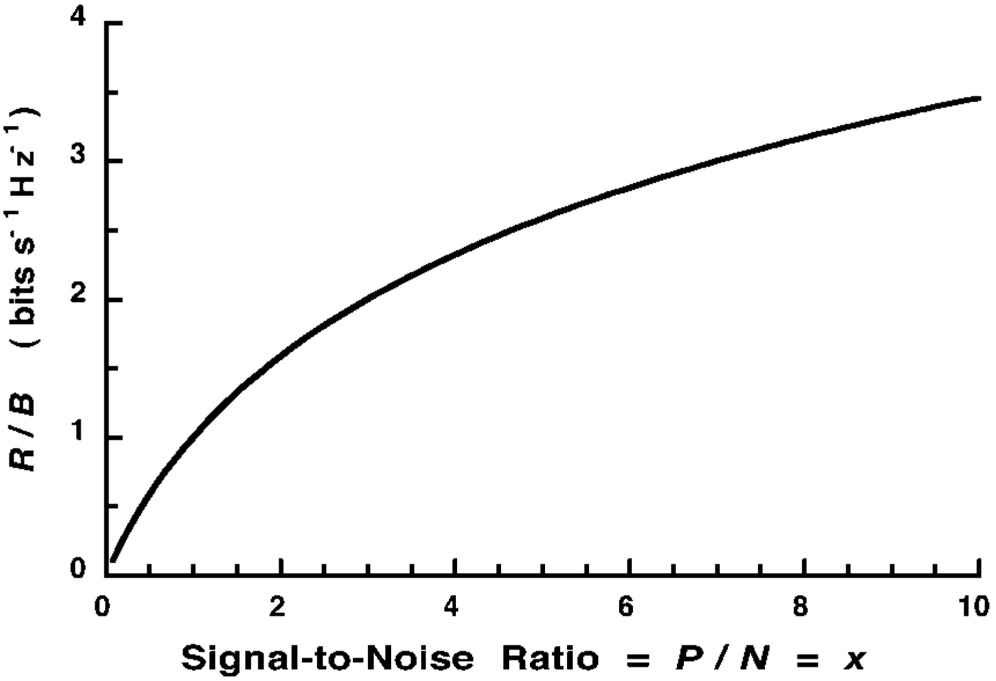

Fig. 3: Channel Capacity R/B (bits s^{-1} Hz^{-1}) versus Signal-to-Noise ratio P / N in bandwidth limited case.

However at high signal-to-noise ratio, when $\ln (1 + x) \approx \ln(x)$

$$R = B \ln(x) / \ln(2) \qquad (11),$$

and one gets ever smaller increments of capacity for equal increases in cost. This is an instance of what economists call the *Law of Diminishing Returns*. It is an unhappy regime to be in.

The general relationship is shown in Fig. 3. At unity signal-to-noise ratio the limiting capacity is 1 bit/sec/Hz. To increase the capacity to 2 bits/sec/Hz requires a three-fold increase of transmitter power. To increase the capacity to 3 bits/sec/Hz requires a 7-fold increase of power. In principle one may send an arbitrarily large number of bits/sec through any finite bandwidth, but one has to pay dearly to do so.

4.2 The Power limited case

We have seen that noise power is generally proportional to the bandwidth. Thus one may write

$$N = \nu B \text{ or } B = P / (\nu x) \qquad (12),$$

where now both P and ν are constants, and ν is the noise power per unit bandwidth. The limiting information rate is

$$R = \left(\frac{P}{\nu}\right) \frac{1}{x} \frac{\ln(1+x)}{\ln(2)} \text{ bits/sec} \qquad (13).$$

Counter-intuitively this increases as the signal-to-noise ratio decreases and achieves the extreme value of

$$R = \left(\frac{P}{\nu}\right) \frac{1}{\ln(2)} \text{ bits/sec} \qquad (14),$$

when the signal-to-noise ratio is vanishing and the bandwidth tends to infinity! This relationship is shown in Fig. 4. We see that actually the result isn't so alarming as it sounds. The limiting rate is very nearly achieved if the bandwidth is increased far enough to make $P/N \approx 0.1$.

There are many real practical situations in which signal power is limited. One thinks of spacecraft and indeed of mobile phones that have rather small batteries. The Channel Capacity Theorem says that if the power is well used one will find oneself using a modulation scheme which spreads the power rather thinly over a relatively wide band and one will operate at very low signal-to-noise ratio. There are indeed systems that have these characteristics: wideband FM broadcasting and Code Division Multiple Access (CDMA) systems in mobile phones. Perhaps they are on the right lines.

4.3 Concluding remarks

1. It is always correct to aim for the lowest possible noise power by making ν as small as possible.

2. Channel capacity always increases with increase of signal power.
3. However if v and P are fixed, the channel capacity is maximized by increasing the bandwidth until the signal-to-noise ratio is much less than unity.

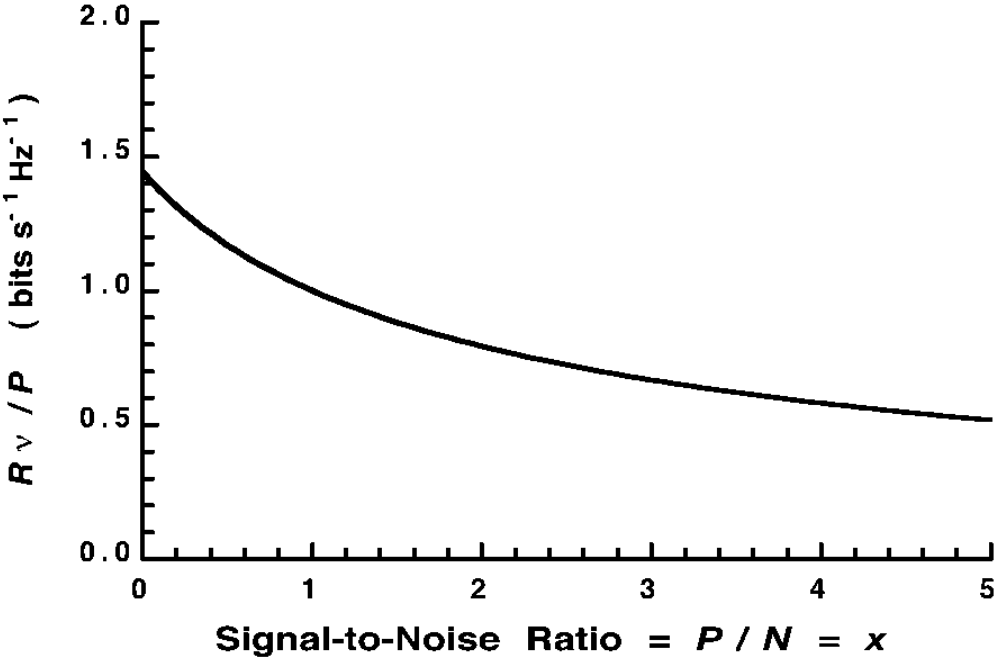

Fig. 4: Channel capacity $R\,\nu / P$ (bits s^{-1} Hz^{-1}) versus Signal-to-Noise ratio P / N in the Power-limited case. Note that the limiting Channel Capacity as x → 0 is 1.443 bits.

5 Fourier Theory of discontinuous functions

I like to follow Bracewell in defining the Fourier Transform (FT) of a function of time $f(t)$ as $F(s)$, where s is frequency in cycles/unit of time, as

$$F(s) = \int_{-\infty}^{+\infty} f(t) \exp(-i\,2\,\pi\,s\,t)\,dt \qquad (15).$$

I shall need to use two results that follow. The first is the so-called *Shift Theorem*. It states how $F(s)$ is modified if $f(t)$ is shifted along the time axis. If $f(t)$ is retarded by a time T, that is to say shifted to the right on the time axis, then it becomes $f(t - T)$ and its FT becomes $F(s)\exp(-\,i\,2\,\pi\,s\,T)$. It acquires a linear negative phase slope. The second, which follows from the first, is the *Derivative Theorem*, which I will express inversely in terms of an integral. If $f(t)$ is integrated with respect to t, its FT becomes

$$F(s) / (i\,2\,\pi\,s).$$

Consider the following development. Start with a delta function of time $\delta(t)$. This has value of 0 for all $t \neq 0$ and its integral from $t = -\varepsilon$ to $+\,\varepsilon$ equals 1 even as $\varepsilon \to 0$. Integrating it with respect to time one obtains the step function shown at the bottom of Fig. 5. Shift this to the left (advance it in time) by amount *T*/2 and shift it to the right (retard it in time) by *T*/2, and subtract the second from the first. We obtain the square pulse or "top hat" function shown one line up. This has width *T*. Repeat the process. The next line up shows the integral of the top hat as a ramp, and the line above again shows the triangular pulse resulting from shifting left and right by *T*/2 and taking the difference. The figure shows the effect of repeating this process twice more.

The process described amounts to repeated convolution by the top hat function

$$\Pi\left(t / T\right) = 1 / T \text{ for } -T/2 < t < +T/2,$$

and is elsewhere zero. The effect of the successive convolutions is to produce an ever-smoother pulse. The top-hat function has abrupt sides, so it is a discontinuous function. On integration the ramp is continuous but it has discontinuity in its slope or first derivative. The next smoother integral is discontinuous in its second derivative and the top one is only discontinuous in its third derivative.

Now the Fourier Transform of the top hat function is well know to be the sinc function

$$\sin\left(\pi s T\right) / \pi s T ,$$

and by the *Convolution Theorem,* which I have not discussed, or from the *Shift Theorem* which I have, we can see that the FT's of the various pulses are

$$\left[\sin\left(\pi s T\right) / \pi s T\right]^{n} ,$$

with $n = 1$ for the top hat, $n = 2$ for the triangular pulse, and so on. We see that the envelope of the FT falls off as s^{-n}. So the smoother the pulse the faster the FT falls off. This is a manifestation of a general rule that a function, which is discontinuous in its n^{th} derivative, has an FT with an envelope that falls asymptotically as $s^{-(n+1)}$ in the frequency domain.

If a signal is composed of a string of pulses, as many are, the form of the resultant power spectrum is the square of the magnitude of the FT of one pulse. So if the pulses are discontinuous in their n^{th} derivatives, the resultant power spectrum falls as $s^{-2(n+1)}$. Viewed on log-log scales the spectrum falls as -6 (n + l) dB/octave or -20 (n + l) dB/decade. These results are very germane to the matter of Out-Of-Band emissions (OOBs).

I have plotted the power spectra corresponding to the pulses of Fig. 5 in Fig. 6, but on a dB scale vertically and a linear frequency scale horizontally. The deep nulls occur at frequencies which are multiples of 1/*T*. I have drawn a vertical dashed line at 5/*T* which is 250 % of (2/*T*).

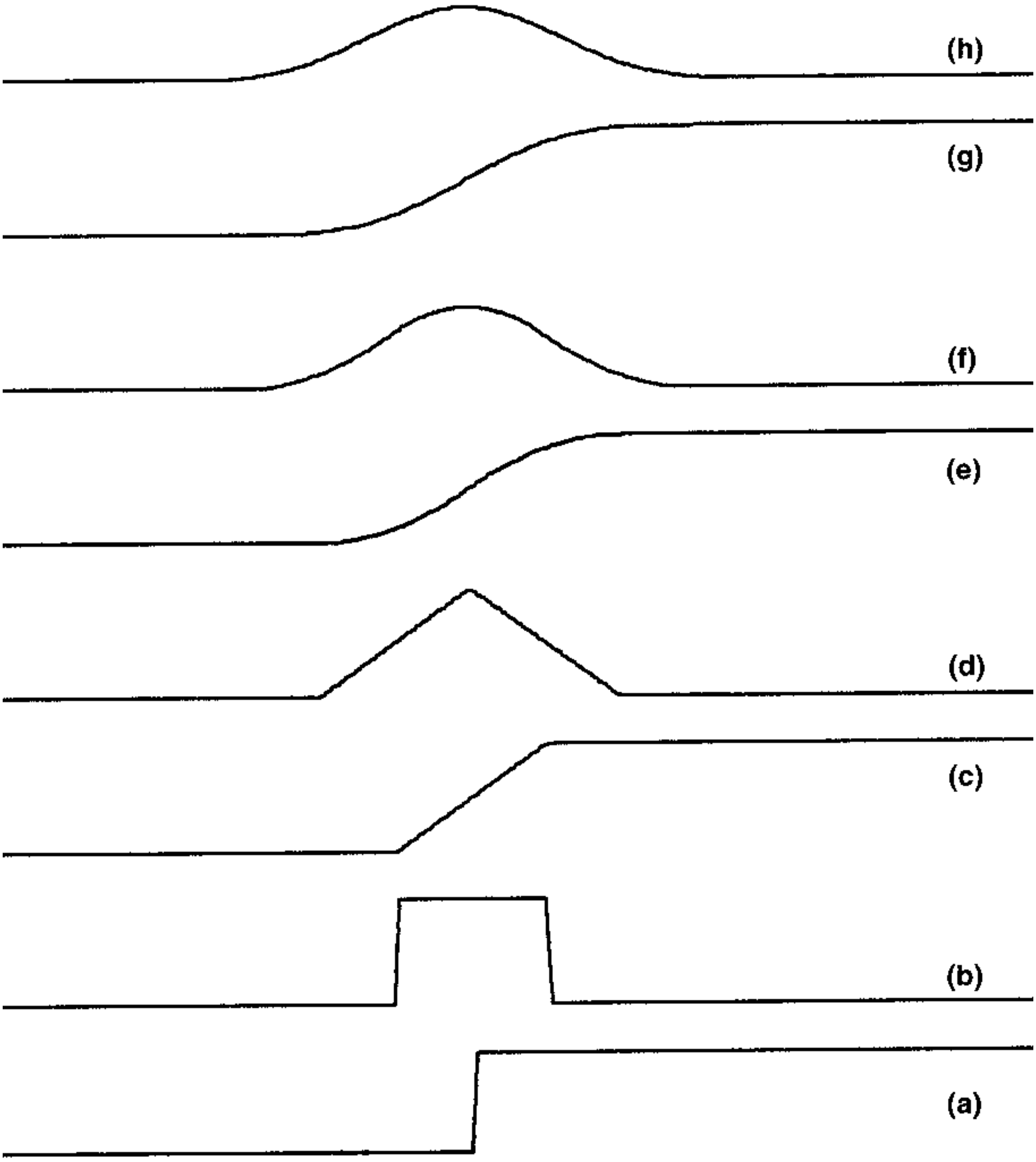

Fig. 5: The successive integration and differencing of a delta function makes successively smoother pulses.

It follows from this result that any signal which is infinitely differentiable will have a power spectrum that falls off faster than any negative power of frequency. The key example is of course the pure sine wave. Its power spectrum is a vanishingly thin delta function. We are back to our boring 60 Hz power line!

A Gaussian shaped pulse is also infinitely differentiable. It has the pleasing property that its FT is also a Gaussian and, indeed, viewed on a log-log scale its power spectrum has no asymptotic rate of fall-off. It falls ever faster as the frequency is increased. But it can't be used for communication because it has a very small but infinite precursor in time. It starts infinitely far back in time. As soon as it is modified so that the precursor is chopped off, one no longer has an infinitely differentiable function and the corresponding power spectrum has an asymptotic rate of fall-off.

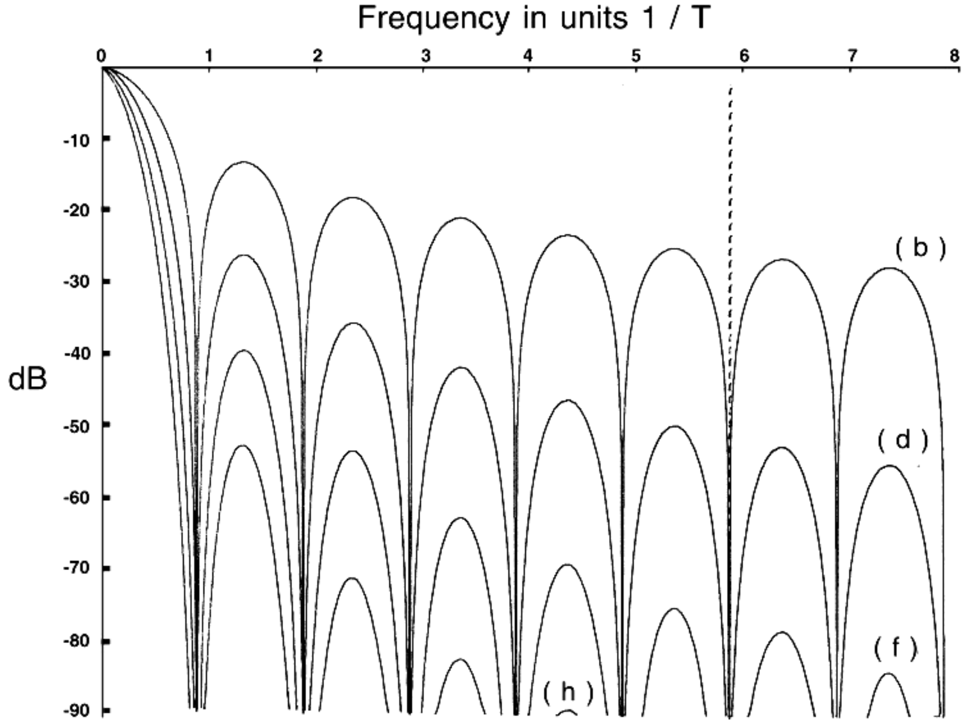

Fig. 6: Power spectra in dB corresponding to the pulse shapes in Fig. 5.

Because an information conveying system must transmit unpredictable messages, the symbols cannot have infinitely long precursors. Thus I maintain all information bearing transmissions must have power spectra that fall asymptotically no faster than some negative power of frequency.

Everything that has been said here about smoothness of pulses and the fall-off of the power spectrum has been treated as if we were concerned with single-sided spectra going down to zero frequency. But everything remains the same if the pulse shapes are the envelopes of a high frequency carrier. Then the rates of fall-off are measured from the carrier frequency.

6 Filters

Presented with a transmitter whose Out-Of-Band (OOBs) are unacceptable, it is natural to suggest that an output filter should be added. If an effective classical electrical filter can be fitted, a filter made up of a number of coupled resonators (Fig. 7), then one must ask what it does to the signal.

Every filter has a frequency response, let us call it $F\ (s)$, which is in general a *complex* function of frequency. Every frequency component of an applied signal gets changed in amplitude and in phase. There is not much scope in design for independent control of the amplitude and phase responses. In fact, for every given amplitude response there is an inherent minimum lagging phase response. One talks of *minimum-phase networks* and most filters are of this type. The constraint stems from the fact that a filter is a *causal* system, it is not clairvoyant, it cannot possibly respond to an impulse before it occurs. Since in an impulse $\delta\ (t)$, all frequencies are present with equal amplitude, the *impulse response I* (*t*) of a filter is simply the Fourier Transform of its *complex* frequency response (see Fig. 8)

$$I(t) = \int_{-\infty}^{+\infty} \mathrm{F}(s) \exp(+ i\, 2\, \pi\, s\, t)\, ds \qquad (16).$$

Since $I(t) \neq 0$ only for $t > 0$, and recalling the *Shift Theorem*, one is not astonished that there has to be at least a certain minimum negative phase slope associated with $\mathrm{F}(s)$.

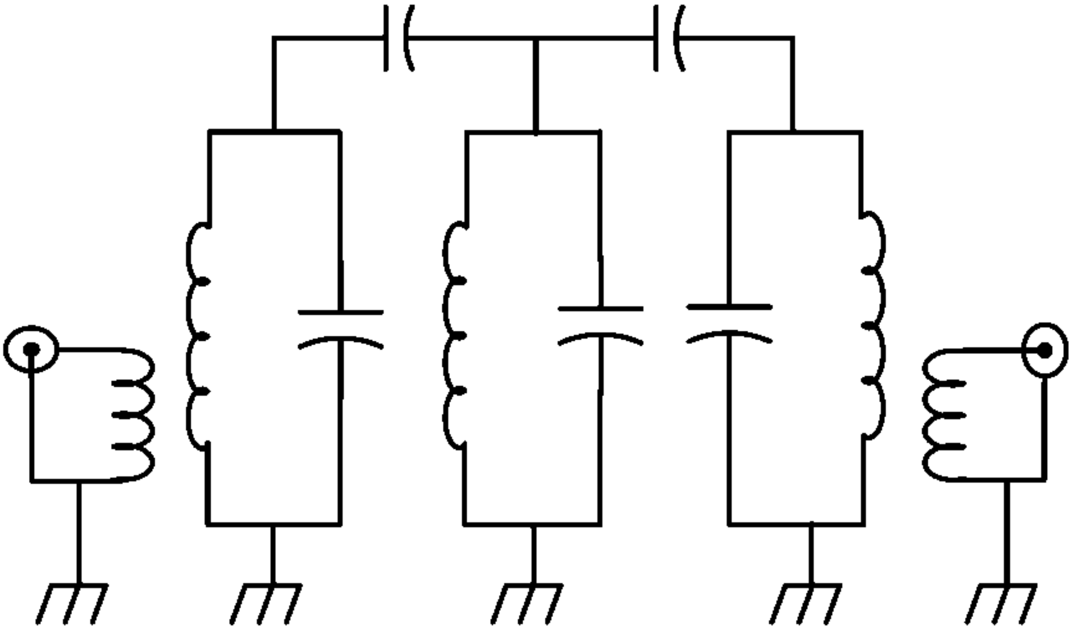

Fig. 7: Typical Band-Pass-Filter.

A filter is certainly a device that changes the amplitude and the phase of every frequency component of the applied signal. And it is easy to fall into the way of thinking that it somehow does a Fourier Analysis of the signal, changes the amplitudes and phase of each component, and then reassembles them to form the output signal. That is quite a task for a few interconnected resonators. One may think that way but it isn't a physically correct description of how a humble filter actually works. This multiplication by the frequency response in the frequency domain is in reality achieved by a convolution in the time domain. How a filter really filters is by convolving the input signal with the filter impulse response,

$$V(t)_{out} = V(t)_{in} * I(t) \qquad (17).$$

The output waveform is the input waveform convolved with the impulse response. Here the * denotes convolution. One may consider the input signal as being subdivided into a succession of elementary contiguous impulses of varying amplitudes. Each one excites the filter's impulse response. The output signal is the superposition of all the elementary impulse responses.

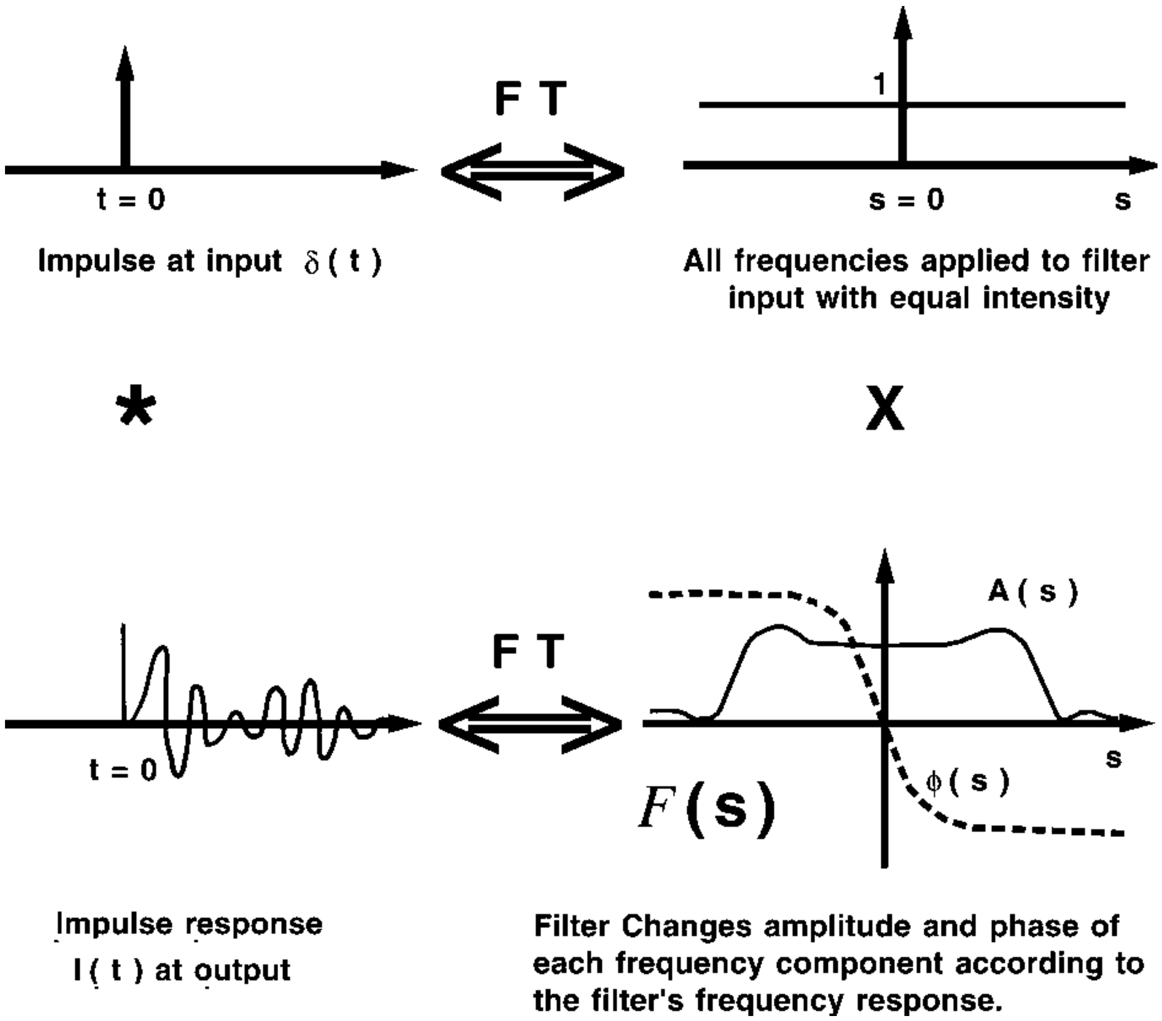

Fig. 8: Fourier Transform of the Impulse and the Impulse-Response of a filter.

6.1 Filtering of constant amplitude signals

We shall come later to various forms of modulation, but at this point we need only say that there are forms of modulation which only alter the phase of the signal and leave the amplitude constant. Frequency modulation (FM), as used for audio broadcasting, is one such form. The modulated signal may be Fourier analyzed into a carrier and a lot of sidebands. It is easy to understand that it requires a very intricate and specific inter-relationship between the amplitudes and phases of all these constant frequency components to make them all add up to form a signal of constant amplitude but varying frequency. The condition is in fact that the autocorrelation function of the FT of the signal should be a delta function

$$\delta(s) = \int F(s_1)\, F^*(s_1 - s)\, ds_1 \qquad (18).$$

Any tampering with the amplitudes and phases of the components will cause departure from this condition and give rise to a signal which is no longer of constant amplitude.

So passing an FM signal through a filter, even one that looks as if its passband is wide enough to pass all the major frequency components, will result in an output signal that is no longer of constant amplitude. The same happens with any constant amplitude signal phase modulated in some way.

A common form of modulation is Binary Phase Shift Keying (BPSK). This is a digital modulation scheme where the 1's and 0's of the data stream are represented by two alternate versions of the RF carrier mutually 180° in phase. An elementary way of modulating such a signal is with a switch as shown on the LHS of Fig. 9. The abrupt phase reversals are discontinuities in the zeroth derivative of the amplitude of the signal and generate sidebands that fall off as s^{-2} in power, where s is now the frequency offset from the carrier. Only the designers of the *GPS* and *GLONASS* systems thought this was an acceptable form of signal to transmit. Generally, some effort is made to reduce the amplitudes of the *unwanted* (an ITU technical term) sidebands. A suitable filter will do it. How it does it is by imposing continuity on a greater number of the signal's derivatives. There is no other way. But modifying the amplitudes and phases of the signal components inevitably causes the signal amplitude to vary. One gets PM to AM conversion: *Phase Modulation* into *Amplitude Modulation.*

This is of no great consequence provided subsequent handling of the signal is entirely linear, as it would be if the filter was between the final power amplifier and the antenna. However, there are good reasons for not wanting to put a narrow band filter there. They have to be made of high-Q resonators which magnify the applied voltages. They are inevitably lossy, and at high power subject to voltage breakdown. High-Q high-power filters are possible, but are very much to be avoided, not least because they will be big, heavy, and expensive.

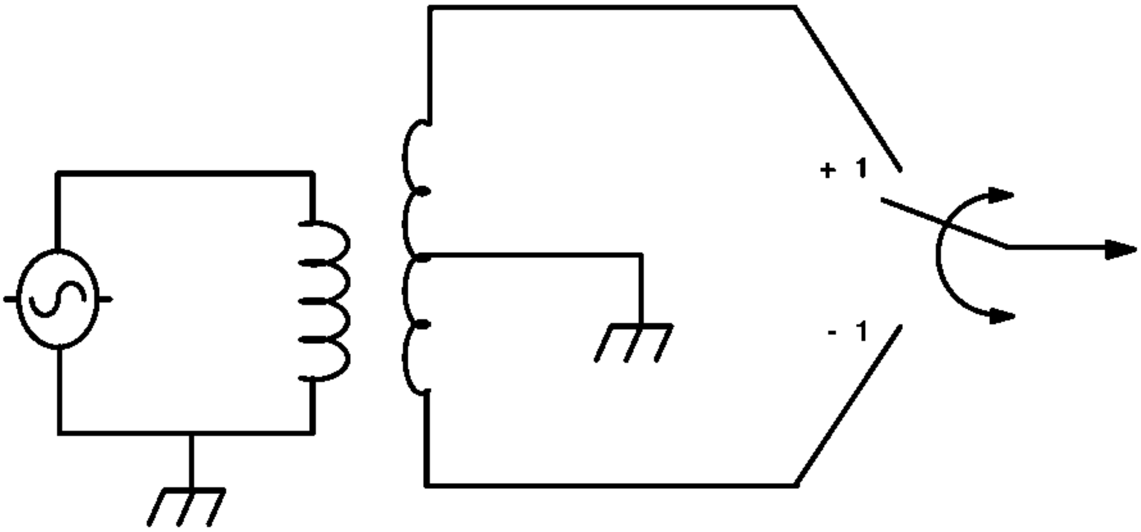

Fig. 9: Reversing switch used to achieve Binary Phase Shift Keying (BPSK).

6.2 Sideband Recovery - Spectral Regrowth

An alternative place to put the filter is before the final Power Amplifier (PA). Here the power level is less, insertion loss is of less consequence, and it would be good provided the final PA was linear. However one of the attractions of these constant amplitude modulation schemes is that the final PA can be run at high efficiency at its maximum power level. That means the amplifier is driven into saturation and in turn means that the amplitude fluctuations at the input don't appear at the output. This reassertion of the constant amplitude condition further modifies the amplitudes and phases of the signal components. It has the effect of undoing some of the good work of the filter. One has the phenomenon of *Sideband Recovery* alias *Spectral Regrowth*: see Fig. 10. I don't know if it is known whether a long chain of filters and saturating amplifiers would eventually produce a signal with both low sidebands and of constant amplitude, it is an interesting academic speculation, but certainly at present people seem simply to accept that they cannot get rid of their unwanted sidebands, and so far as I can see the ITU writes rules which provide no great incentive to find a way around the problem.

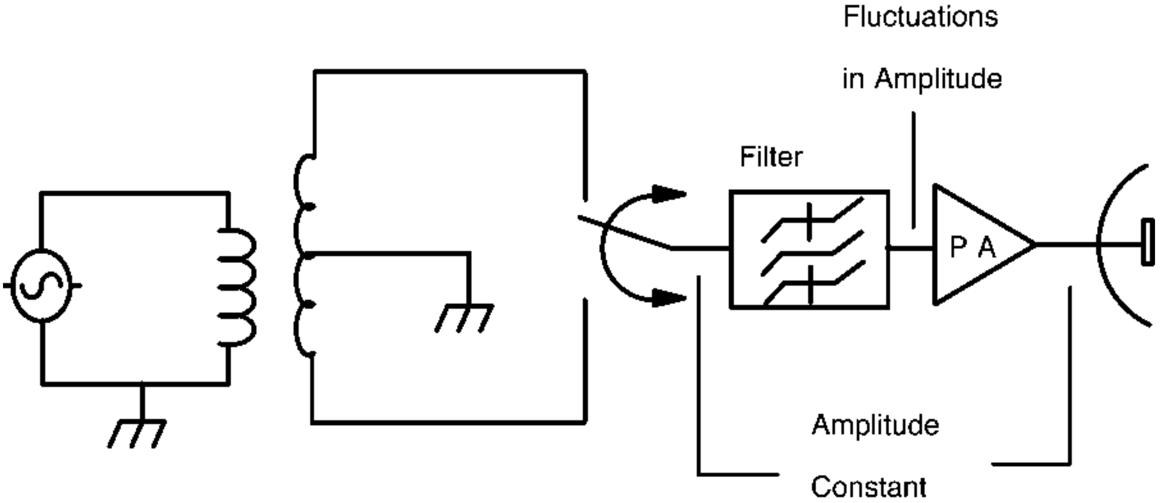

Fig. 10: Sideband Recovery – Spectral Regrowth. The modulator in the first unit introduces sudden phase jumps into a constant amplitude signal, whose spectrum then has far-flung sidebands. Passing this signal to a filter rejects the sidebands, but causes the amplitude to fluctuate. Saturating the power amplifier reimposes a constant amplitude, but sidebands partially return.

In my view it is a mistake to generate sidebands and then try to remove them. I think it is much better to modulate the signal in such a way that the unwanted sidebands are not generated in the first place. I have built a *proof-of-concept* QPSK modulator that does just that. Instead of switching the phase of the signal abruptly from one phase state to another, it is guided slowly in a controlled way from one state to the next. This in an example of what I later learnt was already known as CPM, *Continuous Phase Modulation*. The amplitude of the signal is constant, the phase changes are gradual, the sidebands are inherently low and there is no need for a filter. *Sideband Recovery / Spectral Regrowth* is then not an issue.

7 Modulation

I have already mentioned certain types of modulation. For completeness' sake we must mention the various classical modulations. The earliest type was just ON-OFF keying of a carrier and this was used with Morse Code for *Wireless Telegraphy*. This is still practiced by radio amateurs and it is a minor art form when done well. It was noticed long ago that it was important not to have the transmitter come on too abruptly when the Morse key was pressed, as it caused *Key Clicks* audible on adjacent channels. We now know why.

7.1 AM and SSB

For broadcasting *Amplitude Modulation* (AM) was first adopted. Here the envelope of the carrier is made to vary according to the waveform of the audio signal carried: see Fig. 11. Its chief merit is that it is easy to make a simple detector for recovering the audio signal and this was important in the days when radio sets had very few active components. However, it is a wretchedly inefficient scheme from two points of view. Firstly the amplitude of the carrier has to exceed twice the maximum value of the sum of all the sidebands. Thus most of the RF power goes into radiating a pure monotonous sinewave that is as boring as the 60 Hz on the power lines. So it is inefficient power-wise. It is also by any definition inefficient from the point of view of use of the spectrum. The reason is that the sidebands are generated in mirror-image pairs, an *upper sideband* and *lower sideband*, and each one alone carries the audio signal. So it occupies at least twice the spectrum that it needs. Despite these inefficiencies it is still much used.

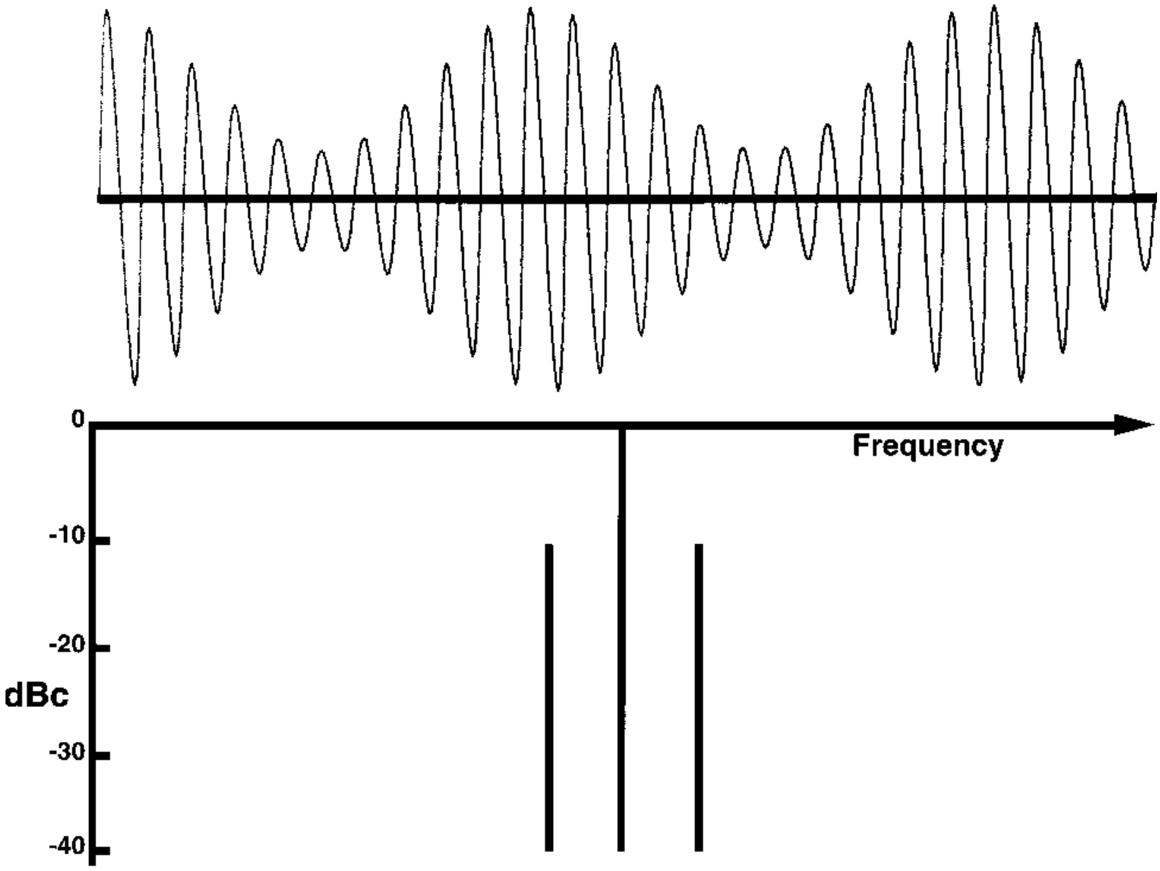

Fig. 11: Amplitude modulation with a modulation index m = 0.6. Each sideband is at -10.45 dBc.

An improvement is *Single Side Band* (SSB). As the name implies only one side band is transmitted. Generally the carrier is also suppressed so the power efficiency is much improved. However the audio signal is now carried in both the amplitude and the phase of the resulting signal, demodulation is more complicated, and the transmitter PA must be strictly linear to carry the signal. There is a move afoot to change over to SSB for shortwave broadcasting, but it will be a very long time before it wholly replaces AM.

7.2 FM

I have already discussed FM. All I need add is that it exists in two forms. Wide deviation FM is used for audio broadcast and narrow deviation FM is used for such things as marine VHF communications. It is interesting that provided the RF signal-to-noise ratio exceeds a certain threshold, the signal-to-noise ratio of the audio at the demodulator output is much better than the RF signal-to-noise ratio at the input.

7.3 Digital modulation

More interesting for us are the various forms of digital modulations. There is a whole class in which the signal moves from one to another discrete phase state. In principle these changes can be at the Nyquist rate for the given bandwidth. These phase states can be represented on an Argand diagram and may be described as "Constellation diagrams". Four such schemes are shown in Fig. 12 and their theoretical limiting performance are tabulated in Table 1.

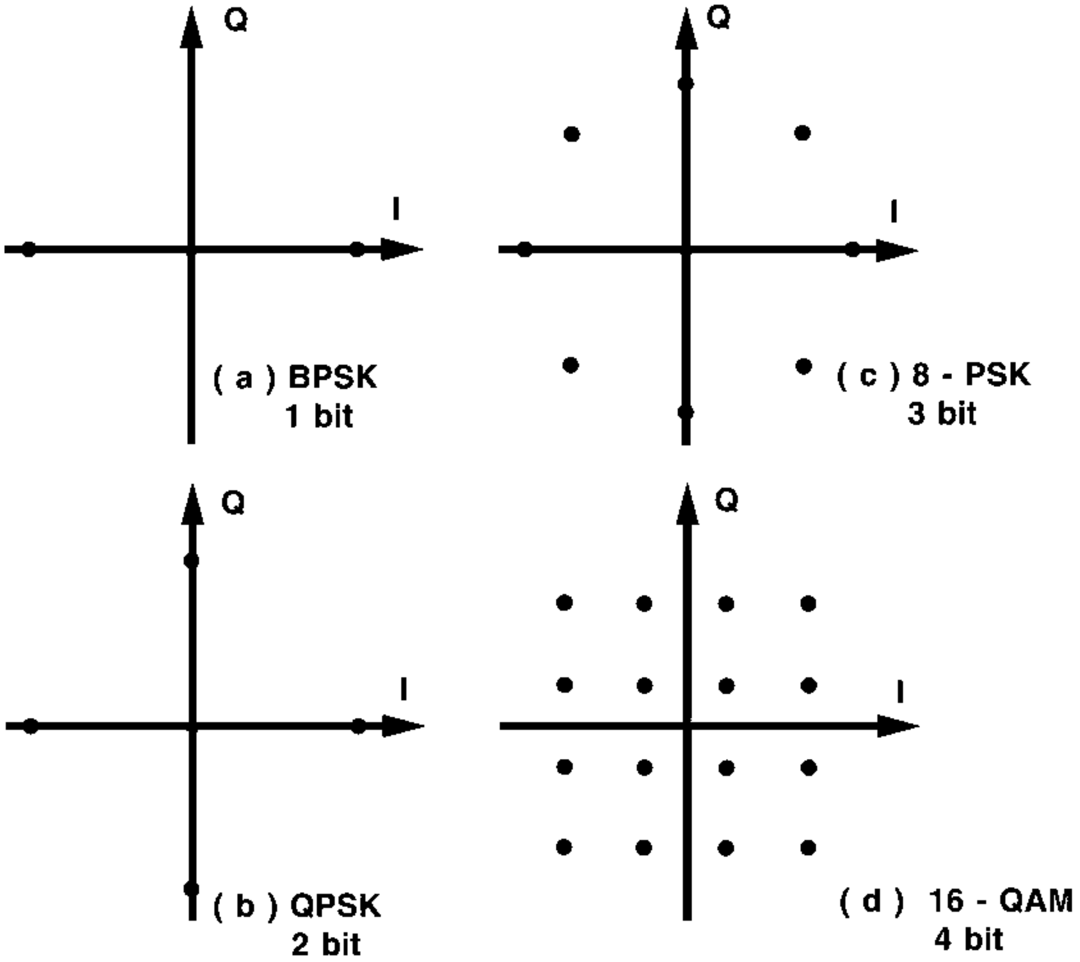

Fig. 12: "Constellation" Diagrams for various digital modulators.

		No. of Phase States	max R bits/sec/Hz
Binary Phase Shift Keying	BPSK	2	2
Quadrature Phase Shift Keying	QPSK	4	4
	8-PSK	8	6
	16-QAM	16	8

Table 1

It will be noticed that the first three operate in principle with a signal of constant amplitude. The last requires the signal to have three distinguishable amplitudes. For this the PA need not be highly linear. Each one listed has variants. For instance with QPSK the x-wise transitions may or may not coincide with the times of the y-wise transitions.

The given bit rates are based on the assumption that the signal can unambiguously adopt a new phase state every $1/(2B)$, at the Nyquist rate. In reality there may be ambiguity because the impulse response of the filters causes some residue of one phase state to be carried over to the next, and this causes *inter symbol interference* (isi). Of course additive noise makes the states indistinct and introduces errors in the bit stream. By adopting error correcting codes, errors can be tolerated, but at the expense of adding "overhead" bits, which then reduce the capacity for the main "payload" bits. There are an enormous number of variants. From the point of view of Spectrum Management, however, the key thing is that all these schemes are conceived in principle as making instantaneous changes of state, and all therefore are inherently prone to emitting a sinc-squared form of power spectrum. Any filter added to reduce the OOBs is certain to add to the isi problem, and therefore users of these schemes cherish their supposedly unwanted emissions.

7.4 Coded Orthogonal Frequency Division Multiplex: COFDM

An interesting and relatively new form of modulation is *Coded Orthogonal Frequency Division Multiplex* (COFDM). It is used for the new Digital TV and Digital Audio Broadcasting (DAB). It is conceived as a large number of very closely spaced carriers each of which is QPSK modulated at some very low rate. From our point of view it has two very interesting properties. One is that it occupies a well-defined band with virtually uniform power spectral density and the power spectrum falls very fast at the edge of the band. The other is that the superposition of the large number of unit amplitude carriers results, by virtue of the *Central Limit Theorem,* in an emitted waveform which very much looks like Gaussian noise. Recall Shannon's Channel Capacity Theorem. I don't know how closely it approaches the theoretical limit, but perhaps it is a move in the right direction. But it does have a down side. That is that the effective peak to rms ratio for Gaussian noise is such that the PA has to be linear and operate in Class-A, which is inherently inefficient from the power point of view.

7.5 Spread Spectrum

There are three types of spread spectrum. All were invented either to provide cryptographically secure communication or to allow covert communication. The difference is that cryptographically secure means that there is no secret that there is a transmission, it is just that it is scrambled in such a fashion that no unauthorized interceptor is able to read the message. Covert however seeks to conceal the very existence of the transmission.

There are three types of spread spectrum. The first is frequency hopping. If a communication system has a large number of otherwise conventional channels, a transmission can be very effectively jumbled up by jumping channels several times per second, possibly at the phoneme rate, and jumping in a prearranged but apparently random fashion between the channels. Naturally such a transmission in effect uses a band as wide as the total spread of the channels. I think this is very straightforward and there is nothing more to be said, except that so far as I know only the military use frequency hopping.

The second type is time-hopping or burst transmission. The presumably digitized message is stored up, and at a prearranged moment transmitted at an enormous data rate, so that the whole event is finished before a would be interceptor has time to get set up to receive it. Again I think this is exclusively a military technique.

The third type, which is what one normally thinks of as *spread spectrum,* is in more general use. For reasons that I don't quite understand, it is called *Direct Sequence Spread Spectrum* (DSSS). The scheme is outlined in Fig. 13. An RF carrier is modulated with BPSK, which simply reverses the phase very fast, according to some prearranged pseudo-random code. The consequence of this in the frequency domain is to spread the energy rather thinly over a wide band. It can be spread so thin that for some receivers it is below the noise level, and thus its very presence is hard to discern. However a receiver "in the know" and provided with an identical generator of the pseudo-random code, and having a similar reversing switch, undoes the effect of the switch in the transmitter. So the sinewave signal is reconstituted. As described

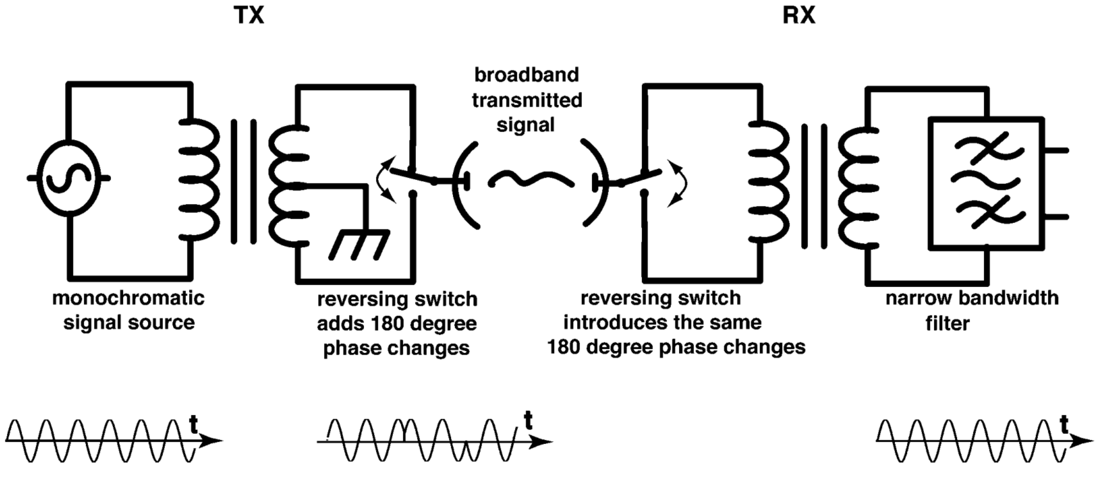

Fig. 13: Direct Sequence Spread Spectrum (DSSS) using BPSK modulation, so the first reversing switch introduces 180 degree phase reversals according to a pseudo-random code, while the second introduces the same reversals to reconstitute the original, narrow-band signal. The output is a “recompressed” narrow-band signal.

there is no communication. But as well as the fast pseudo-random code the outgoing signal can be phase reversal modulated a second time at a much lower data rate at the transmitter, and this second modulation is of course not stripped by the switch in the receiver. The de-spread signal has a much smaller bandwidth than the spread signal, and so in its own bandwidth the signal can be well above noise. Any other transmission entering the receiver that might cause interference gets chopped up by the receiver switch and its energy is spread out and then rejected by internal filters. So this type of transmission may be covert, is cryptographically secure, and is robust against interference whether inadvertent or deliberate.

As well as these properties it may serve another function. The despreading only occurs if the receiver switch is in step with the phase reversals on the incoming signal. If the receiver switch drifts out of synchronization, the despreading is lost. The timing has to be precise to within a fraction of the reciprocal of the so-called *chip rate,* which is just the bit rate of the pseudo-random pulses. It is this feature of DSSS, which makes it the key to the *GPS* and *GLONASS* navigation satellite systems. In *GPS* the civilian so-called C/A code has a chip rate of 1.023 MHz (Note: $2^{10} - 1 = 1023$). A timing shift of ~1 μs is enough for the codes to get completely uncorrelated. But the receiver adjusts its code generator to track the incoming code, using a delay-lock loop, and synchronization is maintained to about 10 ns. By this means the one-way propagation delay from the distant satellite is measured with an error corresponding to a distance error of only a few metres. This is the key to the system's wonderful positional precision. The *GLONASS* system is in effect identical except that its C/A code chip rate is 0.511 MHz (this rate was chosen because $511 = 2^9 - 1$).

This matching of the pseudo-random codes is highly specific and works like a lock matching a key. With *GPS* all the satellites transmit on the same carrier frequency, and therefore the signals from all visible satellites are superimposed at the input to the receiver. But all are below the noise, and even the aggregate of all the signals barely increases the total noise. Independent despreading switches, each controlled by its own pseudo-random code generator, can simultaneously extract and track the signal from its own satellite.

DSSS can of course be used for covert communication, and it is often said that such systems can be "overlaid" across otherwise occupied bands without the users of those bands being aware of it. I believe there was once such a system in Europe that used to overlay the entire broadcasting "Medium Wave Band". Maybe that can be done in a broadcasting band, but it surely can't be done in a radio astronomy band! It would be noticed very quickly.

To my mind such covert overlaying is rather like the old reprehensible practice of coin clipping. In the days when coins were made of precious metal, certain people filed a little off the edge of every coin, thinking the recipient wouldn't notice the loss but little by little they would get rich. I fear this very thing is now being allowed to happen under the name of *Ultra Wide Band.* Perhaps we should consider this a form of spread spectrum. It is certainly in the spirit of coin clipping. It is like stealing from supermarkets. The shoplifter says, "I take so little, they won't notice the loss".

Direct sequence spread spectrum is used with mobile phones under the name *Code Division Multiple Access* or CDMA. Here an integrated system chooses to reuse the same carrier, just like *GPS*, and each user uses his own pseudo-random code. It certainly provides privacy but I can't recall the precise justification for its adoption. From our point of view the worry of it is that the sidebands generated by the spreading process will fall far outside the system's allocated band.

7.6 No Modulation

The ITU treats the Radio Astronomy Service as a sort of "pretend" communication service. Yet there are profound differences between all forms of remote sensing, both active and passive, and communications.

In a communication system there are:

1. Agreed frequencies, modulation scheme, symbols, codes, ciphers, etc.
2. A distant agent is seeking to "inform" an idea in the recipient's mind. Both share a common "universe of discourse".

A radio astronomer in making an observation is not receiving a communication from a distant galaxy. Nature is not sending messages to astronomers any more than the White Cliffs of Dover send messages to a ship's radar. In remote sensing there are:

1. No agreements.
2. No sending agent.
3. There is no rate of transmission in bits/sec.
4. The observer is alone, trying to "inform" his own mind.

Remote Sensing is NOT communication. One would hope that the ITU would come to understand this.

8 On Spectrum Efficiency

I do not know of a satisfactory definition of "spectrum efficiency". Generally in science or engineering efficiency is defined as

$$\frac{\text{What you get out}}{\text{What you have to put in}} \quad \text{or} \quad \frac{\text{What you get}}{\text{What you have to pay for}}$$

and the numerator and denominator are expressed in the same or equivalent units. Such a definition is applicable for instance to a Heat Engine:

(Work out / Heat in)

or a radio transmitter:

(RF power out / DC power in)

With such definitions it is quite clear that efficiency can be expressed as a percentage, and that the very best is 100 %.

But there is no such definition for *efficiency* of use of the radio spectrum, though that doesn't stop people talking about it. They mouth platitudes about the importance of using the spectrum efficiently. But what stops them in their tracks is asking what they mean! One only has to ask oneself what scenario would constitute 100 % efficient use of the spectrum, to see that the expression is devoid of meaning.

There are however many definitions of spectrum efficiency, more than I know. Each may have validity in its own limited context. However I don't believe there is any single universally satisfactory definition. What I will do is list the considerations that I think should enter into a satisfactory definition, and then perhaps we could collectively invent a definition that embraces them all.

1. To some it seems obvious that the spectrum is being well used if lots of information is being communicated. If the spectrum is well occupied. This idea suggests that services that operate only occasionally are inefficient users of the spectrum. But is one to say that Emergency services and bands allocated to Search and Rescue represent inefficient use of the spectrum? Is a marine radar using the spectrum inefficiently when it receives no echoes? Absence of a signal is good news!

   An analogy may help. The bureaucrats who manage our universities view lecture halls as "plant" which should be used "efficiently". It is inefficient they say to have plant unused and standing idle. They are keen that the plant, provided of course at great expense, be used to full capacity. But they are not consistent in this industrial view. It is not the view they adopt for the provision of rest rooms. No one suggests it is inefficient if the rest rooms aren't used to capacity! Everyone agrees the important thing is that the capacity should be available to meet anticipated demand. Telephone engineers install channel capacity on that basis without it being thought inefficient. Telephone systems are designed so that there is *nearly always* considerable unused capacity. *Quality of service*, which includes finding an unused line available on demand, is the decisive criterion. Why should it be different for lecture halls and the radio spectrum?

2. One important aspect is the volume of space or the area of ground in which one user of the spectrum denies its use to another. Clearly the smaller the space occupied, the more often the same frequencies can be used. The ultimate in this regard is the telephone system. Every pair of wires can reuse the same range of frequencies! This effect is recognized in measures of spectrum efficiency of cellular systems. In an urban environment where the propagation losses are high, the same frequency can be reused close by. In open country, where losses are low, the cells have to be much bigger and the "reuse distance" gets greater.

3. The idea that use of spectrum may deny its use to others should also be applied in "frequency space". If the Out-Of-Band emissions (OOBs) of a broadcasting satellite, say, prevent an adjacent band from being used for its intended purpose, then it is using frequency space that is not properly its own, and this "loss of amenity" for its neighbour in frequency space needs to be included in any comprehensive measure of the efficiency with which it uses the spectrum. I know of no measure of spectrum efficiency that

includes this trespass.

4. How should the spectrum usage of the Radio Astronomy Service be measured? Is it using the spectrum inefficiently if every radio observatory is not observing on every band allocated to radio astronomy all the time? Or if it isn't looking in every direction! Is it efficient that the various allocations to the RAS should be like rest rooms, usually unused but available "on demand"?

5. Is it efficient if a band is occupied? Remember that information is conveyed by improbable messages. How improbable are the signals conveyed by a TV signal? All those sync pulses are absolutely predictable and therefore convey no information, in Shannon's sense! One often overhears people speaking into a mobile phone. How often has one overheard something momentous being said? Is it efficient to clutter the spectrum with inconsequential babble? It may be efficient from the point of view of a mobile phone company, but it is not spectrum efficient.

$$\frac{\text{What they get: Income Revenue}}{\text{What is paid for: others (RA) give up their use of the spectrum}}$$

That is called "externalizing your costs"!

9 Transmitters

For our purposes, stripped of inessentials, a radio transmitter is made up of a high power amplifier (PA), which is supplied by a signal source and a source of generally DC power, and is followed by an output filter, a transmission line, and an antenna.

The term *high power* is strictly relative. In a mobile phone it may be less than 1 Watt. On the Arecibo radar it may be 1 MW. But it is nearly always the dominant power consuming part of any radio installation. The power efficiency of a PA is always a matter of concern. At one end it may be because the power determines how long the batteries last, at the other end it is because the electricity bill becomes considerable. On a spacecraft power is always limited.

At low frequencies, one can make one's amplifiers linear by negative feedback, as with the common op-amp, but this is only possible if the amplifying device has a good deal more intrinsic gain than one really needs. At RF gain is not so easily come by and linearity cannot be assured by negative feedback. So one is forced to accept the inherent non-linearity of the amplifying device. It is a great Universal Truth that

ALL AMPLIFIERS ARE NON-LINEAR

For small signals they may be regarded as linear, but when they are pushed to the point that a reasonable fraction of the DC power input gets transformed into RF output power, they manifest non-linearity. The nonlinearity may be manifest not only in a lack of proportionality between the output and input levels, but also as a change in the phase relationship between the input and output. This is particularly true of transistor PAs.

One must understand the effect of amplifier nonlinearity on the signal modulation. It is certain to be distorted. There is only one class of modulation that can be passed through a non-linear amplifier without change of form, and that is a signal of identically constant amplitude. Such a signal must be modulated only in its phase. We have already discussed such signals.

The effect of non-linearity is to add frequency components that were not present in the input signal. The effect of amplifier saturation on an AM signal is shown in Fig. 14. The clipping of the high peaks can be regarded as achieved by the negative addition of the missing portions. In the figure one sees that the negatively added peaks form a series of short pulses and these of course have harmonics which are multiples of the original modulation frequency. In general amplifier saturation leads to intermodulation which is to say the generation of side-bands at sum and difference frequencies of the intended sidebands. These intermodulation components can fall outside the allocated frequency band and constitute OOBs (Out-Of-Band) emissions.

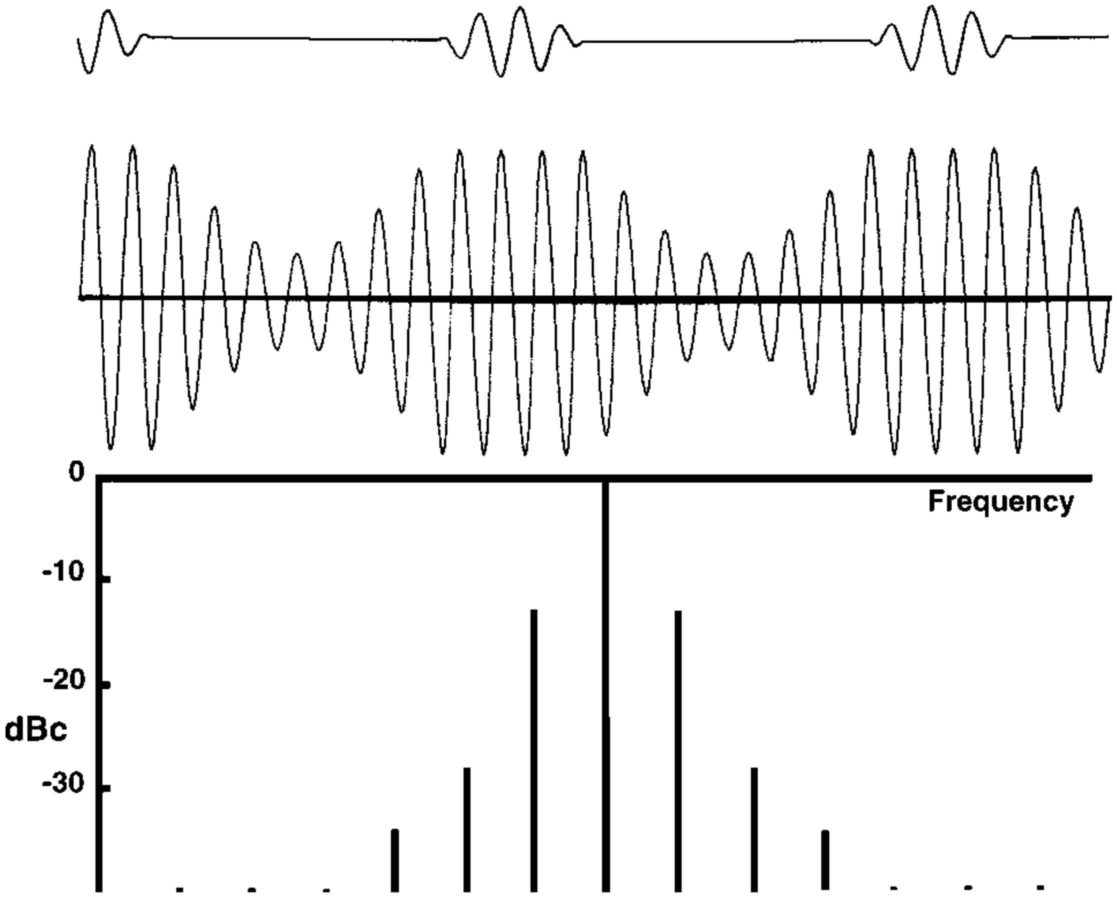

Fig. 14: Intermodulation due to transmitter saturation. Amplitude modulation with m = 0.6 is clipped at +2.27 dBc. In effect the pulses of the first line have been added to the unclipped signal. These pulses are composed of an extended set of sidebands.

This is precisely the problem with the *IRIDIUM* satellites. The PAs have to handle a number of independent carriers simultaneously. The aggregate sum of these must look very like Gaussian noise. Occasionally these add up to a spike which drives the amplifiers into saturation and out-of-band emission is generated. The aggregate signal level of course depends on the number of carriers, so the problem is "traffic" loading dependent.

10 Antennae

An antenna is a passive reciprocal coupling element, ideally loss-free that couples a guided wave, on a transmission line or wave-guide, to an unguided or free-space wave. It can be used to transmit or to receive. Its key parameters are its far-field pattern, the way its sensitivity varies with direction, its bandwidth, and its input impedance. There are many types of antenna.

10.1 Conventional antennae

It is convenient to start by considering an antenna in transmitting mode. The high frequency current in a radiating element, perhaps a dipole or a monopole in a waveguide, generates an electromagnetic field that carries the power away. The EM field can be conceived as divided into three zones. Very close to the radiating element there is an *induction field*. This is largely confined to within about one wavelength of the radiating element. It has field components which fall with distance r as r^{-2} and as r^{-3}, and these rapidly become insignificant compared to the *radiation field* which varies as r^{-1}. For highly directive antennae the *radiation field* itself is separated into the *near-field* or *Fresnel region* (Augustin Jean Fresnel 1788 - 1827,

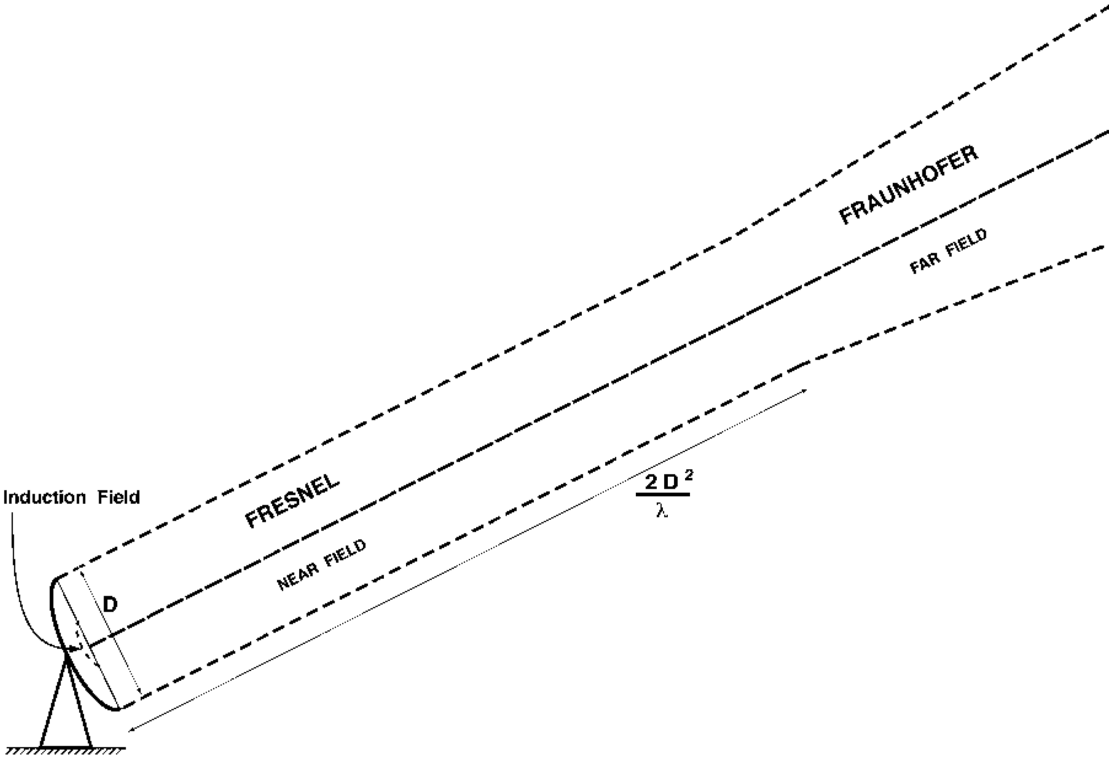

Fig. 15: Field regions associated with a narrow beam antenna in transmitting mode.

French physicist), and the *far-field* or *Fraunhofer region* (Joseph von Fraunhofer 1787-1826, German optician and physicist): note the relationship between their dates. The transition between the two may be defined as at distance r such that $r\lambda = 2D^2$ where λ is the wavelength and D the diameter of the radiating aperture. When a dish antenna is used to transmit, the radiation travels out more or less in a cylinder with the same diameter as the dish, as far as the near/far field transition, and only then spreads out into a conical beam: see Fig. 15. The transition point can be quite a long way away: for example with D = 100 m, $\lambda = 6$ cm, $r \approx 330$ km. To efficiently receive a signal from a source at a distance less than this transition distance requires the dish antenna to be refocused. Large optical telescopes need to be refocused to look at the Moon. It is too close to be regarded as at infinity. The same problem may arise when a large radio telescope deliberately receives signals from a LEO (a satellite in Low Earth Orbit).

Consider a transmitting antenna. It radiates with an *angular power flux density* in the far-field $P(\theta, \phi)$ W steradian^{-1}, where θ & ϕ are the spherical coordinates. When multiplied by an arbitrary constant, $P(\theta, \phi)$ is sometimes simply called the *antenna pattern*. It generally consists of a *main beam* confined to a narrow span of directions, and a multitude of smaller *sidelobes* in other directions.

Assuming no ohmic loss, the integral over all directions must be equal to the transmitter power. Thus

$$\text{Transmitter power} \quad P_{tx} = \iint_{4\pi} P(\theta, \phi)\, d\Omega \qquad (19).$$

If the same power were radiated by a hypothetical isotropic or omnidirectional antenna, which incidentally doesn't exist, the *angular power flux density* would be simply $P_{tx}/4\pi$ in all directions. The real antenna concentrates the power more in some directions than in others, but doesn't make or add any to the total. Nevertheless the extent to which an antenna concentrates its power in a given direction is called its *directive gain* $G(\theta, \phi)$, or simply its *gain*

$$G(\theta, \phi) = \frac{P(\theta, \phi)}{\frac{1}{4\pi}\iint_{4\pi} P(\theta, \phi)\, d\Omega} \qquad (20).$$

The fact that this quantity is referred to as a *gain* is the source of much confusion because an antenna doesn't have gain in the same sense as an amplifier has gain. It would have been better if the quantity had been named the *concentration factor,* as that is all it is.

It is easy to see that if all the power were radiated uniformly into a narrow conical beam of angular radius θ radians, the directive gain would be $4\pi / \left(\pi\theta^2\right) = 4/\theta^2$, which is simply the number of times the beam's solid angle goes into 4π.

The concept of antenna *gain* has natural significance in the context of a transmitting antenna. However when the antenna is used to receive and is exposed to some incident *power flux density* (PFD) W m^{-2}, the received power appears at the output terminals and it is evident dimensionally that the conversion parameter must be an area. For receiving purposes one needs an antenna's *effective area* A_{eff}. For large dish-type antennae, like we see at Green Bank, the effective area is not very much less, possibly between 70 and 80 % of the ordinary physical area of the dish. However for the sort of thin wire antennae that one sees on masts, or for TV antennae, the effective area is vastly greater than the mere physical area of the wires.

Now I think it is obvious that, as a purely passive device an antenna, which when used to transmit concentrates the energy in a narrow range of directions, will likewise be especially sensitive in that direction. Reciprocity applies. So the *directive gain* in a particular direction is proportional to the *effective area* when receiving from the same direction. I won't prove it but there is a universal relationship between *gain* and *effective area*. It is

$$G = 4\pi A_{eff} / \lambda^2 \qquad (21).$$

I emphasize that here the *gain* is that relative to an isotropic antenna. For a large antenna the *gain* can be a large number and it is usual to express it in *decibels*. It is then $10 \log_{10}(G)$ dBi, where the i reminds one that it is relative to an isotropic antenna.

For a uniform conical beam

$$G = 4 / \theta^2 = 4\pi A_{eff} / \lambda^2 \qquad (22),$$

so if we suppose that the aperture efficiency is 100 % for a dish antenna of diameter D, and that $A = \pi D^2 / 4$, we obtain for the angular diameter of the conical beam

$$2\theta = (4/\pi)(\lambda / D) = 1.27(\lambda / D) \qquad (23).$$

This is very close to the *"half-power beam width"* achieved with a large dish antenna.

Example: What is the gain and the beam width of a 32 m diameter dish at wavelength $\lambda = 21$cm?

The physical area is $\pi D^2 / 4 = 256\pi = 804$ m^2

Typically the *aperture efficiency* $\eta = 0.7$ so

the *effective area* $A_{eff} = 0.7 \times 804 = 563$ m^2

The gain $G = 4\pi \times 563 / 0.21^2 = 160{,}428 \Rightarrow +52$ dBi

Beamwidth $\approx 1.3\ (0.21 / 32) \times 180 / \pi \approx 0.5°$

The gain is that on the peak of the main lobe. In other directions both the gain and the effective area fall off dramatically. At some point the gain of a large dish becomes no more than that of an isotropic antenna, which is 1 by definition. At that point its effective area is $\lambda^2/4\pi$, which at 21cm is only 35 cm^2. In reality η might be more or less than 0.7, but the true gain is unlikely to differ from that computed by more than ~ ± 0.6 dB.

It is interesting that the effective area of an isotropic antenna is equal to that of a circle of one wavelength in circumference.

10.2 Active antennae

Despite the usual understanding that an antenna is a passive coupling device, there have been recent developments with integrating radiating and active devices in such a way that there is no distinct interface between the antenna proper and the active amplifier. These integrated devices are referred to as *active antennae.* The antenna proper may be integrated with a low noise amplifier to form an active receiving antenna, or with a PA to form an active transmitting antenna. The *IRIDIUM* satellites' *main mission antennae* are active in both modes and contain embedded T/R switches as well. The development of *active antennae* was not foreseen in the writing of the ITU's RRs. Consequently there is confusion when certain protagonists maintain disingenuously that an *active antenna* is just an *antenna* like any other. It certainly isn't. It presents technical and conceptual difficulties. It is difficult to measure the output power of an active transmitting antenna and the noise factor of an active receiving antenna, and it becomes impossible to specify what may or may not pass on the transmission line between transmitter and antenna, because these isn't one. The absence of a transmission line also makes it impossible to insert a filter.

10.3 Array antennae

Large antennae may be made of arrays of small antennae. At one extreme one has interferometers, which are perhaps to be thought of as sparsely filled arrays, at the other one has things like the *IRIDIUM main mission antennae,* which are composed of 105 individual transmitting and receiving modules laid out on 74" x 34" panels. Each individual "patch antenna" has +4 dBi gain and gives +23.9 dBi for the whole array. The difficulty with arrays in which the elements are close together, is that there is significant interaction between adjacent elements. Consequently the beam doesn't always point in the expected direction, and the element input impedances become functions of beam direction. They are very complicated and I don't think it appropriate to discuss them further.

11 Concluding remarks

I have tried to cover a lot of ground. Each of the topics I've touched on could easily be developed into an extended course. My purpose has been to introduce ideas and subjects with which I believe Spectrum Managers should be familiar. I think the measures of information and channel capacity are especially important, and I have given them prominence not least because I think they may be new to those coming to our subject from a physics background. Possibly the more theoretically inclined with engineering backgrounds may already be familiar with them. However, I've never been made aware that any of the people I've met at meetings concerned with Spectrum Management have been familiar with them, yet they certainly are relevant to discussions of *necessary bandwidth.* In a certain sense there is perhaps no such thing as *necessary bandwidth,* because in principle any bit rate can be passed through any given bandwidth. No wonder I haven't grasped the ITU's concept of *necessary bandwidth*.

I think the discussion of discontinuous derivatives of signals is simple and cuts through all manner of complication when discussing *Out-Of-Band emissions.* The simple message is that to avoid spilling energy outside an allocated band, the signal must be made smooth to a high degree. There is no other way. It is not clear to me that this is sufficiently widely understood. "Make it smooth" is the message.

I haven't said a great deal about transmitters. The Universal Truth is that ALL AMPLIFIERS ARE NON-LINEAR. It is easy to understand that high efficiency is frequently an operational necessity, but that means operation in nonlinear mode and non-linearity necessarily causes intermodulation. Post PA filters are unwelcome for a number of reasons. My own inclination is to urge the use of *Continuous Phase Modulation,* but I am aware that viewed from the point of view of the *Channel Capacity Theorem* a constant amplitude signal cannot be in every sense optimal.

My discussion of antennae has been an independent departure not well connected with my other themes. But antennae are a vast and difficult subject on their own. I hope I have conveyed the rudiments and provided at least some simple rules of thumb.

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Units and Calculations – Using Decibels

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A task that pops up all the time when you are attending spectrum management meetings is the need to do a quick calculation in your head, to add quantitative validity to the discussion. In a more complicated case you might have to sit down and work something out on paper during a lunch break, but you won't have the luxury of several days to think about it. For these reasons, it's very useful to know how to get "good enough" answers quickly.

LOGARITHMIC SCALING

A logarithmic factor of 10 is called a *Bel*, in honor of Alexander Graham Bell. If a quantity is 10^B, then B is its representation in Bels, using the base-10 logarithm rule you learned in school:

$$\mathbf{\log_{10} (10^B) = B \ \ [Bels]}$$

Thus the number 100 is 2 Bels, because $\log 10^2 = 2$. Negative Bel values represent values less than one, so $0.01 = 1/100 = 10^{-2}$ is -2 Bels, because $\log_{10} 10^{-2} = -2$.

While Bels are rarely used, the *decibel*, which is 1/10th of a Bel, is, by contrast, the lingua franca of the engineering community. The abbreviation for the decibel is dB, and the equation relating a quantity D to itself in dB units has an extra '10' in it, such that

$$\mathbf{D = 10 \log_{10} 10^D \ \ [dB].}$$

To return to our examples, the number 100 is 20 decibels, because $10 \log_{10} 10^2 = 20$, and $0.01 = 1/100$ is -20 dB, because $10 \log_{10} 10^{-2} = -20$.

Perhaps we should keep the **B** in 'decibel' capitalized, but the conventional usage is to spell it in lower case. The honorific capitalization does remain in dB, much to the confusion of typists and word processing software.

NUMERICAL INTERLUDE

There's a good reason for using dB – you can calculate to 1 % with almost no memorization. Factors of 10 are fairly obvious:

Value:	1/1000	1/100	1/10	1	10	100	…	1,000,000,000
In dB:	-30	-20	- 10	0	10	20		90

If you can just remember that conversion of a power of 10 to dB gives

"*Number* of zeros, with a zero after it, negative sign if less than 1"

you are home free.

The real advantage comes from two numerical quirks:

1) A factor of 2 is 3.0102999566 dB, but this differs from 3 dB by only 0.34 %.
2) The square root of 10 is exactly 5 dB, but is larger than π by only 0.66 %.

With just these two facts, it is easy to assemble the following three tables, which contain all the integer values for dB, correct within better than 1 %:

Factor:	1	2	4	8
In dB:	0	3	6	9

Factor:	10	5	5/2	5/4
In dB:	10	7	4	1

Factor:	π/2	π	2π	4π
In dB:	2	5	8	11

If you remember where the table entries come from, you only have to memorize that a factor of 2 is 3 dB and a factor of π is 5 dB. You can look at 77 dB, and realize immediately that it is a factor 2 smaller than 10^8, or 50,000,000. When you want the isotropic aperture $\lambda^2/4\pi$ for a wavelength λ of 1 m, you know immediately that it is 11 dB less than one square meter, or 0.080 square meters. Both answers are correct to better than 1 %.

It is very useful to know conversions for small changes:

1/10 dB is close to +2 % (actually, 2.3 %)

+1 dB is close to +25 % (actually 25.9 %)

-1 dB is close to –20 % (actually -20.6 %).

So if a room-temperature wave-guide has a 0.1 dB loss, it will add 2.3 % of room temperature, or 6.7 K, to the system temperature of a receiver. If it is in the output path of a megawatt radar transmitter it will absorb 23 kW.

Finally, an occasionally useful link to optical astronomy:

A difference of +1 stellar magnitude is exactly -4 dB.

Stellar magnitudes arose originally as the smallest difference in apparent brightness discernable by the human eye, with fainter stars having higher magnitudes. This was later quantified by equating 5 magnitudes to the difference in brightness for two identical stars differing in distance by a factor of 10, and so in apparent brightness by a factor of 1/100. Since a factor of 1/100 is -20 dB, and this corresponds to +5 magnitudes, then +1 magnitude is 1/5 of this, or -4 dB.

What about the Units?

Quantities expressed in dB are always ratios, and hence pure numbers. Thus, for the case of power, we have $P\ (\text{dB}) = 10 \log_{10} (P / P_0)$, where there are several options for P_0 – Watts, milliwatts, etc. The *unit* is therefore commonly appended to dB, which in this case becomes dBW, dBm, etc. Note here the notation dBm for the milliwatt unit, though dBm^2 would be used in the case of square metres. Nor is the dB notation limited to power, as for example:

– Bandwidth B: 10 MHz ⇔ 70 dBHz
– Time τ: 2000 seconds ⇔ 33 dBs

Moreover seconds * Hz gives a pure number, so

– $\sqrt{(B\tau)}$: (70 dBHz + 33 dBs) / 2 = 51.5 dB

Useful Definitions

In the expression for power, $P = k\,T\,B$

T is the absolute temperature in Kelvin degrees
B is the bandwidth
k is Boltzman's constant, $1.38\ 10^{-23}$ Joules/Kelvin (-228.6 dBW/Hz/K)

Hence at room temperature (290 K),

$$kT\,dB = -204.0 \text{ dBW/Hz}.$$

Consider next Power Flux Density (PFD), which is the radiated power passing through a given area, and so often has units of W/m^2. The Spectral Power Flux Density is then the PFD per unit bandwidth, or W/m^2/Hz. Hence

1 Jansky is 10^{-26} W/m^2/Hz (sum of both polarizations) ⇔ -260 dBW/m^2/Hz

The *Isotropic Aperture* (unity gain in all directions) at wavelength λ is $A_i = \lambda^2 / 4\pi$ [m^2], which is the area of a circle with a circumference of λ. The isotropic aperture drops off rapidly with increasing frequency:

Wavelength	Isotropic Aperture
1 m	-11 dBm^2
1 mm	-71 dBm^2

Effective Aperture with Gain G is then $A_e = G\ A_i = G\ \lambda^2 / 4\ \pi\ [m^2]$.

Let us work a few examples

For Tsys: if you know that a room temperature of 290 K is –204 dBW/Hz, what is a Tsys = 29 K in these units? Answer -214 dBW/Hz.

For A_i: You are observing at 20 cm. What is your isotropic aperture in dBm^2? -25 dBm^2.

Radiometer Equation: You observe for 2000 seconds with a bandwidth of 10 MHz. What is your ΔT / Tsys = $1 / \sqrt{(B\ \tau)}$? Answer -51.5 dB.

What SPFD arriving in an isotropic sidelobe equals this noise power? That is, what SPFD radiated at 20 cm matches the k ΔT power indicated by the radiometer equation as being equal to the sensitivity of a 29 K Tsys receiver in a 2000 s integration? Answer -241.5 $dBW/m^2/Hz$.
Hint: One needs much more radiated power to compensate for the loss into an antenna, so the answer is an amalgam of the first three examples, namely the SPFD = Tsys * (ΔT / Tsys) / (isotropic aperture), which is numerically {-214 -(-25) -51.5 dB}.

On 2 % by Monte-Carlo

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1. Introduction

It seems that the Radio Astronomy Service (RAS) will accept, in certain circumstances, that 2% of all 2000 second integrations may be lost to interference. Furthermore it is proposed that whether or not a prospective new source of interference, a new satellite system say, will exceed the 2% level should be determined by Monte-Carlo simulation. The implication is that the new system will only be allowed if it causes interference below the 2% level.

This note ignores all the radio technical aspects of such simulations and simply assumes them to be perfect in all regards. It addresses only the statistical aspect of the problem.

The question that it is proposed the Monte-Carlo method should answer is:

"Will more than 2% of integrations suffer unacceptable interference?"

Unfortunately it is not a question to which the Monte-Carlo method can give a definitive answer! Because it is a statistical method it can only give a probable answer to such questions. One would obviously like the answer to have a "reasonably high" probability of being correct. That "reasonably high" probability needs to be stated in the question and agreed in advance by all concerned. For illustrative purposes I've chosen 90% confidence or a 10% risk that the true probability exceeds 2%. Thus the Monte-Carlo method can in principle answer the modified question:

"Can we be C% sure that no more than 2% of integrations will suffer unacceptable interference?"

(C%=90% for illustration) The Monte-Carlo method is inherently ill suited to determining the probability of unlikely events. Because they occur infrequently a great number of simulations must be carried out to build up significant statistics on their frequency. So it requires a very large number of simulated 2000 second integrations to get a reasonably authoritative answer to the modified question.

The modified question may be answered by the method of *Inverse Probability* and the theoretical framework of this method will be developed. It is concerned with the probability of the probability being less than 2%. A computer program (BORP4.EXE) has been developed in conjunction with this report and some numerical results obtained with it will be presented.

2. Rough statistics.

Let us suppose that each 2000 sec simulated integration can be assessed and labelled in a clear cut way, either as an A, meaning that the interference is acceptable, or as a U, meaning the interference is unacceptable. Then a long series of simulated integrations becomes a sequence of the form $\{\mathrm{AAAAAAAAUAAAAAAAAUAAU}\cdots\}$. If the true probability of getting a U is $p = 2\%$ then in a series of N integrations the *expectation value* for the number of U's is $0.02 \times N$. But this will seldom be the actual number of U's. The actual number is subject to statistical fluctuation of order $\sqrt{0.02N}$. For example in Table 1 I give the *expectation value* for the number of U events in N *trial* integrations. Each is subject to a fluctuation of order its square-root. The last column expresses the results as percentages. It is apparent that to get reasonably good statistics the number of simulated 2000 sec integrations must run into the thousands.

N	expectation value	fluctuation	percentages
200	4	2	2% ± 1%
450	9	3	2% ± 0.66%
800	16	4	2% ± 0.50%
1250	25	5	2% ± 0.4%
1800	36	6	2% ± 0.333%

Table 1. Statistics based on $p = 2\%$

3. The Bernoulli Distribution

A more precise approach is to compute the exact probability distributions. But this must be done with some care. The approach is based on the key assumption that each trial 2000 sec integration is totally independent of the rest.

This assumption would be violated if for instance a constellation of satellites were simulated continuously, so that 2000 sec integrations followed consecutively one after another. In that case the configuration of the system at the end of one integration would be the same as at the beginning of the next, and the trials would not then be statistically independent.

To develop the probability distribution let us start with the most elementary case. If only two trials ($N = 2$) are conducted then there are four possible sequences of events:

AA	AU UA	UU
$(1-p)^2$	$2p(1-p)$	p^2

p is the probability of getting a U

Since AU and UA both have the same number of A's and U's they represent indistinguishable cases. Thus there are only three possible outcomes:

Probability of getting two A's is	$(1-p)^2$
Probability of getting one A and one U is	$2p(1-p)$
Probability of getting two U's is	p^2

If $p = 0.02$ the probabilities are: 0.9604, 0.0392 & 0.0004 respectively.

If there are three trials ($N = 3$) there are eight possible sequences of events and four possible outcomes:

AAA			
	AAU		
	AUA		
	UAA		
		AUU	
		UAU	
		UUA	
			UUU
$(1-p)^3$	$3p(1-p)^2$	$3p^2(1-p)$	p^3

If $p = 0.02$ the probabilities are 0.941192, 0.057624, 0.001176 & 0.000008.

If there are four trials ($N = 4$) there are sixteen sequences of events and five possible outcomes:

AAAA				
	AAAU			
	AAUA			
		AAUU		
	AUAA			
		AUAU		
		AUUA		
			AUUU	
	UAAA			
		UAAU		
		UAUA		
			UAUU	
		UUAA		
			UAUU	
			UUUA	
				UUUU
$(1-p)^4$	$4p(1-p)^3$	$6p^2(1-p)^2$	$4p^3(1-p)$	p^4

It is easy to see the emerging pattern. The numerical factors are Binomial coefficients, the powers of p ascend from the left and the powers of $(1-p)$ descend. There are 2^N sequences of events and $(N+1)$ possible outcomes. The n^{th} term is:

$$\frac{N!}{n!(N-n)!}p^n(1-p)^{N-n} \qquad n = 0, 1, 2, 3, ...(N-1), N \qquad (N+1) \text{ terms in all.}$$

and is the probability of getting n U's with $(N-n)$ A's in N *trial* integrations. The zeroth term, all A's, with $n=0$ is $(1-p)^N$ and the last term, the Nth, with $n=N$, corresponding to all U's, is p^N. This well known result is known as Bernoulli's Theorem. See Woodward (1953).

Using $P(x)$ to mean "the probability of x" rather than some specific function of x, the *Bernoulli Distribution* can be written as:

$$P_p(n) = \frac{N!}{n!(N-n)!} p^n (1-p)^{N-n} \tag{1}$$

meaning the probability of getting n U's given the specific value of p. It is a discrete distribution having value only at integer values of n. It is a proper probability distribution however in so far as it sums to unity.

$$\sum_{n=0}^{N} P_p(n) = 1 \tag{2}$$

However the problem that faces us is to determine the distribution

$$P_n(p)$$

which is the probability distribution for p (the probability of the probability p) given a specific value for n, which has been obtained as a result of N Monte-Carlo simulated integrations. This is the so called *"Inverse Probability"* problem.

4. Inverse Probability.

Again following Woodward the product law for probabilities is

$$P(x,y) \;=\; P(x)P_x(y) \;=\; P_y(x)P(y) \tag{3a, b}$$

Here $P(x,y)$ is the joint probability that two variables named X and Y have specified values x and y simultaneously. $P(x)$ is the probability of X alone having the specified value x. Likewise $P(y)$ is the probability of Y alone having the specified value y. $P_x(y)$ is the *conditional probability* that Y has the value y given that X has the specified value x, and $P_y(x)$ is the *conditional probability* that X has the value x given that Y has the specified value y. Should it happen that $P_x(y)$ is independent of x, then $P_x(y) = P(y)$ and the law reduces to the more familiar form

$$P(x,y) \;=\; P(x)P(y) \tag{4}$$

which applies when X and Y are statistically independent.

Taking equation (3b) and changing the notation to the case of interest we can write

$$P(p)P_p(n) \;=\; P_n(p)P(n) \tag{5}$$

or

$$P_n(p) \;=\; P(p)P_p(n)/P(n) \tag{6}$$

Now the result of our N trials is a specific value of n. Call it n'. So we want to find the probability distribution for p given n':

$$P_{n'}(p) \;=\; P(p)P_p(n')/P(n') \tag{7}$$

Since we know the specific n' the quantity $P(n')$ is of no consequence, it is so to speak history, so again following Woodward we write

$$P_{n'}(p) \;=\; k\,P(p)P_p(n') \tag{8}$$

where k is a constant to be determined retrospectively by normalization.

We must now consider the *prior* probability distribution for p: $P(p)$. Is there any *a priori* reason to expect any particular values of p to occur with greater or lesser probability than others? Certainly we expect $P(p)$ to be small for high values of p, unless the interference is quite appalling, but down in the few % region it is surely substantially constant. So it is fair to write

$$P_{n'}(p) \;=\; k\,P_p(n') \tag{9}$$

(If this is found unsatisfying there are whole treatises to be read on the *PRIOR*-problem.) Here the RHS is the discrete Bernoulli Distribution evaluated at $n = n'$ over a range of values of p. We can imagine in the (n, p) plane $P_p(n)$ as horizontal cuts at constant p, whilst $P_n(p)$ are vertical cuts at constant n. $P_{n'}(p)$, which is a continuous function of p, is one such specific vertical cut. Unfortunately the integral along one such vertical cut

$$\int_{p=0}^{p=1} P_p(n)\,dp \;=\; \int_{p=0}^{p=1} \frac{N!}{n!(N-n)!}\,p^n(1-p)^{N-n}\,dp \;\neq\; 1 \tag{10}$$

(for clarity I now drop the prime on n) so the vertical cuts are not properly normalized probability distributions. It can be shown however, see Appendix, that the integral evaluates to $1/(N+1)$. So

$$P_n(p) \;=\; \frac{(N+1)!}{n!(N-n)!}\,p^n(1-p)^{N-n} \tag{11}$$

is the properly normalized continuous probability distribution for the probability p given the single value n.

This probability distribution may be integrated numerically upwards from $p = 0$ so that the upper limit p_C may be identified such that it is C% certain that the true value of p lies below p_C according to:

$$\int_{p=0}^{p=p_C} P_n(p)\,dp \;=\; C \tag{12}$$

If $C = 0.9$ and $p_{90} \leq 0.02$ then the Monte-Carlo simulation answers the modified question with 90% confidence that the true value of p, the probability that one 2000 sec integration will suffer unacceptable interference, is less than 2%.

5. Computation.

The program BORP4.EXE requires as input three numbers, N the number of trials, n the number of U results and C% the desired confidence limit. It plots on screen the function $P_n(p)$ given by equation (11). At the same time it performs a numerical integration which is used to detect the value of p_C. The integration is continued and the total area under the curve given by the value of sigma. For all normal cases this should give the value 1.000 thus showing that the function is indeed correctly normalized. As the curve is plotted, passage of the $C\%$ point is indicated by a change of colour. The safe part of the curve, below the $C\%$ point, appears in green. The dangerous part, above the $C\%$ point, appears in red. When $n << N$ and both are small the curve is markedly asymmetric. When the *expectation value* for p, n/N, is neither close to 0 nor to 1, and N is large, then as expected the curve has Gaussian form. The expectation value and p_C are given numerically and as coloured marks on the p axis. Examination of the plotted curve gives one a feel for the statistics and allows one to judge just how big the true value of p might be should ill fortune have yielded a value for n subject to an unusually large negative fluctuation. The plotting and the numerical integration proceed in steps $\Delta p = 1/4000$. Consequently p is always given as a multiple of 0.025%.

6. Numerical Results.

A few interesting results are given in Table 2. which all give $p_{90} = 2\%$.

N	n	(n/N) %	P_{90}%
191 thru 193	1	0.52%	2%
262 thru 265	2	0.76%	2%
330 thru 333	3	0.91%	2%
395 thru 399	4	1.01%	2%
458 thru 463	5	1.08%	2%
521 thru 525	6	1.14%	2%
582 thru 588	7	1.19%	2%
643 thru 650	8	1.23%	2%
97 thru 1008	14	1.39%	2%

Table 2. Some values of N and n that all give $P_{90} = 2\%$.

The reader is urged to obtain more by running the program.

7. Discussion.

This methodology always gives a value for p_C which is somewhat greater than the expectation value n/N. The difference between them naturally gets smaller as N increases but only very slowly. To be sure, with $C\%$ confidence, that the true probability p is less than 2% means that very often it will be considerably less, but there is no way this can be known. There is of course a $(100 - C)\%$ risk that it will be higher and this too cannot be known. Just how much above 2% it might be can be judged by examining the red portions of the curves.

Insofar as the true value of p will often be substantially less than p_C adoption of this methodology will be to the advantage of the RAS. But this is not a manifestation of any sort of hidden bias, it is simply a consequence of taking the modified question seriously.

In all the talk within SE21 and TG1/5 about Monte-Carlo simulation, I have never heard any estimates of how many simulations are necessary to obtain reasonably reliable results. This report and the accompanying program allows this question to be addressed.

A word of warning. It is most important that the number N be decided in advance. The methodology would be invalidated if simulations are run with an eye on how the expectation value n/N is getting on and stopping when is seems to be making a negative fluctuation. That would seriously prejudice the methodology.

8. Conclusion.

It has been pointed out that the question:

"Will more than 2% of integrations suffer unacceptable interference?"

cannot be answered by Monte-Carlo simulation. Only a modified question of the form:

"Can we be C% sure that no more than 2% of integrations will suffer unacceptable interference?"

can be addressed. I've adopted $C\% = 90\%$ for illustration. The RAS may decide on an alternative figure. Some say 95% would be more appropriate.

The methodology of *Inverse Probability* has been described and applied to a Bernoulli probability distribution. A program implementing it, BORP4.EXE, is presented which computes the probability of the probability p given n, and produces an answer to the modified question. It is clear that to get reasonably accurate results the number of independent 2000 sec integrations that must be simulated runs into the thousands.

Adoption of this interpretative methodology will be to the advantage of the Radio Astronomy Service but one must therefore expect it to be resisted by its opponents. However it is the only rational and honest approach I know to interpret the Monte-Carlo simulations.

Appendix.

The integral on the Left Hand Side of the inequality of equation(10) may be evaluated as follows. We are concerned to prove that

$$\frac{N!}{n!(N-n)!}\int_0^1 x^n(1-x)^{N-n}\,dx \;=\; \frac{1}{N+1} \tag{A1}$$

where N and n are positive integers such that $n < N$.

PROOF:

Write $(N-n) \;=\; m$ and define

$$I_{m,n} = \frac{(m+n)!}{m!n!}\int_0^1 x^n(1-x)^m\,dx \tag{A2}$$

Integrate by parts to get

$$I_{m,n} \;=\; \frac{(m+n)!}{m!n!}\left\{\left[\frac{(1-x)^m\,x^{n+1}}{n+1}\right]_0^1 - \int_0^1 \frac{(-1)\,x^{n+1}\,m(1-x)^{m-1}}{n+1}\,dx\right\} \tag{A3}$$

$$= \;\frac{(m+n)!}{(m-1)!(n+1)!}\int_0^1 x^{n+1}(1-x)^{m-1}\,dx \;=\; I_{m-1,n+1} \tag{A4}$$

since $\frac{m}{m!} \;=\; \frac{1}{(m-1)!}$ and $\frac{1}{(n+1)n!} \;=\; \frac{1}{(n+1)!}$.

We now see that

$$I_{m,n} \; = \; I_{m-1,n+1} \; = \; I_{m-2,n+2} \; = \; I_{m-3,n+3} \; = \; \cdots \; = \; I_{0,m+n} \tag{A5}$$

But

$$I_{0,n+m} \; = \; \frac{(m+n)!}{(m-m)!(n+m)!} \int_0^1 x^{n+m}\, dx \; = \; \left[\frac{x^{m+n+1}}{(m+n+1)} \right]_0^1 \; = \; \frac{1}{(m+n+1)} \tag{A6}$$

therefore

$$I_{m,n} \; = \; \frac{1}{(m+n+1)} \; = \; \frac{1}{N+1} \tag{A7}$$

QED.

Bibliography.

Woodward, P. M., *Probability and Information Theory with Applications to Radar*, Pergamon Press, London, 1953, 1964; McGraw-Hill, New York, 1953.
This is a much quoted classic and seminal work.

Propagation Models

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Abstract:
The propagation of radio frequency energy at the surface of the Earth poses scientific and regulatory issues for users of the spectrum: decisions are often based on results obtained from propagation models. This paper introduces the context which models have to represent, outlines their role and purpose, as well as introducing several of the more popular models.

1. Introduction

The propagation of radio waves at the surface of the Earth is both the reason for their use in communication systems, and at the heart of spectrum management, as it introduces a need for regulation to protect different services with some degree of geographical proximity. This in turn is very frequency dependent, and can be affected by a diversity of other factors, such, for instance, as the physical terrain or reflection from the ionosphere. There is consequently a host of ITU regulations pertaining to the definitions of relevant terms, to aspects of radio propagation in ionized and neutral media or around obstacles, and on how to model the variety of situations occurring in practice. These recommendations are listed in the Appendix. The purpose of this paper is to touch on the key aspects affecting the propagation of radio waves, so we appreciate the circumstances that need to be modeled, and can then briefly consider the salient features of several of the more popular models.

2. Modes of propagation & propagation loss

(a) *Free space propagation* is the simplest, as the intensity of radiation is then frequency independent and decreases as the inverse square of the distance, D, from the transmitter. The received pfd (W m^{-2}) = $P / (4 \pi D^2) = 10 \, . \log(P) - 11 - 20 \, . \log(D)$ in dBW, where P is EIRP (Watts). The EIRP (Watts) is similarly related to the electric field strength, E (V m^{-1}), by $E = \sqrt{(30 \, . P)} / D = 173 \sqrt{P} / D$, where D is in meters. Finally the received pfd (W m^{-2}) = $E^2 / Z_o \equiv E^2 / (120 \, . \pi)$, with Z_0 the characteristic impedance of free space.

(b) *Free space loss.* While the translation from EIRP (W) to pfd (W m^{-2}) is frequency independent, the loss in the transition from an isotropic transmitting antenna propagating to an isotropic receiving antenna increases as frequency squared, so

$$P_{\mathrm{rx}} = \{P_{\mathrm{eirp}} / (4 \pi D^2)\} * \{\lambda^2 / (4 \pi)\}$$

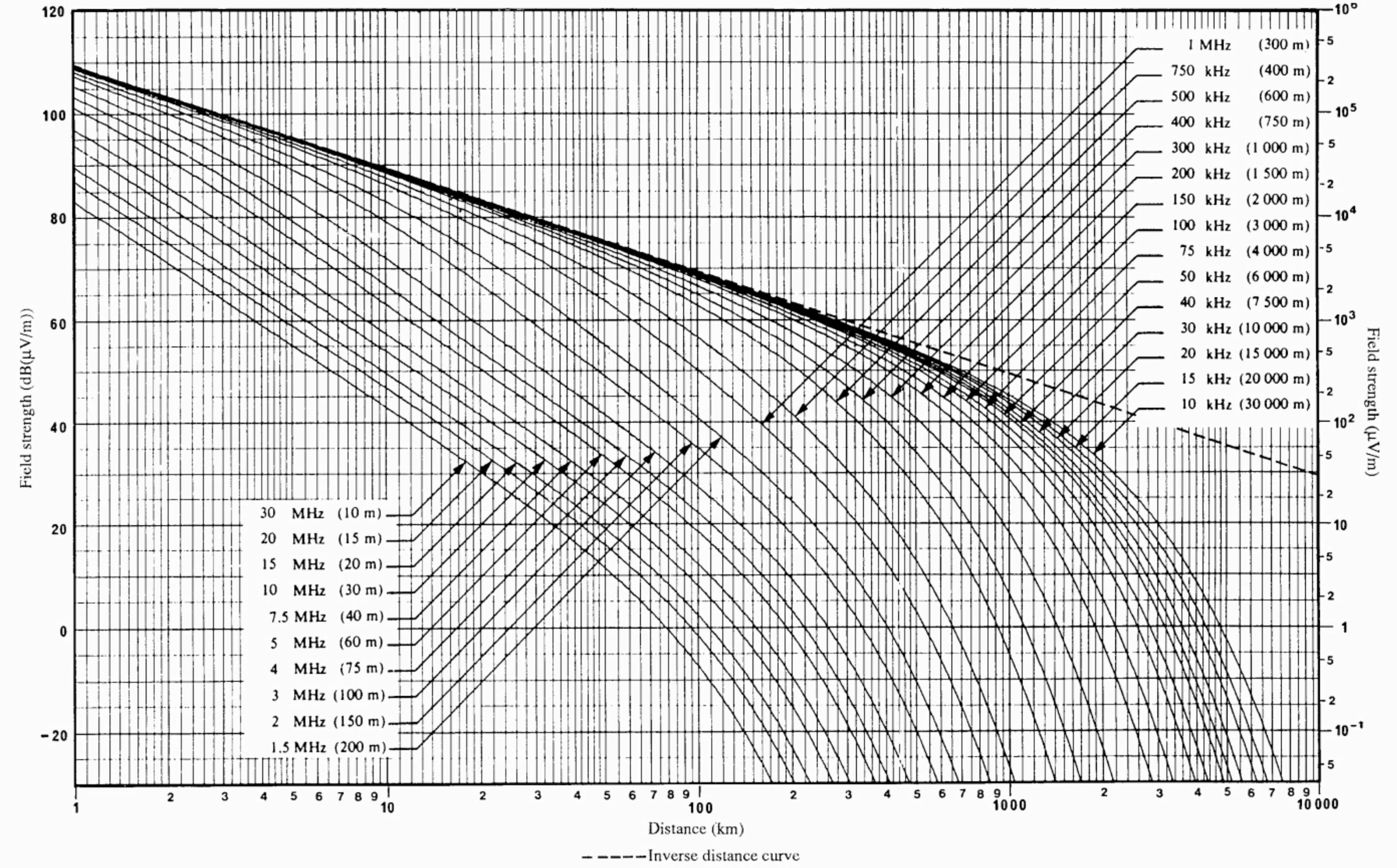

Fig. 1: Ground-wave propagation curves over wet ground as a function of frequency and distance (calculated σ = 10^{-2} S / m and ε = 30).

where $\{\lambda^2 / (4\pi)\}$ corresponds to the capture area of an isotropic antenna, at wavelength λ. (It is interesting to note that if the capture area of an isotropic antenna is regarded as a circular disk, then the circumference of that disk is precisely one wavelength.)

(c) *Ground wave propagation* is concerned with diffraction around a smooth Earth and with ground reflections, factors which are of most relevance to the propagation of low (less than 30 MHz) frequencies. This mode depends on such electrical properties of the ground as conductivity & permittivity, and is the subject of several ITU recommendations, such as ITU-R P.368. The ITU makes the program GRWAVE available on its web pages, which provides estimates for the field strength as a function of frequency and distance under a variety of conditions. An example, which is taken from Fig. 5 of ITU-R P.368-7, is shown here as Fig. 1 for the propagation of radio waves over wet ground. Similar curves are available for propagation over fresh water, the sea, etc.

(d) *Ionospheric reflection* is most relevant in increasing the range of radio wave propagation at frequencies up to ~30 MHz. But there are many modes of propagation making this a complicated topic, which is made yet more complicated still by the high degree of ionospheric variability occurring between day/night-time conditions as well as with the progress of the Solar Sunspot Cycle. Moreover the sporadic E layer in particular can be important to the propagation of frequencies up to 70 MHz (ITU-R P.534).

(e) *Tropospheric factors,* such as variations of radio refractive index and its "normal" change with height, enable radio-wave propagation over a greater than line-of-sight range. This effect is often taken into approximate account by assuming an increased radius for the Earth, e.g. by a factor of 4/3. Moreover temperature inversions can cause ducting, with relatively low attenuation over large distances beyond the horizon. Similarly small-scale irregularities within the troposphere can be responsible for forward

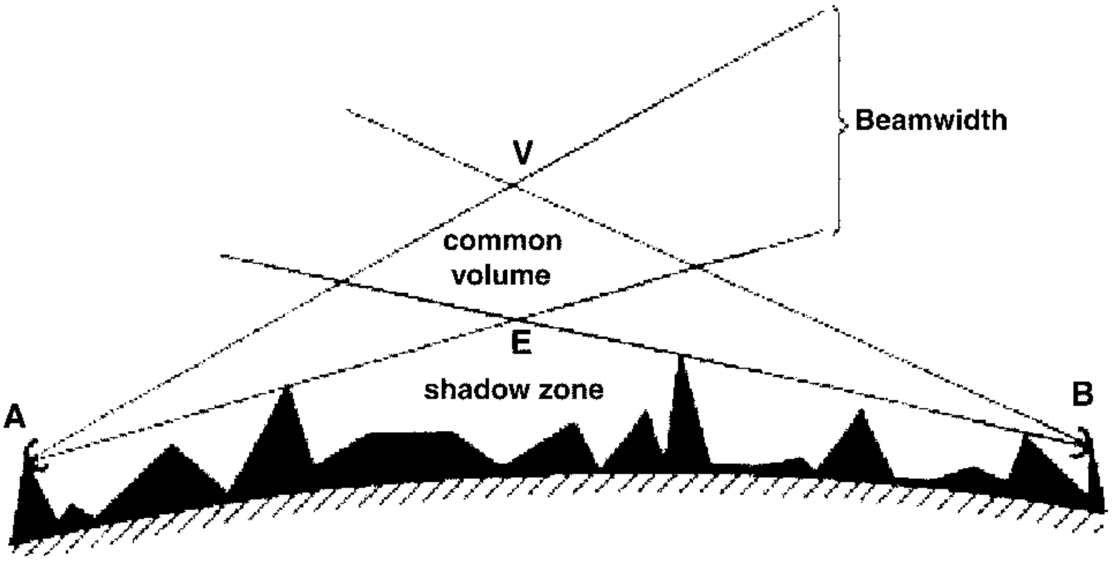

Fig. 2: Profile of a typical tropo-scatter path.

scatter propagation, while rain scatter can sometimes be a dominant mode.

(f) *Obstacles*, such as buildings and terrain features, usually attenuate signals. But in some circumstances knife-edge diffraction can greatly enhance propagation beyond the horizon. There is then always a question as to whether an apparent obstruction is in fact completely obstructing the ray path, as the cartoon in Fig. 3 shows. Such circumstances can be modeled: for example, the *OKUMURA-HATA* model calculates attenuation taking account in a statistical sense of the percentage of buildings in the path, as well as natural terrain features.

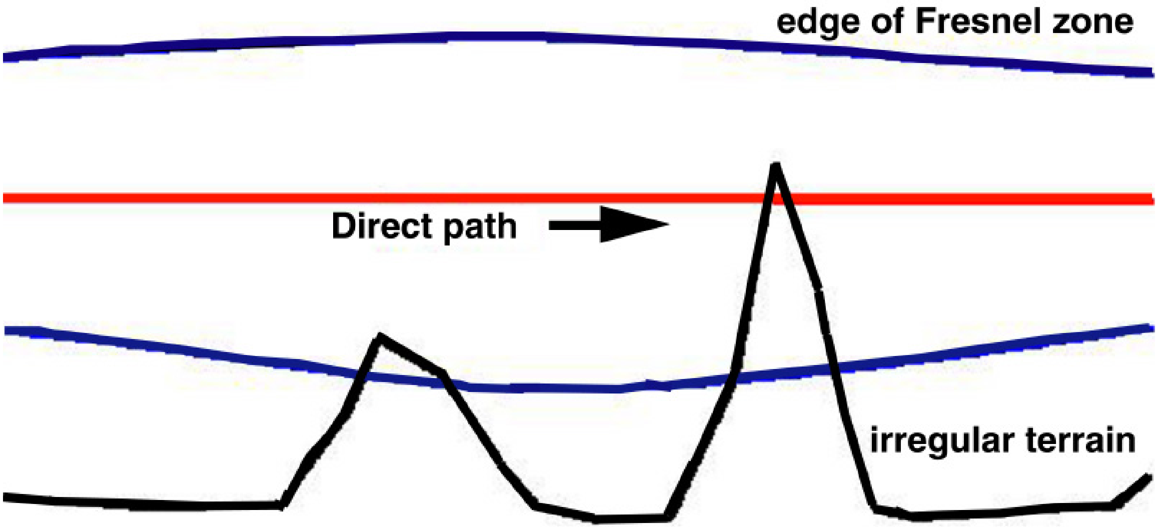

Fig. 3: Is an obstruction obstructing? Ray paths over irregular terrain.

In studying radio-wave propagation between two points A & B, the intervening space can be subdivided by a family of ellipsoids, known as Fresnel ellipsoids, all having their focal points at A & B such that any point M on one ellipsoid satisfies the relation

$$\mathrm{AM} + \mathrm{MB} = \mathrm{AB} + \mathrm{n}\,\lambda / 2 \quad ,$$

where λ is the wavelength and n a whole number characterizing the ellipsoid, whereupon n = 1 corresponds to the first Fresnel ellipsoid. As a practical rule, if there is no obstacle within the first Fresnel zone anywhere along a propagation path, diffraction effects can be ignored and free space propagation rules apply: clearance by 0.6 of the Fresnel zone radius is then often taken as a sufficient criterion to assume free space propagation.

The radius of an ellipsoid at a point between the transmitter and the receiver is

$$R_n = \left[\frac{n \lambda \, d_1 d_2}{\left(d_1 + d_2 \right)} \right]^{1/2}$$

Or, in practical units by

$$R_n = 550 \left[\frac{n \, d_1 d_2}{\left(d_1 + d_2 \right) f} \right]^{1/2}$$

where f is the frequency (MHz) and d_1 & d_2 the distance (km) between the transmitter and receiver at the point where the ellipsoid radius (m) is calculated.

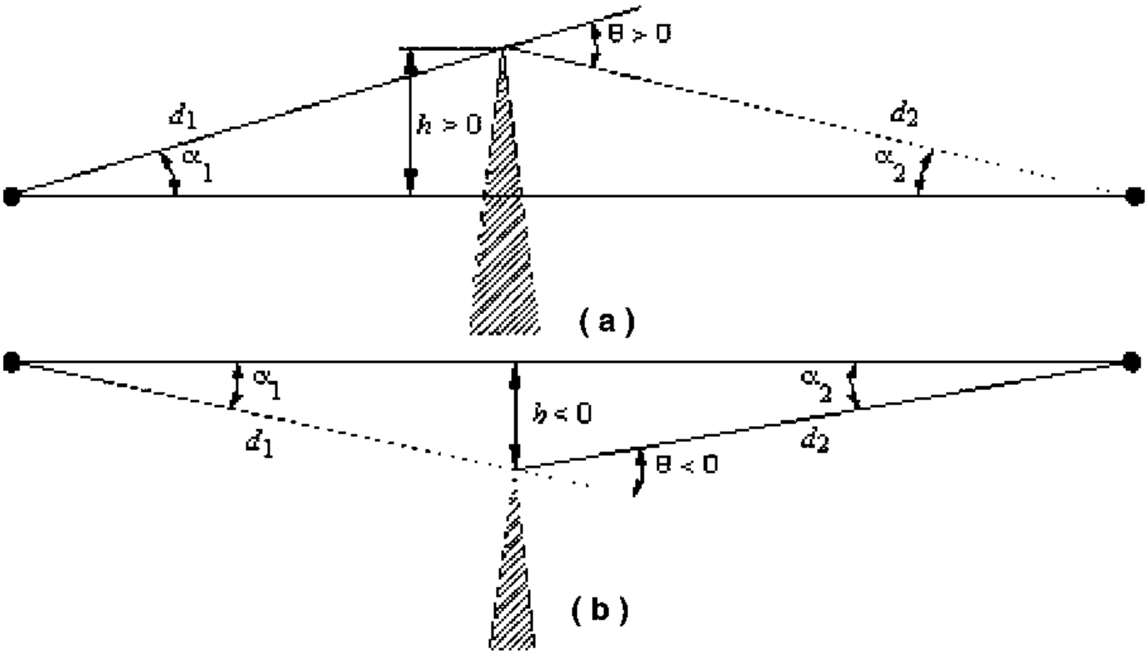

Fig. 4: Schematic for knife-edge diffraction.

There is a handy approximation for calculating the path length just achieving a clearance of 0.6 of the first Fresnel zone over a smooth Earth, for a given frequency, f (MHz), and antenna heights h_1 & h_2 in meters. This is given approximately by

$$D_{0.6} = \frac{D_f \, . \, D_h}{D_f + D_h}$$

where the frequency dependent term is

$$D_f = 0.0000389 f h_1 h_2$$

and the asymptotic term defined by the radio horizon is

$$D_h = 4.1\left(\sqrt{h_1} + \sqrt{h_2}\right)$$

Figure 5 plots the attenuation, compared to free-space propagation, introduced by a knife-edge obstacle. The attenuation J (ν) is shown, in dB, as a function of the parameter ν. This parameter ν can be derived in a number of ways (see e.g. recommendation ITU-P.526), with one convenient expression being:

$$\nu = \sqrt{(2 \, . \, d / \lambda) . \alpha_1 . \alpha_2}$$

where d is the total length of the path, λ the wavelength, and α_1 and α_2 are the angles between the top of the obstacle and one end, as seen from the other end. As an example, if the obstacle is mid-way between transmitter and receiver, assumed to be at the same elevation, then $\alpha_1 = \alpha_2$. If the distance between transmitter and receiver d = 1640 wavelengths, then the values of ν along the abscissa of Figure 5 would correspond to degrees. In this particular example, with $\nu = 1$, the free-space line of sight between the transmitter and receiver would be 2 degrees below the top of the knife edge, and yet the signal is only attenuated 14 dB below the free-space propagation value; if propagation had been over a smooth, spherical earth without the knife edge, the attenuation might have been much higher. Note also that if $\nu \sim -1.2$, the presence of the knife-edge actually introduces an ENHANCEMENT over free-space propagation, by about 1.4 dB. Note also that if the free-space line of sight just skims the top of the knife-edge, the attenuation is 6 dB (a factor of 4 in power) rather than the perhaps intuitive 3 dB. Figure 6 shows the propagation loss in the presence of a representative amount of clutter, or obstacles, for different antenna heights.

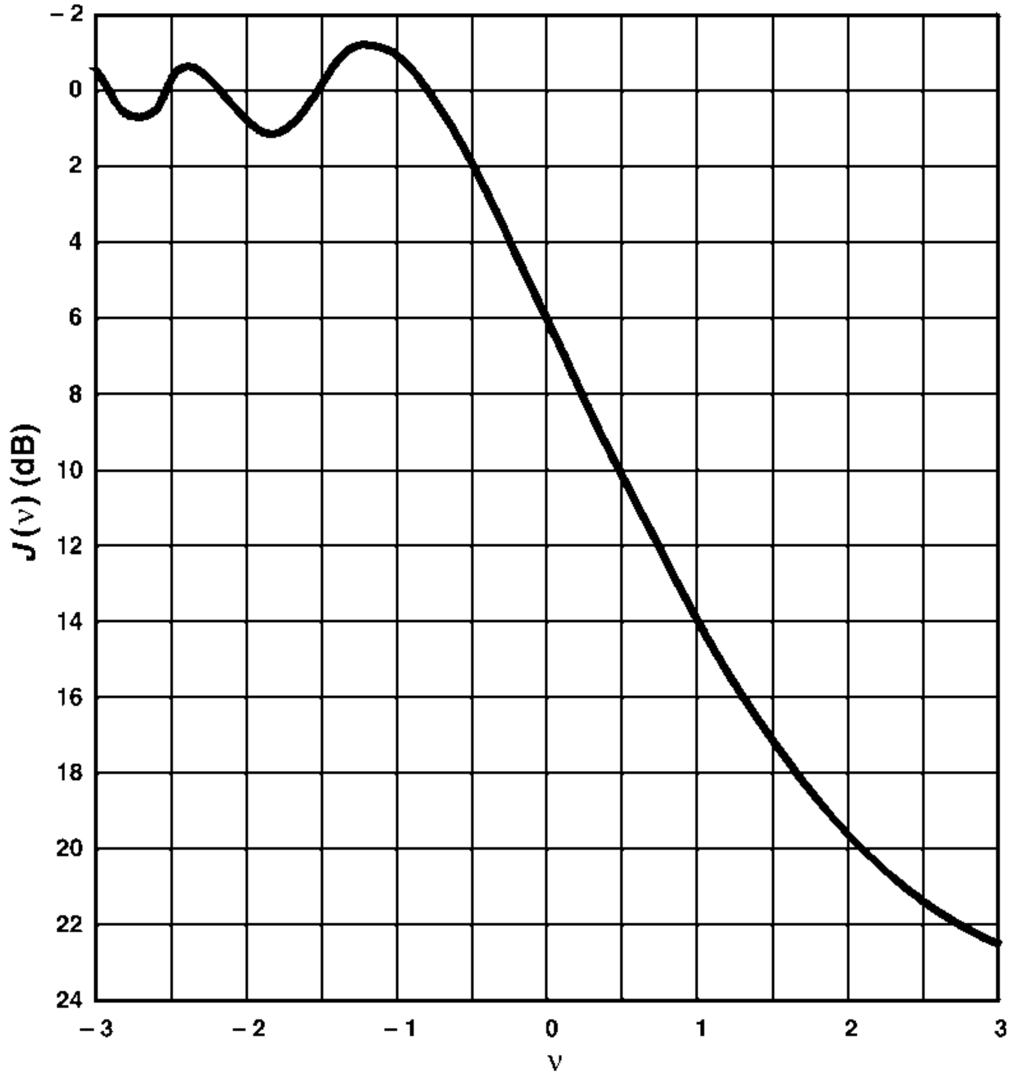

Fig. 5: Attenuation at a knife-edge.

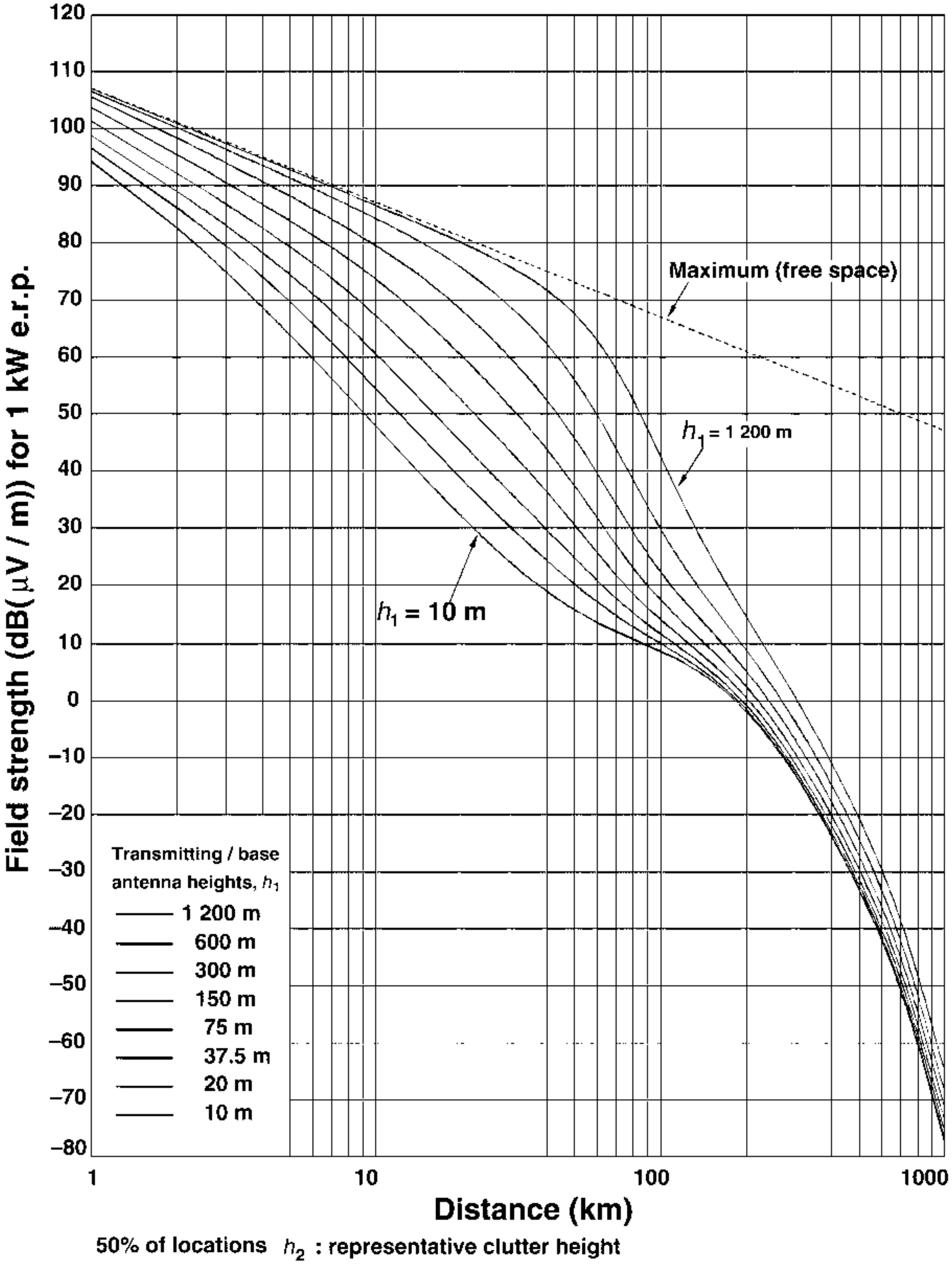

Fig. 6: Field strength versus distance, for a frequency of 2 GHz. The indicated field strength will be exceeded for 50% of locations at a given distance. A transmitter power of 1 kW erp is assumed, and curves are shown for transmitter antenna heights of from 10 to 1200 meters. A representative clutter height along the path is assumed.

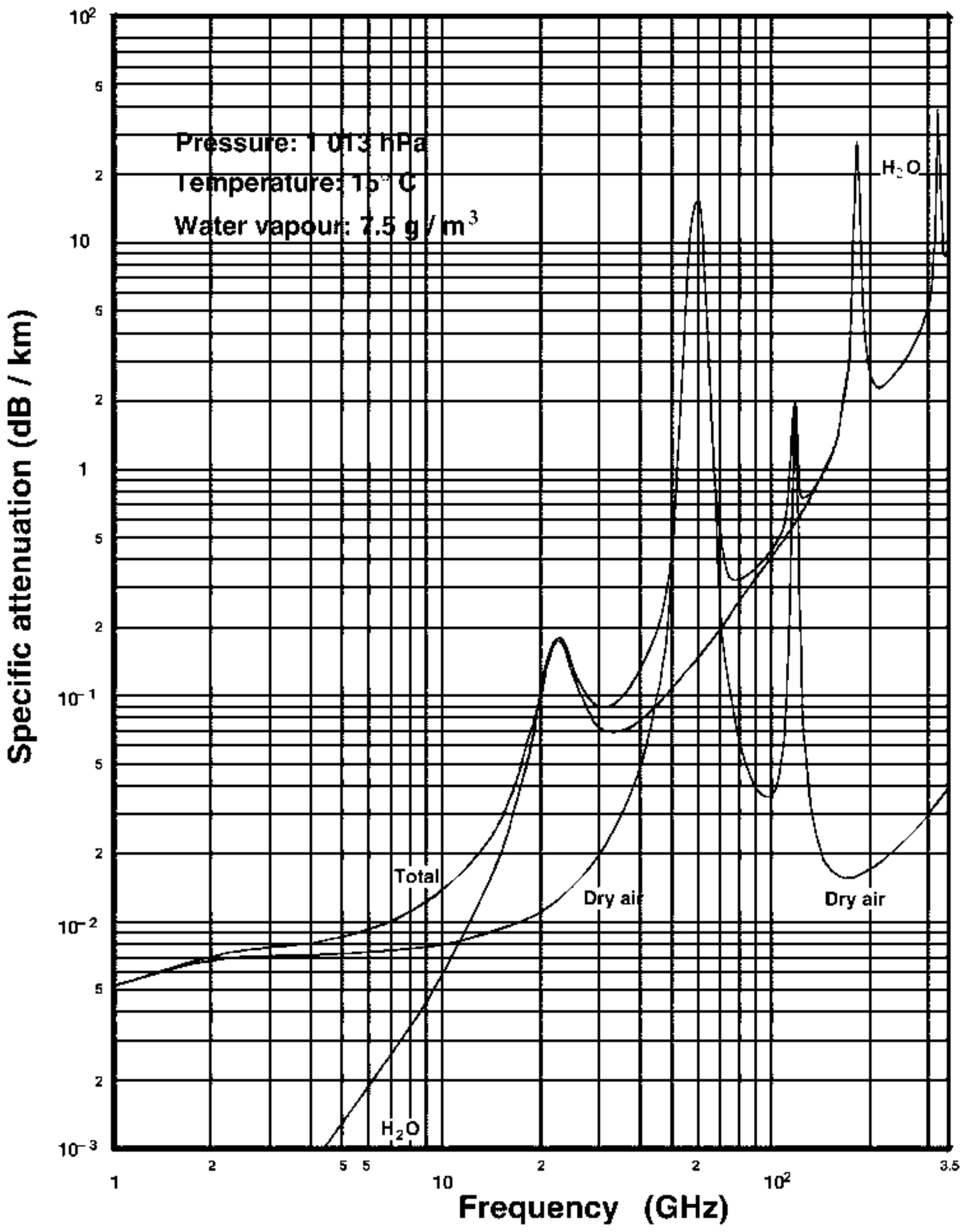

Fig. 7: Specific attenuation by atmospheric gases over the frequency range 1 to 300 GHz.

Recent implementations of propagation models, such as NRAO's TAP model (see below), often incorporate dual knife-edge propagation, where the signal diffracted over one knife-edge is subsequently diffracted over a second edge along the path. In some circumstances this can be the dominant propagation mode between two points.

(g) *Atmospheric attenuation,* which starts to be relevant at frequencies above about 5 GHz, depends primarily, but not exclusively, on the water vapor content of the atmosphere. This of course varies according to location, altitude, path elevation angle etc., and can add to the system noise as well as attenuating the desired signal. Moreover precipitation also has a significant effect. Figure 7 shows the attenuation introduced by propagation loss; for example, Figure 7 shows that at ~183 GHz (one of the water vapor lines), the atmospheric attenuation reaches nearly 30 dB per km. Conversely, at ~2 GHz, the attenuation is only ~0.007 dB/km and can safely be ignored.

3. Propagation models

ITU Recommendations give many "approved" methods and models. Two of the more popular are the Okumura-Hata model and the Longley-Rice model. Let's introduce these.

(i) *Okumura-Hata*

In essence this model calculates the expected electric field strength as a function of frequency at a distance, d, from a transmitter due to normal propagation, using a statistical estimate of obstacles such as buildings. It is used by evaluating equation 1

$$E = 69.82 - 6.16 \log f + 13.82 \log H_1 + a\left(H_2\right) - \left(44.9 - 6.55 \log\left(H_1\right)\right)\left(\log d\right)^b \quad (1),$$

where E is the electric field strength in units of dB (μV / m) for 1 kW e.r.p., f is the frequency in MHz, H_1 the base-station effective antenna height above ground (m) in the range from 30 to 200 m, H_2 the mobile-station antenna height above ground (m) in the range 1 to 10 m, and d is the distance between them in kilometers. Further,

$$a\left(H_2\right) = \left(1.1 \log f - 0.7\right) H_2 - \left(1.56 \log f - 0.8\right)$$

and $b \equiv 1$ for $d \leq 20$ km, but is given by

$$b = 1 + \left(0.14 + 0.000187 f + 0.00107 H_1'\right)\left(\log\left(0.05 d\right)\right)^{\mathbf{0.8}}$$

when $d > 20$ km, in which

$$H_1' = H_1 / \sqrt{1 + 0.000007 H_1^2}\ .$$

Nevertheless, the Okumura-Hata model has other features, including an ability to deal with diffraction effects over obstacles. A particular evaluation of equation 1 is illustrated in Fig. 8.

(ii) *Longley-Rice Model*

The Longley-Rice model makes predictions for transmission loss along tropospheric paths. It has been adopted by the FCC, so there are many software implementations available commercially. This model includes most of the relevant propagation modes [multiple knife & rounded edge diffraction, atmospheric attenuation, tropospheric propagation modes (forward scatter etc.), precipitation, diffraction over irregular terrain, polarization, specific terrain data, atmospheric stratification, different climatic regions, etc.

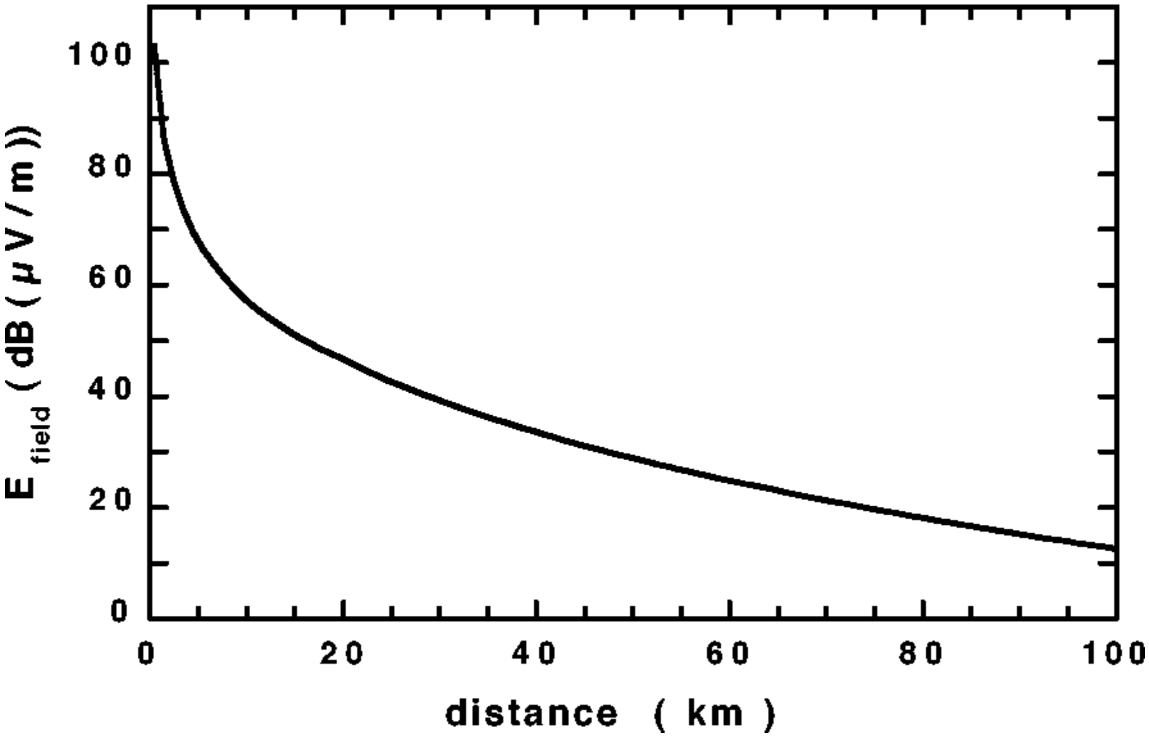

Fig. 8: illustrates the evaluation of equation 1 of the Okumura-Hata model for f = 380 MHz, H_1 = 30 m, H_2 = 10 m, as a function of distance.

(iii) *NRAO's TAP Model*
The Longley-Rice model predicts long-term median transmission loss over irregular terrain relative to free-space transmission loss. The model was designed for frequencies between 20 MHz and 40 GHz and for path lengths between 1 km and 2000 km. NRAO's program predicts tropospheric radio transmission loss over irregular terrain (the Longley-Rice Model) within a Terrain Analysis Package (TAP). This is a commercial implementation of the Longley-Rice Model, from SoftWright, which is based on Version 1.2.2 of the model, dated September 1984. Note also that the version 1.2.2 does not utilize several other corrections to the model proposed since the method was first published (see A. G. Longley, "Radio propagation in urban areas," OT Rep. 78-144, Apr. 1978; and A. G. Longley, "Local variability of transmission-loss in land mobile and broadcast systems," OT Rep., May 1976).

4. Problems with models

All models have limitations. Thus, for example, the Longley Rice Model does not allow for the ionosphere, which limits its applicability at lower frequencies. So some skill is needed in choosing the right model for a given set of circumstances. Clearly models need good input data (e.g. terrain models), but even so their accuracy is necessarily limited, and their results may need statistical interpretation. The resolution of the tabulation of terrain models can seriously affect results; with too coarse a resolution, the roughness and existence of sharp terrain features (such as might support knife-edge diffraction modes) may be significantly underestimated. Their applicability can also be affected with respect to radio astronomy concerns by such tricky questions as "What is the height of a radio telescope?" Is it at the top of a large dish, the bottom of the dish, at the focal point, or where? Moreover different models may give different answers.

Any model that is deployed to give results which need to be accepted by other spectrum users clearly needs to have fairly universal acceptance. Thus general acceptability may often be more important than absolute accuracy.

So where does this leave us? In spite of the difficulties propagation models have come a long way from those initially deployed. Nor can we live without them. They provide us with the best *a priori* guide we have as to whether a given terrestrial transmission will cause interference to a radio telescope, and are also the best guide we have as to whether a given size of coordination zone will be adequate. If greater precision is required in a specific case, or even just to give a high level of confidence to propagation over a given path, an experimental determination of the propagation characteristics may be necessary.

Appendix: ITU Recommendations on Radiowave propagation

P.310	Definitions of terms relating to propagation in non-ionized media
P.311	Acquisition, presentation and analysis of data in studies of tropospheric propagation
P.313	Exchange of information for short-term forecasts and transmission of ionospheric disturbance warnings
P.341	The concept of transmission loss for radio links
P.368	Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz
P.369	Reference atmosphere for refraction
P.370	VHF and UHF propagation curves for the frequency range from 30 MHz to 1 GHz broadcasting services
P.371	Choice of indices for long-term ionospheric predictions
P.372	Radio noise
P.373	Definitions of maximum and minimum transmission frequencies
P.434	ITU-R reference ionospheric characteristics and methods of basic MUF, operational MUF and ray-path prediction
P.435	Sky-wave field-strength prediction method for the broadcasting service in the frequency range 150 to 1600 kHz
P.452	Prediction procedure for the evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz
P.453	The radio refractive index: its formula and refractivity data
P.525	Calculation of free-space attenuation
P.526	Propagation by diffraction
P.527	Electrical characteristics of the surface of the Earth
P.528	Propagation curves for aeronautical mobile and radionavigation services using the VHF, UHF and SHF bands
P.529	Prediction methods for the terrestrial land mobile service in the VHF and UHF bands
P.530	Propagation data and prediction methods required for the design of terrestrial line-of-sight systems
P.531	Ionospheric propagation data and prediction methods required for the design of satellite services and systems
P.532	Ionospheric effects and operational considerations associated with artificial modification of the ionosphere and the radio-wave channel

P.533	HF propagation prediction method
P.534	Method for calculating sporadic-E field strength
P.581	The concept of "worst month"
P.616	Propagation data for terrestrial maritime mobile services operating at frequencies above 30 MHz
P.617	Propagation prediction techniques and data required for the design of trans-horizon radio-relay systems
P.618	Propagation data and prediction methods required for the design of Earth-space telecommunication systems
P.619	Propagation data required for the evaluation of interference between stations in space and those on the surface of the Earth
P.620	Propagation data required for the evaluation of coordination distances in the frequency range 100 MHz to 105 GHz
P.676	Attenuation by atmospheric gases
P.678	Characterization of the natural variability of propagation phenomena
P.679	Propagation data required for the design of broadcasting-satellite systems
P.680	Propagation data required for the design of Earth-space maritime mobile telecommunication systems
P.681	Propagation data required for the design of Earth-space land mobile telecommunication systems
P.682	Propagation data required for the design of Earth-space aeronautical mobile telecommunication systems
P.683	Sky-wave field strength prediction method for propagation to aircraft at about 500 kHz
P.684	Prediction of field strength at frequencies below about 150 kHz
P.832	World Atlas of Ground Conductivities
P.833	Attenuation in vegetation
P.834	Effects of tropospheric refraction on radiowave propagation
P.835	Reference standard atmospheres
P.836	Water vapour: surface density and total columnar content
P.837	Characteristics of precipitation for propagation modelling
P.838	Specific attenuation model for rain for use in prediction methods
P.839	Rain height model for prediction methods
P.840	Attenuation due to clouds and fog

P.841	Conversion of annual statistics to worst-month statistics
P.842	Computation of reliability and compatibility of HF radio systems
P.843	Communication by meteor-burst propagation
P.844	Ionospheric factors affecting frequency sharing in the VHF and UHF bands (30 MHz-3 GHz)
P.845	HF field-strength measurement
P.846	Measurements of ionospheric and related characteristics
P.1057	Probability distributions relevant to radiowave propagation modelling
P.1058	Digital topographic databases for propagation studies
P.1059	Method for predicting sky-wave field strengths in the frequency range 1605 to 1705 kHz
P.1060	Propagation factors affecting frequency sharing in HF terrestrial systems
P.1144	Guide to the application of the propagation methods of Radiocommunication Study Group 3
P.1145	Propagation data for the terrestrial land mobile service in the VHF and UHF bands
P.1146	The prediction of field strength for land mobile and terrestrial broadcasting services in the frequency range from 1 to 3 GHz
P.1147	Prediction of sky-wave field strength at frequencies between about 150 and 1700 kHz
P.1148	Standardized procedure for comparing predicted and observed HF sky-wave signal intensities and the presentation of such comparisons
P.1238	Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz
P.1239	ITU-R Reference ionospheric characteristics
P.1240	ITU-R Methods of basic MUF, operational MUF and ray-path prediction
P.1321	Propagation factors affecting systems using digital modulation techniques at LF and MF
P.1322	Radiometric estimation of atmospheric attenuation
P.1406	Propagation effects relating to terrestrial land mobile service in the VHF and UHF bands
P.1407	Multipath propagation and parameterization of its characteristics
P.1409	Propagation data and prediction methods required for the design of systems using high altitude platform stations at about 47 GHz
P.1410	Propagation data and prediction methods required for the design of terrestrial broadband millimetric radio access systems operating in a frequency range of about 20-50 GHz

P.1411	Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz
P.1412	Propagation data for the evaluation of coordination between Earth stations working in the bidirectionally allocated frequency bands
P.1510	Annual mean surface temperature
P.1511	Topography for Earth-to-space propagation modelling
P.1546	Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz
P.1621	Propagation data required for the design of Earth-space systems operating between 20 THz and 375 THz
P.1622	Prediction methods required for the design of Earth-space systems operating between 20 THz and 375 THz
P.1623	Prediction method of fade dynamics on Earth-space paths

Components of Radio Astronomy Receivers

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Abstract

The receiver front-end of a radio telescope is generally considered to encompass components that amplify, filter, and frequency convert signals, provided by the antenna, to a level and frequency range appropriate for detection. This presentation will discuss critical parts of the centimeter wave radio astronomy front-end, and factors impacting the design and performance.

The feed efficiently converts propagating electromagnetic fields near a reflector antenna's focal point to a guided wave in coax or waveguide. Some types of feeds inherently detect and separate polarizations; other types require an orthomode transducer to deliver orthogonal polarizations to separate channels. Low-noise amplifiers, usually cryogenically cooled, amplify the signal and set the receiver noise level, and are followed by filters, mixers, and additional amplification. All the passive and active components add electrical noise to the signal, and models used during receiver design will be presented, explaining why loss and noise introduced in the early stages of the receiver are critical. The linear operating range of active components is limited by their power handling capacity, and how these limitations are considered will be discussed. We will also discuss stability of the receiver, and practical means to achieve the required performance.

1 Introduction

Figure 1 shows a very simplified block diagram of a typical heterodyne receiver front-end. (The term *front-end* generally excludes the part of a receiver that involves data acquisition, the *backend*). A heterodyne receiver involves at least one frequency conversion, or mix, and is by far the most common type of front-end for radio astronomy in the centimeter regime. This paper will provide an introduction to the major components in such a front-end and the system aspects typically faced by a designer.

2 Feeds

The feed is placed at or near a focal point of a reflector. The angle subtended by the reflector as seen by the feed, Figure 2, strongly influences the types of feeds that may be used, and the details of their design. Generally, smaller angles require larger feeds in units of wavelengths.

The feed interfaces in an efficient manner between EM fields at the focal point and a guided transmission line. Compromises involve bandwidth, efficiency, size, polarization purity, beam shape, and other performance considerations. The gain required and practical considerations dictate the type of designs that may be considered.

Dipoles in a cavity or with a combination of reflectors are common at long wavelengths and at prime focus where their low gain is not a problem, and their small size in wavelengths is an advantage. Corrugated horns typically provide high gain and superior performance in most applications. Good circular symmetry of the beam, good polarization performance, and high efficiency are achieved. [1, 2]

3 Orthomode Transducer and Polarizer

The Orthomode Transducer, Figure 3 provides dual polarization reception, necessary in order to gather all the photons. OMTs come in many forms, depending on the wavelength and bandwidth needed [3]. In general, they have a square or circular waveguide port that connects to the feed horn and supports orthogonal linear polarizations, and two output ports separating the polarizations into two channels. By adding to the OMT input or output a phase shifter that delays one polarization by 90 degrees with respect to the other, circular polarization may be received or transmitted, Figure 4. It is difficult to design a broadband phase shifter, and this component currently limits the bandwidth of many receivers.

4 Thermal Noise in Receivers

Thermal noise, aka Johnson noise, arises from random motion of free electrons in a conductor, due to thermal agitation [4, 5, 6]. Figure 5 shows an electrical resistance at physical temperature T, connected to a band-limiting filter. The open-circuit rms voltage that will be measured at the output terminals is given in the figure. The quantities h and k are Planck's and Boltzmann's constants respectively, and f is frequency. If $hf/kT << 1$, the integral reduces to B, the form commonly used in microwave system analysis. However, the inequality needs to be checked if $f/T > 1$ GHz/Kelvin. Common electrical circuit theory says that for any voltage source, maximum power is available when load resistance is equal to the source resistance. Under this condition, the available power from the thermal noise source is kBT, Figure 6. The concept of equivalent source temperature is used for convenience when the statistics of any signal resembles gaussian noise. The true source is replaced with an equivalent thermal noise source that produces a noise power at the same level, Figure 7. The equivalent noise temperature, T_s, may be a function of frequency, but should be flat over the filter bandwidth B.

If we connect a thermal noise source to a microwave amplifier input, and measure the amplifier output power at various source temperatures, we will find that the output power is the noise source power times the amplifier gain plus a constant term, Figure 8. This constant is noise added by the amplifier, and we model that noise by thermal noise at the amplifier input.

Amplifier noise is not entirely thermal. That is, it is not directly proportional to the amplifier temperature, and is generally a function of frequency. GaAs or InP HFET (HEMT) devices are now used almost exclusively to build low-noise microwave amplifiers. In addition to being inherently low-noise, high gain, and stable, they can be designed to cool well - that is, much of their noise is thermal and decreases when cooled, Figure 9.

In a cascade of amplifiers, the noise contribution of a particular stage is divided by the gain of preceding stages, Figure 10. Therefore, one wants the first stages of a receiver to have high gain and low noise. Most radio astronomy receivers have cryogenically cooled amplifiers for the first stages of gain. Figure 11 shows that when losses exist at the input of a receiver, two negative effects plague the system. An ohmic loss adds noise at a level proportional to its temperature, plus it attenuates the input signal. The net effect is to both add noise, and to multiply the effective noise temperature of following stages.

5 Frequency Conversion

Figure 12 shows a receiver using a mixer for frequency conversion. The mixer has at its output multiple instances of the input RF and LO signals shifted up and down in frequency by integer multiples. Use of filters allows selection of the m,n coefficients for the output signal. Use of mixing within a receiver provides several advantages:

Tunability: By using a narrow IF filter and a variable LO frequency, the detected RF frequency can be varied over a wide range.

Cost: Amplifiers, transmission lines, and other components are generally less expensive at IF frequencies.

Stability: Large amounts of gain at one frequency can cause instability due to leakage from the output circuits coupling back to the input stages. In a hetrodyne receiver, the gain is distributed at two or three frequency ranges, reducing the likelyhood of feedback coupling. Also, amplifiers tend to be less sensitive to temperature and other environmental effects.

RFI: Down-conversion of a frequency range increases the ratio of frequencies in the IF passband. Filtering out unwanted signals at the IF is simplified because filter responses scale by the ratio of frequencies. Hence fewer filter resonators are required for a given level of rejection.

6 Filters

Filters are necessary in most any receiver system, to reject interference, select desired mixer products, and to define the receiver passband. Digital filters provide many advantages, but currently most filters remain analog designs for reasons of cost and simplicity, particularly at frequencies above 100MHz.

The most common general purpose filter response is the *Tchebyscheff* or *Equal-Ripple* type. The Tchebyscheff equations describe filter insertion loss response using only two parameters: the number of resonators, and the magnitude of the passband loss ripple. Figure 13 shows the Tchebyscheff equations and a lowpass filter response with five resonators, for 0.1, 1, and 3dB passband ripple. Higher passband ripple yields steeper rejection slopes above the cutoff frequency, but keep in mind that the filters reflect power rather than absorb it. So, 3dB passband ripple means half the input power is reflected back toward the source at the peaks of the ripples.

Figure 14 shows the Tchebyscheff lowpass response for filters with 3, 5, 7, and 9 resonators and 0.1dB passband ripple. Such curves can be used to determine the minimum number of poles required to achieve specified rejection. For example, if 40dB rejection is required at a frequency 1.5 times the filter cutoff frequency, at least 7 poles are required. Note that one faces diminishing returns as poles are added, because the improvement in rejection at a given frequency decreases as the number of poles increase.

Once an appropriate lowpass response has been chosen, equations are available [8] to determine circuit elements that will realize the response. Figure 15 shows the classic lowpass filter topology using inductors and capacitors. At RF frequencies, lumped elements have significant parasitic elements which must be accounted for. Computer modeling and optimization is often necessary. At microwave frequencies, transmission line elements must substitute for lumped elements to achieve acceptable filter performance.

Design of a bandpass filter often begins with selection of a lowpass prototype response, which then can be mapped to a bandpass response by simple substitution of the frequency variable. Figure 16 illustrates the variable substitution and a Tchebyscheff 0.1dB ripple, 5-pole response mapped to frequency of 19.8 to 20.2. Figure 17 shows how a lowpass prototype circuit can be transformed to a bandpass topology. Inductors are replaced by series resonators and capacitors by shunt resonators. Good lumped elements are generally not available at microwave frequencies, so microwave filters are realized using transmission line resonators. Various transmission line forms (microstrip, stripline, coaxial, waveguide) may be used, based on tradeoffs involving size, cost, and performance.

7 Receiver Stability

Figure 18 shows a greatly simplified diagram of a total power receiver. The receiver gain is represented by G, and typically consists of many amplifiers, mixers, and other microwave and IF components with net gain well over 100 dB. The IF signal presented to the detector is band-limited gaussian noise with effective noise bandwidth of B. The output voltage of the square-law detector is proportional to the power of the input signal. The detected output is then integrated with time constant τ, represented by a RC circuit. The output voltage V_o, proportional to the detected power, has both DC and AC components. The ratio of these two components is inversely proportional to the square root of the product of B and τ [7], assuming the receiver gain and noise temperature is constant. A radiometer's sensitivity is often defined as the change in antenna equivalent temperature which results in a change of V_o equal to the rms value of V_{ac}. However, since a change in G also results in a change in V_o, the receiver gain must be much more stable than V_{ac}/V_{dc} for periods greater than τ.

Gain stability is achieved by temperature control, both active and passive, design of components that are not sensitive to vibration and shock, and avoidance of stress on cables and connectors by careful alignment of components. Even so, sophisticated switching techniques are often required to achieve adequate sensitivity.

8 Receiver Linearity

Any practical amplifier, mixer, or other active device has limited power-handling capability. At some level of output power, the gain begins to become non-linear, and eventually the output power saturates, figure 19. For sinusoidal inputs, the output voltage becomes clipped and approaches a square wave, producing harmonics in the output frequency spectrum. Sum and difference terms arise in the output spectrum if multiple frequencies are present at the input [9].

The most troublesome intermodulation products are usually odd-order difference terms. The strongest of these are the third-order products, Figure 20. For two closely spaced input tones F1 and F2, the 2F1-F2 and 2F2-F1 products fall near F1 and F2 and are often impossible to filter out. A log-log plot of the third-order product level has a slope of 3:1. For example, if the level of F1 and F2 is dropped by 10 dB, the third-order products drop by 30 dB, a relative improvement of 20 dB.

The third-order performance of a component is usually specified by the *third-order intercept*, a fictitious power level where the fundamental and third-order curves intersect. The device is usually not capable of actually producing that level of power, but knowing this point and the slopes, the relative third-order levels can be calculated for any reasonable fundamental output power. For example, if the fundamental tones are 20 dB below the intercept point for a particular amplifier, the third-order products will be 60 dB below the intercept, or 40 dB below the fundamental tones.

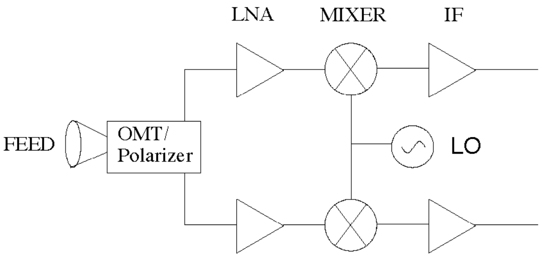


Figure 1: A simplified block diagram of a typical radio astronomy receiver.

9 Summary

The most common topology for centimeter-wave radioastronomy receivers is dual-polarization heterodyne with cooled HEMT low-noise amplifiers. The feed, OMT, polarizer, and first amplifiers are often the most critical components. Gain stability has a large effect on data quality and observing efficiency and most be considered and measured during receiver design and construction. The linearity and power handling of the receiver determines its performance in the presence of strong unwanted signals such as interference from man-made terrestrial or space-borne sources.

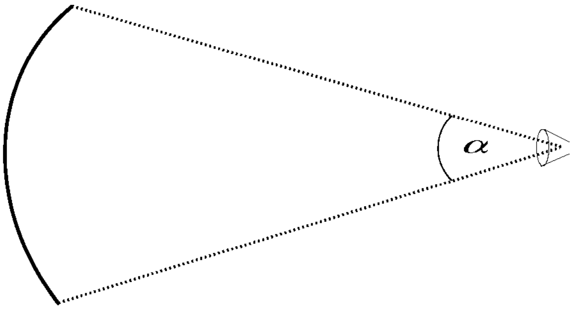


Figure 2: The angle subtended by the reflector as seen by the feedhorn is an important parameter. As the angle gets small, the feedhorn size increases in terms of wavelengths in order to maintain high efficiency and avoid excessive spillover.

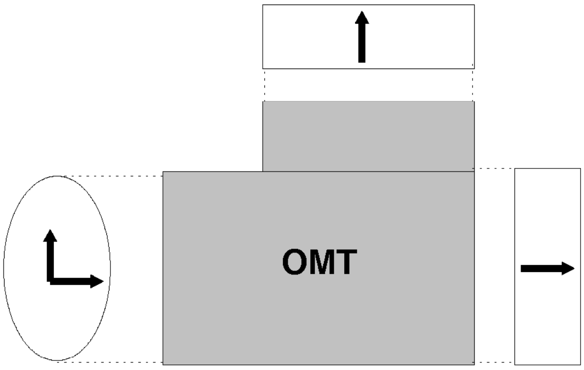


Figure 3: The Orthomode Transducer (OMT) separates dual-linear polarizations at its square or round input port into two output ports, usually rectangular waveguide or coax.

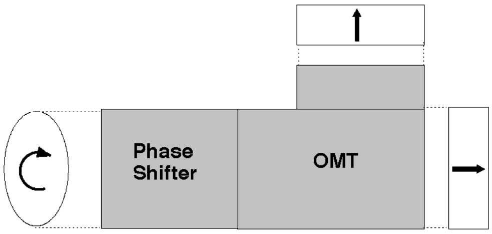
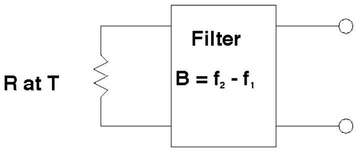


Figure 4: The addition of a phase shifter, which retards one polarization by 90°, at the input of an OMT causes the device to respond to circular polarizations.



$$V_{rms}^{2} = 4kTR\int_{f1}^{f2}\left(\frac{\alpha}{e^{\alpha}-1}\right)df$$

$$\alpha = \frac{hf}{kT}$$

$$\text{If } \alpha << 1, \quad V_{rms}^{2} = 4RkBT$$

Figure 5: Random voltage fluctuations generated by ohmic conductors were discovered experimentally by Johnson [5], and theoretical equations were developed by Nyquist [6].

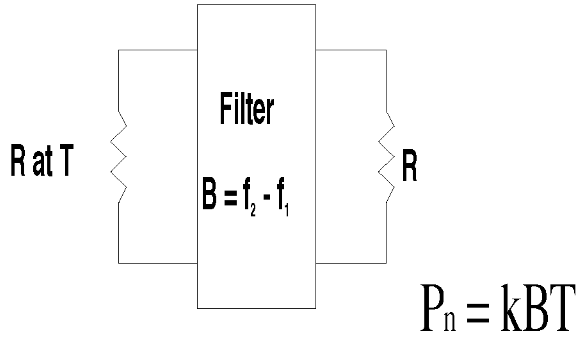


Figure 6: The available thermal noise power under matched impedance conditions is given by $P_n = kBT$.

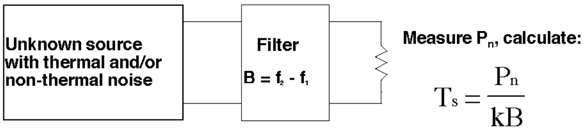
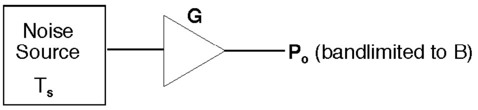


Figure 7: An unknown source of gaussian noise can be characterized by the temperature of a thermal source which produces the same noise power over the frequency range of interest.

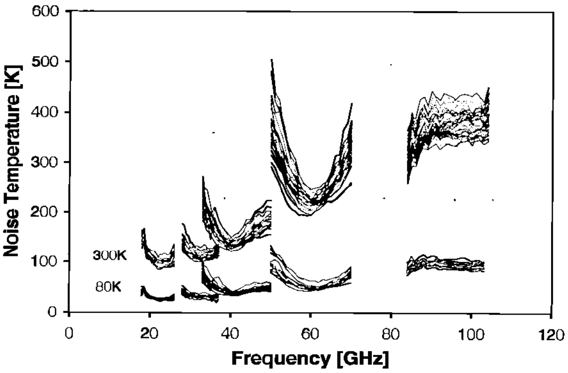


$$P_o = GkBT_s + K$$

Define $K = GkBT_e$

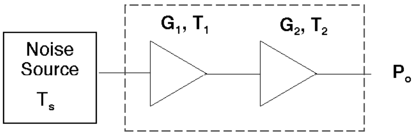
Then, $P_o = GkB(T_s + T_e)$

Figure 8: Amplifiers generate noise internally by thermal and non-thermal mechanisms. The noisy amplifier may be represented by an equivalent noiseless amplifier with a thermal noise source at its input.



Data courtesy M. Pospieszalski of NRAO Central Development Laboratory

Figure 9: Measured data for over 100 low-noise HFET amplifiers produced by the NRAO Central Development Lab for a recent project. Data from five amplifier types at 300 Kelvin and at 80 Kelvin is shown. Note the noise generally increases with frequency and decreases markedly with cooling.



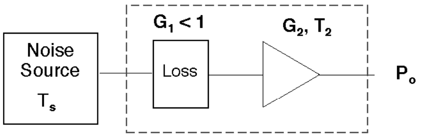
$$P_o = G_1G_2kBT_s + G_1G_2kBT_1 + G_2kBT_2$$

or,

$$P_o = G_1G_2kB\,(\,T_s + (T_1 + T_2/G_1))$$

So, Amplifier Cascade has equivalent noise $T_1 + T_2/G_1$

Figure 10: The noise and gain of the first amplifier in a cascade dominates the total noise temperature. The first amplifier in a receiver is chosen to have low-noise and high gain for this reason.



Let $L = 1/G_1$, then for ohmic loss at physical temperature T_o,

the effective noise temperature of the loss is $(L-1)T_o$.

Effective noise temperature of the loss - amplifier cascade

is: $\boxed{(L-1)T_o + LT_2}$.

Figure 11: Loss before the first receiver amplifier adds noise due to its ohmic loss, and effectively multiplies the noise temperature of following stages.

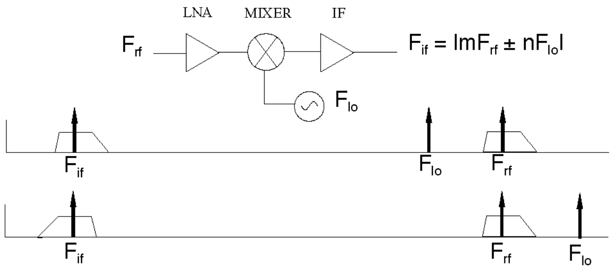


Figure 12: A simplified block diagram of a frequency down-converter is shown. The middle diagram illustrates a upper-sideband conversion in which the LO is below the RF band. The bottom diagram illustrates a upper-sideband conversion in which the LO is above the RF band. Note that in the latter case, the RF spectrum is inverted at the IF frequency. The selection of upper or lower sidebands and the IF range is defined by filters which are not shown.

Tchebyscheff filter response in dB:

$$\mathrm{Tcheby}(n,\omega,\varepsilon) := \left|\begin{array}{ll} \left(10\cdot\log\left(1+\varepsilon\cdot\cos(n\cdot\mathrm{acos}(\omega))^{2}\right)\right) & \text{if } \omega\leq 1 \\ \left(10\cdot\log\left(1+\varepsilon\cdot\cosh(n\cdot\mathrm{acosh}(\omega))^{2}\right)\right) & \text{if } \omega>1 \end{array}\right.$$

$n := 5$ Number of Resonators

$\varepsilon 1 := 10^{\left(\frac{0.1}{10}\right)} - 1$ 0.1dB Ripple $\varepsilon 2 := 10^{\left(\frac{1}{10}\right)} - 1$ 1dB Ripple $\varepsilon 3 := 10^{\left(\frac{3}{10}\right)} - 1$ 3 dB Ripple

$\omega := 0.1, 0.15 .. 3$

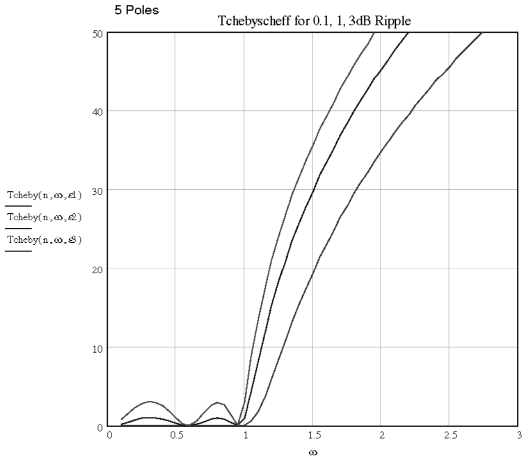


Figure 13: Tchebyscheff low-pass filter response is shown, along with the governing equations, for three levels of passband ripple. The x-axis is frequency, normalized to the filter cutoff frequency. Note how the filter rejection curve gets steeper as passband ripple increases.

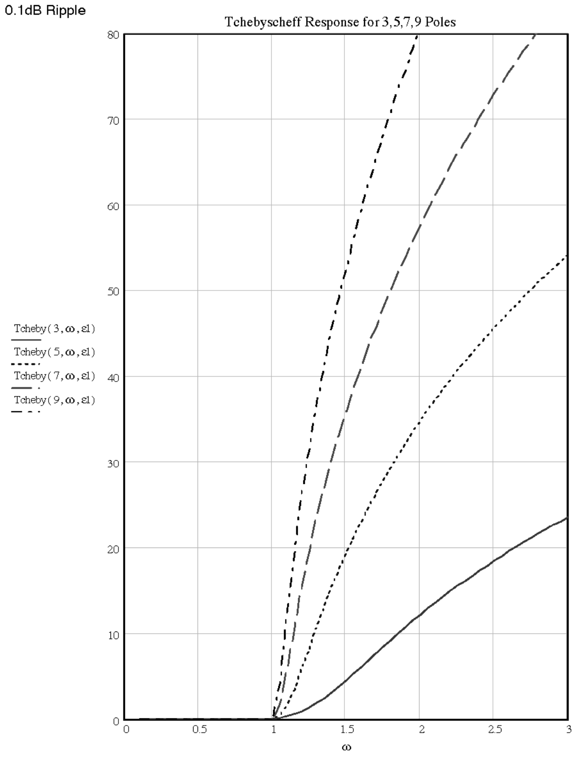


Figure 14: Tchebyscheff response for 3, 5, 7, or 9 filter resonators (poles).

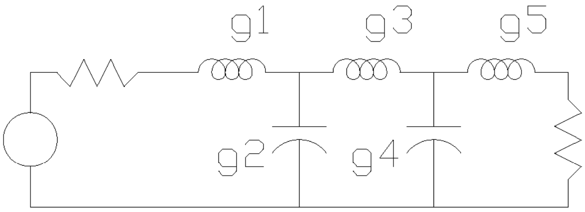


Figure 15: The classic lowpass filter circuit topology using ideal (lumped) inductors and capacitors.

Lowpass to Bandpass Mapping

$$\omega lpf(\omega, \omega o, B) := \frac{1}{B} \cdot \left(\frac{\omega}{\omega o} - \frac{\omega o}{\omega} \right)$$

$\omega 1 := 19.8$ $\omega 2 := 20.2$ $\omega o := \sqrt{\omega 1 \cdot \omega 2}$ $B := \frac{\omega 2 - \omega 1}{\omega o}$

$\omega := 18, 18.05 .. 22$

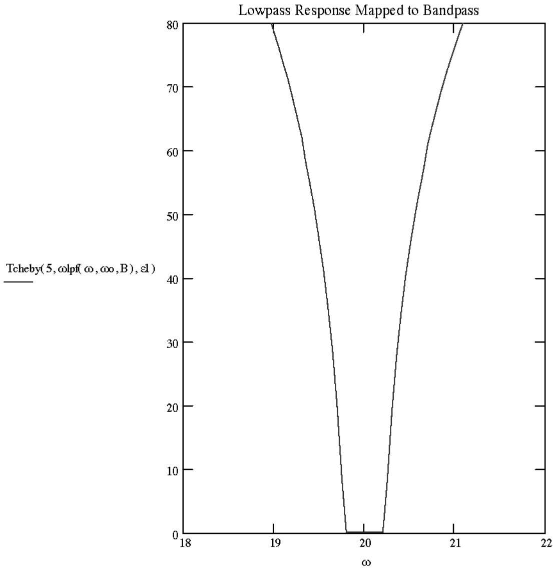


Figure 16: A lowpass filter response can be mapped to a bandpass response using a substitution of the frequency variable.

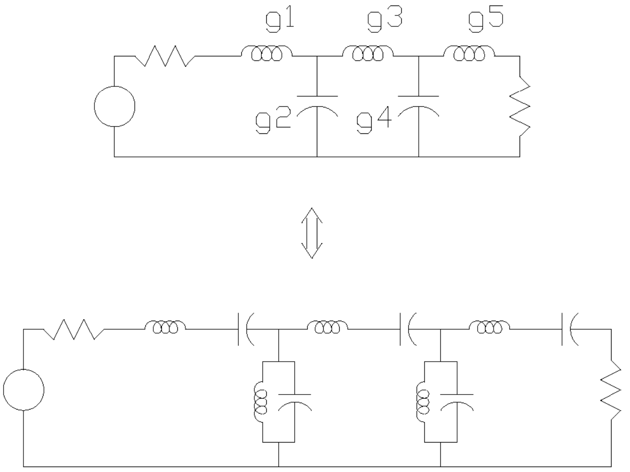


Figure 17: The lowpass topology can be transformed to a bandpass topology, replacing inductors with series resonators and capacitors with shunt resonators. Equations for the transformation are given in [8].

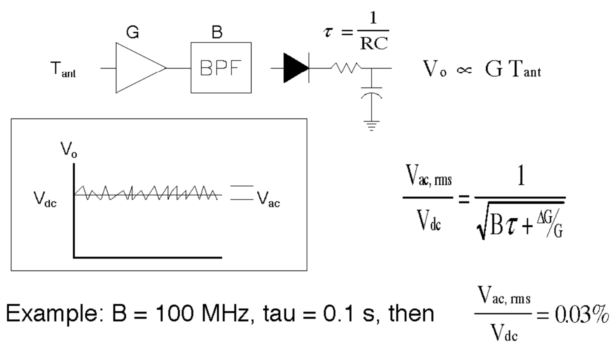


Figure 18: A simplified receiver detection diagram. The output voltage fluctuates about a DC value, and the amplitude of the fluctuations is inversely proportional to the square-root of the pre-detection bandwidth and the RC time constant, as long as gain fluctuations are kept small.

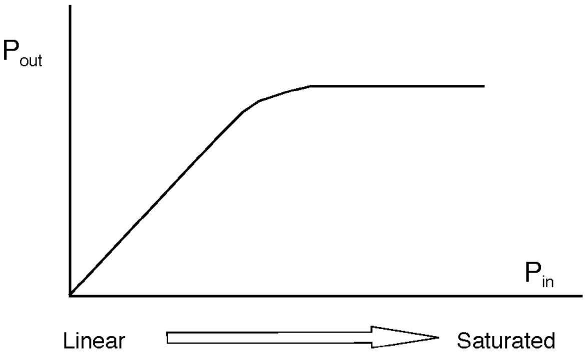


Figure 19: Amplifiers or other active components have limited output power capability.

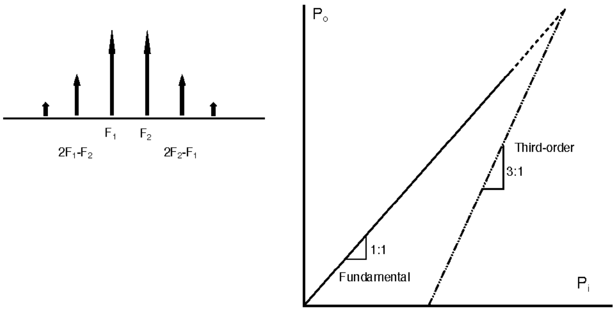


Figure 20: Non-linearity in a component gives rise to intermodulation products as strong input signals mix and produce products that can be difficult or impossible to remove by filters.

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Regulatory Structure of U.S. Radiocommunications

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1. Introduction

The fundamental law providing for the regulation of telecommunications by radio (as well as by wire) in the U.S.A. is the 1934 Telecommunications Act (the Act), as amended. The Act established a management structure that is unique to the U.S.A. with respect to the use of the radio spectrum. It created the Federal Communications Commission (FCC), and put it in charge of regulating matters related to private sector (including State and Local Government) telecommunications. Functions related to the Federal Government's use of the radio spectrum, on the other hand, were conferred upon the President. Through re-delegation, these functions were transferred at various times to other government entities; for over 20 years this entity has been the National Telecommunications and Information Administration (NTIA), a bureau of the Department of Commerce. This dual structure with respect to the management of the radio spectrum is reflected in all related activities, including scientific uses of the spectrum. The NSF Electromagnetic Spectrum Manager is charged with securing access to the spectrum for the government science enterprise, mostly radio telescopes operated by the national centers (NRAO and NAIC). The Committee on Radio Frequencies (CORF) of the National Academy of Sciences (NRC) represents radio astronomy interests, when it comes to proceedings of the FCC. There is extensive coordination at all levels between the entities representing government and non-government radio spectrum interests. Consensus is sought between the FCC and NTIA with regard to spectrum issues, with the State Department retaining authority over the decision when formal representation is required at international fora (e.g. World Radiocommunication Conferences), and a consensus position between the government (NTIA) and non-government (FCC) position cannot be reached.

Spectrum policy regarding scientific research is contained in the Telecommunications Policy statement detailing US Government spectrum policy objectives, that states that:

"The United States is vitally dependent upon the use of the radio spectrum to carry out national policies and achieve national goals."…

...

"Specifically, in support of national policies and the achievement of national goals, the primary objectives are:

...

…i) to promote scientific research, development and exploration;"

" Priorities among these areas of interest are normally determined on a case-by-case basis, and are dependent upon many factors, including past and foreseen political and administrative decisions." [1]

2. The US regulatory structure

a) Government spectrum regulation

NTIA, headed by the Assistant Secretary for Telecommunications and Information, houses the Office of Spectrum Management (OSM) that is directly responsible for managing the spectrum for the Federal Government. NTIA/OSM spectrum management functions include, but are not limited to:

-Serving as the President's principal advisor on telecommunications policies,

-To develop (in cooperation with the Federal Communications Commission) a comprehensive plan for management of all electromagnetic spectrum resources, including jointly determining the National Table of Frequency Allocations,

-To develop (in coordination with the Secretary of State and other interested agencies) plans, policies, and programs which relate to international telecommunications issues, conferences, and negotiations,

-To assign frequencies to radio stations belonging to and operated by the United States

-To acquire, analyze and disseminate data and perform research on the description and prediction of electromagnetic wave propagation, and the conditions which affect propagation, on the nature of electromagnetic noise and interference, and on methods for the more efficient use of the electromagnetic spectrum for telecommunications purposes

-To conduct research and analysis of radio systems characteristics and operating techniques affecting the utilization of the electromagnetic spectrum, in coordination with specialized, related research and analysis performed by other Federal agencies in their areas of responsibility.

The Interdepartment Radio Advisory Committee (IRAC) advises the Assistant Secretary for Telecommunications and Information on the spectrum requirements of the agencies of the federal government, and about related issues. The IRAC, made up of representatives of 20 member departments or agencies and an FCC liaison member, meets twice monthly chaired by a Deputy Assistant Secretary for Telecommunications

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[1] Manual of Regulations and Procedures for Federal Radio Frequency Management, Chapter 2.1.

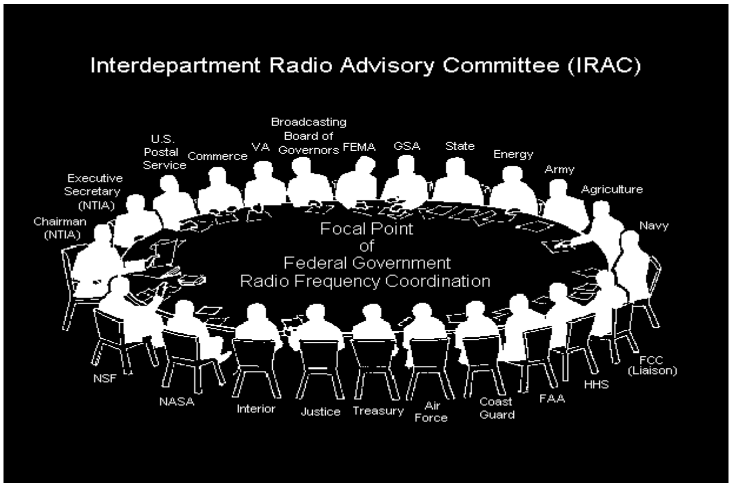

Fig. 1. Composition of the Interdepartment Radio Advisory Committee [2]

and Information, who represents NTIA on the committee. Since 1974, NSF has been one of the member agencies of the IRAC. The composition of the IRAC is shown in Fig. 1.

In addition to the main committee, the permanent structure of the IRAC consists of several standing subcommittees that deal with specific processes or issues. Among these, the Frequency Assignment Subcommittee (FAS) coordinates frequency assignments and licenses, the Spectrum Planning Subcommittee (SPS) analyzes major systems for spectrum availab-ility, the Radio Conference Subcommittee (RCS) carries out government preparations for world radio communication conferences, and other major international telecommunication meetings, the Technical Subcommittee (TSC) analyzes technical matters, and the Space Systems Subcommittee (SSS) deals with registration and coordination of satellite systems. A number of ad-hoc committees deal with specialized issues, e.g. implementation of the actions of a specific world radio communication conference (WRC), or coordination of radio stations along the border with the Mexican or the Canadian government.

Details about NTIA, the IRAC and its various subcommittees and ad-hoc committees, as well as about the procedures used in federal government spectrum management can be found in the "Manual of Regulations and Procedures for Federal Radio Frequency Management", often referred to as "the Red Book". The manual is available on-line at:

http://www.ntia.doc.gov/osmhome/redbook/redbook.html

b) The FCC

Under the Communications Act, the FCC is responsible for managing the spectrum to meet the needs of the private sector and state and local governments. The Commission

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[2] The composition of the IRAC, as shown in fig.1, and a number of other details in this article reflect the situation at the time of the Workshop and may no longer be current. It should be kept in mind that the U.S. spectrum management structure undergoes frequent changes in response to changing requirements; even if it's major features have subsisted for about two decades.

does so by employing multiple instruments it has at its disposal, such as Advisory Committees of limited duration and responsibility, e.g. to prepare for a WRC, rulemaking procedures, etc. The structure of the FCC, a description of the responsibilities of the various Bureaus, and extensive documentation on FCC actions can be found on its very useful website:

http://www.fcc.gov/

The spectrum itself is divided into bands that may be mixed government - nongovernment use, and others that are exclusively used either by the government or by the private sector. Most bands fall into the mixed government - nongovernment use category, and decisions related to these bands require coordinated actions by the NTIA and the FCC.

c) The ITAC-R

A standing advisory committee, the U.S. International Telecommunications Advisory Committee-R(adio) (ITAC-R) advises the Dept. of State on matters related to international radiocommunications. The ITAC-R operates under the Federal Advisory Committee Act (FACA), and its structure mirrors that of the various groups that operate within the ITU. In particular, the ITAC-R mirrors the ITU-R Study Group structure. Thus, for example, US Study Group 1 discussing the US documents that are to be submitted to meetings of the international SG 1. US SG 7, the study group dealing with science services, is currently chaired by Dave Struba, from NASA, while I chair US WP 7D. US WP 7D usually holds 4-6 meetings per year that are accessible by phone to participants. Once the corresponding Study Group or Working Party approves a document, they also have to be reviewed and approved by the US National Committee (USNC), prior to being submitted to the corresponding ITU Study Groups. The USNC is composed of ~100 individuals from government agencies, industry and academia. As a rule, documents approved by a US Study Group or Working party are posted to a website for a period of 2-3 weeks, for comment by members of the USNC. If there is a disagreement, and no consensus can be reached, representatives from NTIA, the FCC and the State Department jointly determine the disposition of the paper.

3. How to get involved?

Membership in CORF is by invitation of the National Academy of Sciences / National Research Council. Membership in US ITU-R Study Groups, Working Parties and other temporary ITU-R groups is open, as provided by the Federal Advisory Committee Act (FACA) that regulates their functioning. Study group meeting dates and places *have to* be announced in an official publication (the Federal Register), 30 days in advance of the date of the meeting. As they are considered subcommittees of the main group, WP meetings do not need to be similarly advertised. Participation in these groups requires no more than contacting the Chair or showing up at the meeting. The members of US Delegations to World Radiocommunication Conferences (WRCs) are selected by the State Dept., acting on the Recommendation of the NTIA and/or the FCC.

European frequency management and the role of CRAF for radio astronomy

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Abstract
In Europe, radio frequency regulation is managed by the CEPT, the *Conference of European Posts and Telecommunications Administrations* (under an MoU with the European Commission). The CEPT develops guidelines and provides national Administrations with tools for harmonised European frequency management. In frequency management matters, the European radio astronomy community is represented by CRAF, the Committee on Radio Astronomy Frequencies of the ESF, the European Science Foundation. CRAF at present has members from 17 CEPT countries and a number of international organisations and it employs a full-time pan-European spectrum manager. Like several other non-government organis-ations, CRAF participates actively in this process through collaboration and communication with national Administrations and at CEPT level. CRAF has an observer status within the CEPT and is a Sector Member of the ITU-R, allowing it to participate in its own right in European and global fora dealing with radio frequency management.

1. Introduction

The task of accommodating all competing radio services and systems within the finite usable range of the radio frequency spectrum comes under the generic title of *spectrum management* or *frequency management*. This process is mainly the responsibility of government Administrations and it is imperative that those Administrations coordinate their efforts internationally. The international Administrative cooperation body that has the responsibility for coordinating spectrum management at the global level is the *International Telecommunication Union*, ITU.

The global framework for radio frequency management is provided by the Radio Regulations of the ITU (ITU 2001), which have international treaty status and thus are binding for all members of the ITU. They provide rules to national Administrations that allow them to regulate equitable access to the radio spectrum for

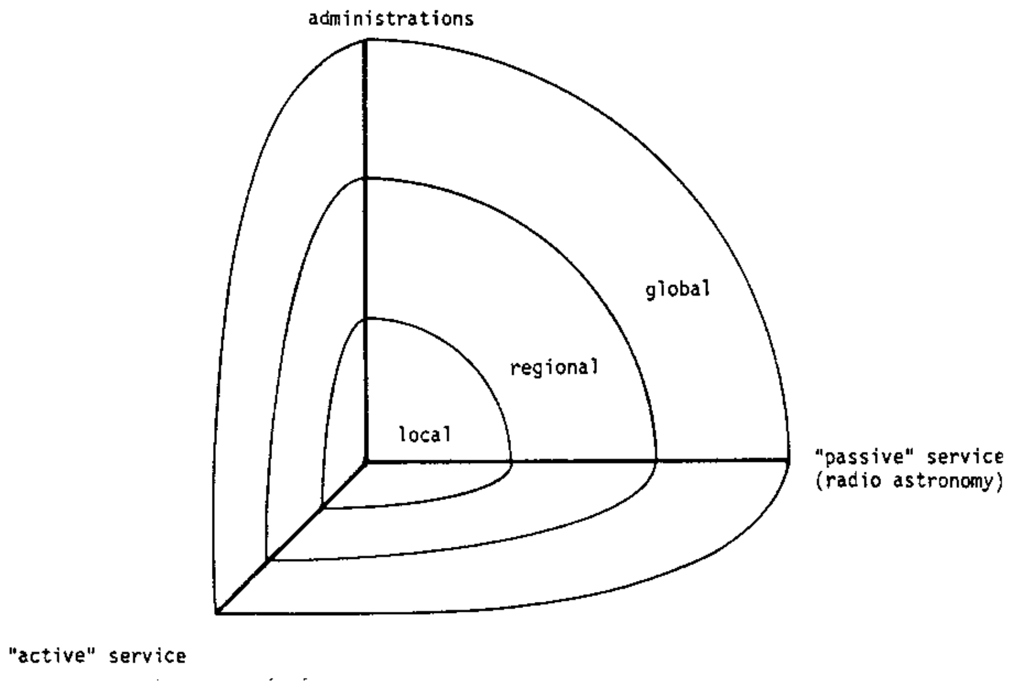

Figure 1: The “problem space” of spectrum management.

all entities requiring frequency allocations: telecommunication industry, safety services, aeronautical services, various scientific and hobby uses, etc. The Radio Regulations contain the international *Frequency Allocation Table*. For the purpose of this table, Europe lies within ITU Region 1, together with the Middle East, Africa and Asia north of the Himalayas. The ITU Radio Regulations contain much more than this table alone, such as rules for the use and operation of frequencies, operating procedures for stations and procedures for the coordination of frequencies.

Between the broad framework established at the global level by the ITU and the detailed frequency planning necessary for national Administrations, there has always been a need for regional coordination. The forum for achieving such regional harmonisation in Europe is the *Electronic Communications Committee*, ECC, of the CEPT, the *Conference of European Posts and Telecommunications Administrations*. In the Americas it is the *Inter-American Telecommunication Commission*, CITEL, and in the Asia Pacific region the *Asia Pacific Telecommunity*, APT. Similar organisations are emerging in other regions of the world.

2. Regional Regulatory Coordination in Europe

Although, especially from the outside, “Europe” is commonly regarded as equivalent to those countries assembled in the European Union, for frequency management matters, Europe covers a considerably larger territory: the 44 countries of the CEPT (see Section 2.2).

In Europe the key ‘players’ on frequency management issues are the following:

- Administrations
- CEPT - Conference of European Posts and Telecommunications Administrations
- EC - European Commission
- Standardisation InstitutesOther interested parties (including CRAF for radio astronomy)

2.1 Administrations

The ITU Radio Regulations define an Administration as "*any governmental department or service responsible for discharging the obligations undertaken in the Constitution of the International Telecommunication Union, in the Convention of the International Telecommunication Union and in the Administrative Regulations*" (ITU Constitution – Annex 1002).

Each sovereign state has, in some way or other, its own Administration with the mandate to use all means possible to facilitate and regulate radiocommunication in that country. The mandate and terms of reference of a Regulatory Authority are usually defined by national telecommunication law, which in EC member states and affiliated countries is defined within the framework of EC telecommunication Directives. Such laws also include a national frequency allocation table, which is the national articulation of the ITU Radio Regulations. These national regulations concern the application of national frequency policy, the enforcement of regulations and the protection of the interests of private and public users of radio frequencies. In Europe, the CEPT and the European Commission provide the framework for national regulations.

2.2 CEPT

The CEPT was formed in 1959 to bring together the postal and telecommunications Administrations of Western Europe. At present, it comprises 44 countries of Western, Central and Eastern Europe, and its membership continues to grow. Only European Administrations that are members of the ITU or of the *Universal Postal Union*, UPU, can become a member of CEPT. In 2001 the *Electronic Communications Committee*, ECC, was established as a body of radio Regulatory Authorities. Although in principle the CEPT committees come under the CEPT *Plenary Assembly*, in practice they have a great deal of autonomy.

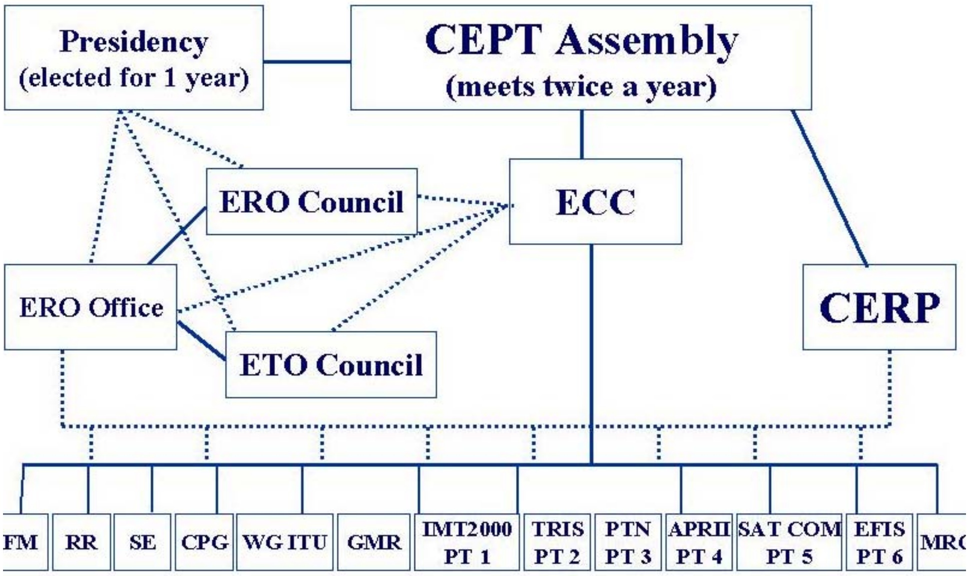

Fig. 2: The organisational structure of the *Conference of European Posts and Telecommunications Administrations,* CEPT.

The ECC is the highest body within the CEPT mandated to develop policy on spectrum management issues and to decide on European radiocommunication issues. The ECC has several working groups, addressing different aspects of spectrum management. The secretariat of the CEPT is the European Radiocommunications Office, ERO, in Copenhagen.

At a regional, European level the CEPT plays a key role in spectrum management. Regional regulations in Europe include the development of the European Common Allocation Table (which will come into force in 2008). Among its other tasks are the following :

- development of a common policy on electronic communications activities in a European context, taking account of European and international legislation and regulations;
- preparation of European common positions and proposals for use in the framework of international and regional bodies;
- planning and harmonization of the efficient use of the radio spectrum, satellite orbit, and numbering resources in Europe, so as to satisfy the requirements of European users and industry;
- development and approval of Decisions and other deliverables;
- implementing the strategic decisions of the CEPT Assembly;
- proposing issues for consideration by the Assembly.

In summary, the CEPT provides European Administrations with a wealth of management elements in a framework reflecting the ITU Radio Regulations, which these Administrations can adapt to meet their national requirements.

The CEPT is based on voluntary cooperation between Administrations. It makes political agreements, Decisions and Recommendations. In a legal sense, its Recommendations and Decisions have about the same status. Since the CEPT community is not bound by a treaty that regulates these Decisions and Directives, they are only binding for those Administrations that chose to adopt them.

2.3 European Union and European Commission

The European Union consists of 15 Member States, which delegate sovereignty to independent institutions. The European Commission in Brussels upholds the interests of the Union as a whole, while each national government is represented within the Council, and the European Parliament is directly elected by its citizens.

The EC is a political body and the driving force in the institutional system of the EU in the following respects:

1. drafting of legislation and presenting legislative proposals to the Parliament and the Council;
2. implementing European legislation, budget and programmes adopted by the Parliament and the Council;
3. representing the Union on the international stage and in negotiating international agreements;
4. enforcing Community law (jointly with the Court of Justice).

The role of the European Commission is different from that of the CEPT, because of the EU treaty that binds them. Frequency-regulatory issues have been delegated by the EC to the CEPT through an MoU. Their structural difference implies a difference in legal status of the regulatory ‘products’ of the CEPT and of the EC.

EU Directives prevail over CEPT Decisions and are legally binding for European telecommunication regulation within the *European Economic Area*, EEA, and the EC member states, even for states that do not approve of them (the handling of deviating views has also been regulated). If any national legislation is not in harmony with EU law, this has to be corrected in due course. Also CEPT Decisions and Recommendations must not be incompatible with EU law.

EU Directives and CEPT Decisions must be seen as instruments serving the interests of the Community, which allow national regulatory authorities to impose licensing conditions that are linked to efficient frequency use. Any such condition must be justifiable and is subject to the principle of proportionality. Regulators must use the least restrictive regulatory means to achieve the required conditions. Given the different mandates of the CEPT and the EC, their views on spectrum management and policy are rather different.

The EC is gradually working to increase its influence on radio frequency issues. It favours a spectrum policy governed by the interests and requirements of the active radiocommunication services, and it lacks a strategic view on the specific interests and requirements of passive (i.e. receive-only) services and applications with respect to those of the active services. This lopsidedness reduces the balance of its spectrum policy. An explanation for this is readily found in the priority the EC gives to commercial and industrial interests.

2.4 Standardisation institutes

In Europe, the following bodies address standardisation issues:

- CEN	the European Committee for Standardisation
- CENELEC	the European Committee for Electrotechnical Standardisation
- ETSI	the European Telecommunications Standards Institute.

Besides these, many national standards bodies exist within Europe. Regarding global telecommunications standards, the ITU-T sector is the responsible body. Within Europe, the *European Telecommunications Standards Institute*, ETSI, plays this role and increasingly so with the focus being put on European standards development.

2.4.1 ETSI

ETSI was created by the CEPT in 1988, and is aimed at the common European goals: to facilitate the integration of the telecommunications infrastructure, to assure the proper inter-working of future telecommunications services and the compatibility of terminal equipment, and to create new pan-European telecommunications networks.Since the ITU-T Recommendations very often contain options and/or are not detailed enough in order to allow, for instance, end-to-end compatibility of terminal equipment, the European standardisation in ETSI plays a key role in the development of voluntarily harmonised standards within the EU, and serves worldwide standards development. This is done through the construction of a coordinated European solution, which can be offered as a European contribution to the ITU, and adopted as a European standard. As such, it constitutes a useful instrument for speeding up the work at a European level, rather than a hurdle on the way to international standardisation.

The guidelines of the European standardisation process in ETSI can be summarized as follows:

* to prepare a common European position for the work in worldwide standardisation bodies (ITU, IEC, ISO, etc.) and to support the adopted European standards in these bodies;

* to complete the standards according to the European requirements, defining one option only;

- * to anticipate the activity of the worldwide standards bodies through the adoption of European standards.

Since the CEPT is the founding organisation of ETSI, an ETSI Member must be from a CEPT member country. The ETSI membership consists *inter alia* of Administrations, Administrative Bodies and National Standards Organisations and Manufacturers, Private Service Providers, Research Bodies, Consultancy Companies / Partnerships, and others (the large majority).

It is the goal of ETSI to meet the standardisation needs of the whole of Europe. ETSI is open to Central and Eastern European states and has already established closer contacts in that region with Administrations, network operators and manufacturers in the telecommunications field in order to fulfill this objective.

Since a standard is a voluntary agreement or 'tool' to facilitate industry, it is not legally binding.CENELEC and ETSI can only work on standard development after CEPT has approved the frequency selection, when relevant. Also draft system reference documents and draft standards need approval of CEPT before official publication.

2.5 Other interested parties

Apart from Administrations and standardisation institutes, there are many more organisations that are interested in proper frequency management. In Europe, these include:

CRAF	Committee on Radio Astronomy Frequencies
EBU	European Broadcasting Union
ESA	European Space Agency
IARU	International Radio Amateur Union
NATO	North Atlantic Treaty Organisation

These organisations have a formal observer status in CEPT, which enables them to participate in the work of the CEPT in all its commissions, working groups and project teams from the ECC to the lowest level.

Such a relation is also desired with the European Commission, where the interests of industrial and commercial are well served, while in practice this is not the case for the science services and the space service. A similar situation applies to the standardisation institutes, where the active participation of science services is difficult since the cost of joining these institutes is prohibitive.

3. The Role of CRAF

In frequency management matters, the European radio astronomy community is represented by CRAF, the Committee on Radio Astronomy Frequencies of ESF, the European Science Foundation. CRAF, which was founded in 1987, was established as an ESF committee in 1988. Its members represent the radio astronomical observatories of 17 CEPT countries, the European VLBI Network (EVN), the Joint Institute for VLBI in Europe (JIVE), and three other multi-national organisations (EISCAT, ESA and IRAM). Together, these observatories cover the entire ITU frequency allocation range, from 13 MHz to 275 GHz.

The European Science Foundation (ESF) acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan, and implement pan-European scientific and science policy initiatives. It is an association of the 70 major national funding agencies devoted to scientific research in 27 countries, and it represents all scientific disciplines.

The role of CRAF is “to keep the frequency bands used by radio astronomers free of interference”. To this end it operates both at an administrative and at a technical level: CRAF co-ordinates the relevant representations concerning radio astronomy made to the various national and supranational radio regulatory bodies within Europe, it acts as the European voice in concert with other groups of radio astronomers in discussions within the international bodies that allocate frequencies, and it initiates and encourages scientific studies aimed both at reducing interference at source and the effects of interference.

Since January 1, 1997, CRAF has employed a full-time pan-European radio astronomy Spectrum Manager. Funding for this position is provided by the member Institutes or their funding Agencies, and financial support within the sixth Framework Programme, FP6, of the EU will be sought as part of the Radio Astronomy Integrated Activity proposal.

Within the CEPT (see Section 2.2) CRAF has observer status, which enables it to participate in its own right in CEPT work at various levels, such as the ERC Working groups FM (Frequency Management) and SE (Spectrum Efficiency), on various FM and SE project teams, and in the preparation of European Common Positions on WRC issues. Through its CEPT status it can communicate directly with other organisations, such as NATO and IARU. CRAF’s relationship with the European Commission is at present only incidental, as the CEPT handles frequency management issues within Europe (of which the EU countries are a subset). These ties will need to be reinvigorated, given the EC’s views about the proliferation of active spectrum applications that are potentially detrimental for the passive services, such as Ultra Wide-Band applications. CRAF deals with ETSI only in consultative processes for the development of industrial standards.

At the global level, CRAF is an ITU-R sector member. In general, however, CRAF does not contribute input papers directly to the various ITU-R fora, nor does it send its representatives to their meetings, since it prefers to make its positions know there through collaboration and consultation with IUCAF, the sole worldwide organisation of radio astronomers. At present, three members of CRAF are also IUCAF members. CRAF has an official liaison with CORF, which represents US radio astronomy, an association which we also hope to arrange with the recently-created RAFCAP, which represents radio astronomers in the Asia-Pacific region.

CRAF also has an educational role in making others, particularly active radio spectrum users, aware of the sensitivity and consequent need for protection of the RAS. This function is being fulfilled for example by the publication of the CRAF Handbook for Radio Astronomy (2nd ed., 1997) and the CRAF Handbook for Frequency Management (2001), which are made widely available. Furthermore, CRAF regularly publishes a Newsletter, which is distributed in print and is available on the Web at http://www.astron.nl/craf.

4. Important Current European frequency Issues

Currently (2002) the most important radiocommunication issues for the passive services in Europe are:

- preparation for WRC-03 (which has a very full agenda);
- RAS (in-)compatibility with Ultra-Wide Band (UWB) and Short Range Radars;
- RAS (in-)compatibility with Power Line Communication systems;
- Broadcasting re-planning (T-DAB/S-DAB);

- UMTS/IMT2000 developments;
- establishment of a European Common Allocation Table (ECA).

5. Literature

CRAF, 1997, Handbook for Radio Astronomy – 2nd edition (European Science Foundation, Strasbourg)

CRAF, 2002, Handbook for Frequency Management (European Science Foundation, Strasbourg)

ITU-R Radio Regulations, edition 2001 (International Telecommunication Union, Geneva)

6. Abbreviations

APT	Asia Pacific Telecommunity
CENELEC	European Committee for Electrotechnical Standardisation
CEPT	Conference of European Posts and Telecommunications Administrations
CERP	European Committee on Postal Regulation
CITEL	Inter-American Telecommunication Commission
CORF	Committee on Radio Frequencies (USA)
CRAF	Committee on Radio Astronomy Frequencies of the European Science Foundation
DAB	Digital Audio Broadcasting
ECA	European Common Allocation Table (CEPT)
EEA	European Economic Area
EBU	European Broadcasting Union
EC	European Commission
ECC	Electronic Communications Committee (CEPT)
ESA	European Space Agency (member of CRAF)
EISCAT	European Incoherent Scatter Scientific Association (member of CRAF)
ETSI	European Telecommunications Standards Institute
EU	European Union
EVN	European VLBI Network
IARU	International Radio Amateur Union
IMT-2000	International Mobile Telecommunication System
IRAM	Institut de radio astronomie millimétrique (member of CRAF)
ITU	International Telecommunication Union
JIVE	Joint Institute for VLBI in Europe
MoU	Memorandum of Understanding
NATO	North Atlantic Treaty Organisation
RAFCAP	Radio Astronomy Frequency Committee in the Asia-Pacific Region
S-DAB	Satellite - Digital Audio Broadcasting
T-DAB	Terrestrial Digital Audio Broadcasting
UMTS	Universal Mobile Telecommunication System
UPU	Universal Postal Union
UWB	Ultra-Wide Band
WRC	World Radiocommunication Conference (ITU)

Radio Spectrum Management in the Asia-Pacific region

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1. Introduction

The Asia-Pacific region primarily comprises countries in ITU-R Region 3 from South and East Asia, Oceania and the Pacific islands, while excluding the Americas. Organisations in the Asia- Pacific region face special challenges in coping with the very diverse cultures and languages of the different nations. Telecommunications in each country are usually administered by a single National Communications Administration, which in the case of Australia is the Australian Communications Authority (ACA).

The main organisations in the region of relevance to Radio Astronomy are:

- The Asia Pacific Telecommunity (APT)
- The Radio Astronomy Frequency Committee in the Asia Pacific region (RAFCAP)
- The Pacific Telecommunications Council (PTC)

Brief descriptions of these organisations are given below. Detailed and constantly updated information on all of these is available on the web via the links shown.

2. APT (www.aptsec.org/)

The Asia-Pacific Telecommunity was established in 1979 via a treaty-level inter-governmental agreement. It has 32 full members and 4 associate members, mainly represented by national communication ministries or communication administrations. Enterprises and other organisations active in telecommunications services or information infrastructure within the region are eligible for affiliate membership, so there are 96 affiliate members in the APT.

2.1 Objectives of the APT

The objective of the Telecommunity is to foster the development of telecommunications services and information infrastructure throughout the region, with a particular focus on the expansion thereof in less developed areas. To achieve this, the Telecommunity may:

(a) Promote the expansion of telecommunication services and information infrastructure and the maximization of the benefits of information and telecommunications technology for the welfare of the people in the region;

(b) Develop regional cooperation in areas of common interest, including radio-communications and standards development;

(c) Undertake studies relating to developments in telecommunications and information-infrastructure technology, policy, and regulation in coordination with other international organizations, where pertinent;

(d) Encourage technology transfer, human resource development, and the exchange of information for the balanced development of telecommunications services and information infrastructure within the region; and

(e) Facilitate coordination within the region with regard to major issues pertaining to telecommunications services and information infrastructure with a view to strengthening the region's international position.

2.2 APT Programs

The APT fosters a diverse program of activities in telecommunications in the region, with a particular focus on Information and Communications Technology (ICT). Some of the current major programs are:

- **AIIS - Asia-Pacific Initiatives for the Information Society,** to focus on assisting members to bridge the digital divide and make the most of digital opportunities
- **ASTAP - Asia-Pacific Telecommunity Standardization Program,** to establish regional cooperation and to harmonize standardization activities in the region
- **AWF - APT Wireless Forum,** to promote a harmonised vision of wireless communication systems and services in the Asia-Pacific region
- **IWG - The Regional Interagency Working Group on ICT,** to enhance synergies in ICT in the Asia-Pacific region
- **HRD - APT Human Resource Development (HRD) Program,** a collaborative program for the exchange of ICT Researchers and Engineers
- **APTYPS - APT Young Professionals and Students Forum,** to encourage young professional's interest in the field of ICT and to utilize their huge, untapped enthusiasm and energy

The APT also runs four major **Study Groups (SG),** to conduct studies on telecommunications issues that are of concern to members. The study groups operate in three year cycles, broadly in line with the ITU WRC cycles. Currently, the APT study groups are:

- **Study Group 1: Networks**
- **Study Group 2: User issues**

- **Study Group 3: Applications and Services**
- **Study Group 4: Broadband issues**

However, the program that has the most impact on radio astronomy is the **APG,** the **APT Preparatory Group** for the ITU World Radiocommunications Conference (WRC). The APG aims to harmonise the views of APT Members and develop common proposals for submission to the WRC. Regionally harmonised proposals are very influential at the WRC and are often very successful in promoting the views and interests of the APT members. The APG is the natural arena to represent radio astronomy interests in the region and garner support for issues at the ITU.

3. RAFCAP (www.atnf.csiro.au/rafcap/)

The Radio Astronomy Frequency Committee in the Asia-Pacific region (RAFCAP), was established at the regional URSI meeting AP-RASC'01 (August 2001, Tokyo). It arose from a perceived need for a radio-astronomy committee to coordinate spectrum management activities in the region. It is modelled on the European Committee on Radio Astronomy Frequencies (CRAF). The main forum for RAFCAP activities is the APT, and more specifically the WRC preparations at the APG. RAFCAP is recognised in the APT as a regional organisation, and is invited to participate in APT activities.

RAFCAP acts as the scientific expert committee on frequency issues for the Asia-Pacific radio astronomy and related sciences. The **mission** of RAFCAP is:

(a) to keep the frequency bands used for radio astronomical observations free from interference

(b) to argue the scientific needs of radio astronomy for continued access to and availability of the radio spectrum for radio astronomy within the Asia-Pacific region

(c) to support related science communities in their need for interference-free radio frequency bands for passive use.

The RAFCAP membership at the founding date was:

- **Chairperson** -- Masatoshi Ohishi (NAO, Japan)
- **Secretary** -- Tasso Tzioumis (ATNF, Australia)
- Makoto Inoue (NRO, NAO, Japan)
- S. Ananthakrishnan and T.L. Venkatasubramani (GMRT, TIFR, India)
- Uday Shankar (RRI, India)
- X. Hong (Shanghai Obs., China)
- S. Wu (National Astr. Obs., China)
- H.S. Chung (Korea Astr. Obs., South Korea)
- Jeremy Lim (IAA, Chinese Taipei)

RAFCAP is supported by the parent institutions of its members, and membership is periodically changed to reflect organisational changes.

As a new regional organization, RAFCAP faces many challenges to become recognized and effective in the region. It needs to increase the involvement of all regional radio astronomy observatories, especially in countries that radio astronomers have little past involvement in radio spectrum issues. The focus of RAFCAP activity are the APG meetings and it is intended for RAFCAP to actively participate in all future APG activities. RAFCAP meetings will generally be held in conjunction with participation at the APG.

4. PTC (www.ptc.org)

The Pacific Telecommunications Council (PTC) is a unique international, non-profit, non-governmental membership organisation. The Council is regional in nature, embracing members from all countries that play a role in the development of Pacific Telecommunications and thus includes Asia Pacific and countries from the Americas. The PTC was founded in 1980 and now boasts more than 900 member representatives from over 40 countries.

The people who comprise PTC cover every aspect of communications: carriers, communication- satellite service providers, cable entities, broadcasters, equipment manufacturers, users of telecom services, universities, law firms, consultancies, government ministries and agencies, and a wide variety of individuals encompassing other aspects of telecommunications and information systems and services.

4.1 PTC Purposes

From the Articles of Incorporation of the PTC, the purposes of its Council are:

A. To provide a forum for discussion and interchange of information, ideas, and the expression of views regarding telecommunications and related aspects of the information society and economy in the Pacific for a multi-faceted, diverse body of members, which includes policy-makers, planners, regulators, users, researchers, academics, and providers of equipment, software, and content

B. To promote a general awareness of the varied telecommunications requirements of the Pacific area

C. To organize conferences and seminars to promote the free flow and interchange of the varied views and requirements of the Pacific area, as well as to address specific tele-communications issues to assist in solving near-term and future issues

D. To communicate viewpoints and recommendations of the Council to the established national, regional, and international organizations responsible for policies in telecommunications

E. To advance the Council’s role for social and economic good

4.2 PTC activities

PTC serves the communication world by organizing a major annual conference, regional seminars, research activities, by publishing the PTR (Pacific Telecommunications Review) as well as a variety of other publications, and through various other services and activities. Some recent activities include:

- PTC2002 (Hawaii) – “Next Generation Communications: Making IT Work”
- PTC2003 – “Global Broadband – Global Challenges”
- PTC mid-year 2002 – “Building Strong Partnerships”
- WWW2002 & WWW2003 conferences

5. References

1. The CRAF Handbook for frequency management, 2002. Editor: T. Spoelstra. www.astron.nl/craf/
2. APT – www.aptsec.org
3. RAFCAP – www.atnf.csiro.au/rafcap/
4. PTC – www.ptc.org

IUCAF

Darrel Emerson

NRAO, Tucson

1. Introduction

IUCAF is the international organization representing the unfettered views of passive scientific users of the radio-frequency spectrum at the ITU (International Telecommun-ication Union). It operates under the auspices of ICSU, the International Council for Science, which is part of UNESCO. IUCAF is sponsored by the International Astronomical Union (IAU), the International Union of Radio Science (URSI), and by the Committee on Space Research (COSPAR). ICSU set up IUCAF in 1960 to work towards keeping parts of the radio spectrum clear of interference for passive scientific use. This action was partly stimulated by the potential threat posed at that time by Project WESTFORD (Robinson 1999), which would have placed metallic needles into Earth orbit, as well as by the then recent successes in observing 21 cm emission from neutral hydrogen, which had just led to a major reappraisal of knowledge of our own Galaxy, and our position in it. Indeed CORF, the United States counterpart to IUCAF, was only established by the US National Academy of Science in 1961.

The "IUCAF" acronym used to stand for the "**I**nter-**U**nion **C**ommission on the **A**llocation of **F**requencies for Space Research and Radio Astronomy". This title was later changed to the "Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science", but **"**IUCAF**"** had by then become so well known that it was decided to keep the acronym.

2. Terms of Reference

The directive setting up IUCAF, and its terms of reference, follows.
"

CONSTITUTION AND TERMS OF REFERENCE OF THE
INTER-UNION COMMISION ON FREQUENCY ALLOCATIONS
FOR RADIO ASTRONOMY AND SPACE SCIENCE (IUCAF)

Considering that for research in radio astronomy and space science it is urgently necessary to have the use of an adequate number of frequency channels that are sufficiently protected from interference with scientific observations, ICSU established, under URSI as Parent Union, an Inter-Union Commission between URSI and IAU in conjunction with COSPAR, with no more than four representatives of each of the adhering bodies; with the Secretary of the Commission as full member ex officio. The Commission will have the power to co-opt not more than three members not representing the constituent bodies.

The terms of reference are as follows:

a) To study the requirements for frequency channels and radio frequency protection for passive radio science research in fields such as radio astronomy, space research and remote sensing

b) To co-ordinate these requirements for the three constituent bodies which may set up special committees for the purpose;

c) To formulate proposals for frequency allocations which are adequate to meet these requirements;

d) To bring these proposals to the attention of the appropriate national frequency allocation authorities with the assistance of the national member bodies which may establish joint national committees for the purpose;

e) To initiate necessary action to get these proposals placed on the agenda of the International Telecommunication Union (ITU);

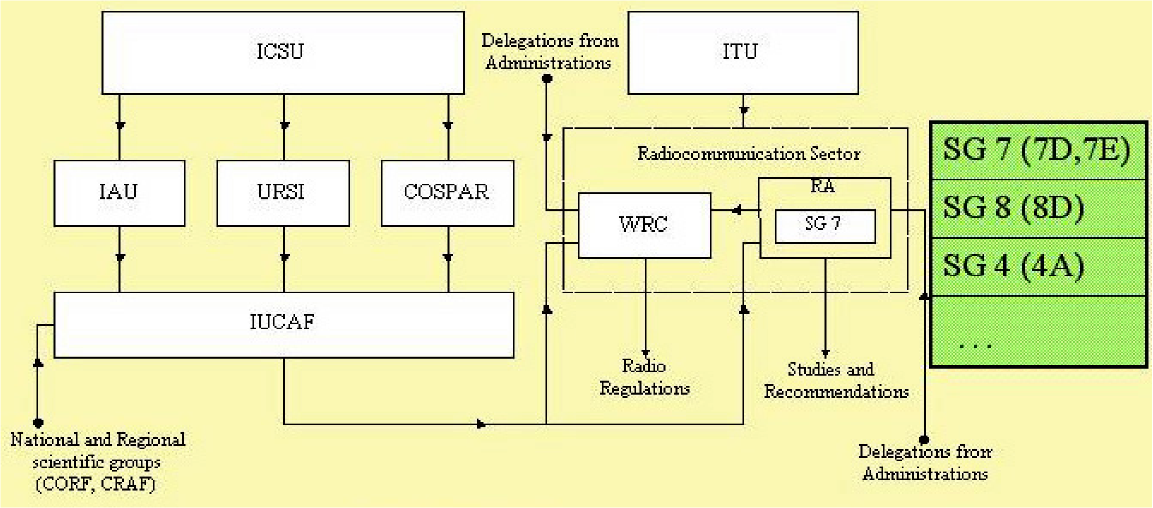
f) To initiate such other action as is deemed appropriate under the charter of ICSU to ensure favourable action on these proposals by the International Radio Consultative Committee (CCIR) and ITU;

g) To note that any formal communication from the Commission to CCIR or ITU will be sent on behalf of the three bodies by the Secretary of the Inter-Union Commission on Frequency Allocations for Radio Astronomy and Space Science."

The current (April 2002) members of IUCAF are:-

URSI	W. A. Baan	The Netherlands
	M. M. Davis	USA
	W. van Driel	France
	A. van Eyken	Norway
	P. Poiares Baptista	The Netherlands
	K. Ruf	Germany
	A. Tzioumis	Australia
IAU	S. Ananthkrishnan	India
	R. J. Cohen	United Kingdom
	D. T. Emerson (Chair)	USA
	M. Ohishi	Japan
	K. F. Tapping	Canada
COSPAR	S. Gulkis	USA
	J. Romney	USA

Figure 1 shows the organizational block diagram relating IUCAF to the ITU. IUCAF members are elected by the different scientific unions to represent radio astronomy and other passive science services at World Radio Conferences (WRCs) and at meetings of relevant ITU-R study groups, working parties and task groups. Initially IUCAF's main forum at the ITU was the Working Party 7D, the specialist



where (in alphabetical order):

CORF	Committee on Radio Frequencies
COSPAR	Committee on Space Research
CRAF	Committee on Radio Astronomical Frequencies
IAU	International Astronomical Union
ICSU	International Council of Scientific Unions
ITU	International Telecommunication Union
IUCAF	Inter-Union Commission for the Allocation of Frequencies for Radio Astronomy and Space Science
RA	Radiocommunication Assembly
SG 7	Radiocommunication Study Group7
URSI	International Union of Radio Science
WRC	World Radiocommunication Conference

Fig. 1 : The organizational block diagram relating IUCAF to its parent bodies within ICSU, and its interaction with the subcommittees of the ITU, is based on that in the ITU-R Handbook on Radio Astronomy (1995).

group concerned just with Radio Astronomy. These Working Party meetings at the ITU are open to other delegates, and at some recent WP7D meetings in Geneva the true radio astronomers have found themselves outnumbered by other delegates representing, for example, the satellite industries. In response to this, IUCAF now aims to have its own representative within other ITU Working Parties such as WP8D and WP4A, that may be concerned primarily with satellite emission, but which of course may have a serious impact on radio astronomy. We have had some success in modifying the wording in documents coming from these groups, but clearly this has put a strain on IUCAF's limited resources.

While much of the focused activity of IUCAF occurs at the ITU, particularly during meetings of Working Party 7D (Radio Astronomy), its members keep in close touch these days via the internet. But the world-wide distribution of members, and the diversity of their scientific interests, also results in small meetings being held whenever several members find themselves together for any reason, as occurs from time to time at the IAU, URSI, or one of the national astronomical societies. Moreover, while in Geneva, many members meet after ITU sessions at the *Lord Jim*.

3. Past Successes

IUCAF has been lucky to have had a sequence of effective chairmen since its inception. These were J-F. Denisse (1960 - 1964), F. G. Smith (1964 - 1975), J. P. Hagen (1975 - 1981), J. W. Findlay (1981 - 1987), B. J. Robinson (1987 - 1995), W. A. Baan (1995 - 1999), and K. Ruf (1999 - 2001). These chairmen have led it to some notable successes. Thus India was induced to propose at WARC 1979 that the 322-326.8 MHz band be allocated to radio astronomy, to enable the detection of deuterium, an allocation supported by NATO countries. But this was still very much the "cold-war" period, when the Soviet Union had an extensive radar network around the Middle East at 327 MHz, which it had used in 1960 to track the Gary Powers U2 spy plane over its territory. Thus the acquisition of the radio astronomy allocation at 327 MHz effectively shut down a Soviet radar network.

The Russian counterpart to the US GPS satellite system is GLONASS, which has an ITU allocation to operate in the 1602-1615.6 MHz band. Jim Cohen discusses this system in detail elsewhere in this volume. IUCAF's concern began in 1983, when GLONASS started to produce strong interference in the 1610.6-1613.8 MHz radio astronomy band containing the important emission line of the OH radical at 1612.23 MHz, which provides the type-defining signature of the OH/IR class of stars. In 1983 radio astronomy had exactly equal status with the navigational services in its band, so astronomers had no official grounds to complain. However IUCAF did contact the Russian administration to see what could be done to ameliorate the situation. As a consequence, eventually during WARC-92, an Australian proposal to enhance the status of radio astronomy at 1612 MHz was approved. With that vote, radio astronomy gained full primary status in the band. IUCAF subsequently reached a memorandum of understanding with the Russians that was signed in 1993, and continues to discuss the issue with them, as the Russians are expected to launch a more heavily-filtered version of their satellite when stocks of the initial model are depleted.

Brian Robinson (1999) summarizes the IUCAF scenario:

> "IUCAF members had to evolve from being starry-eyed astronomers as they encountered a world of politics, lobbying, entertainment, threats, espionage and bribery. On one occasion, an offer (in Geneva) of two million dollars in cash '*to shut up*' proved no match for dedication to the joys and excitement of twentieth-century astrophysics."

4. Current Issues

Satellite systems continue to be a current issue for IUCAF, as they have the potential to produce very high levels of unwanted emissions into adjacent radio astronomy bands, and their operating companies are politically powerful adversaries. IUCAF is also involved with coordination issues, as the protection of a radio astronomy band everywhere across the globe is no longer assured. In some cases, such as the 1668.0 to 1670.0 MHz band, only the immediate location of listed radio astronomy observatories is now protected, even in the supposedly "exclusive" radio astronomy bands.

The current drive to speed-up and modernize spectrum management, so as to squeeze ever more systems into the spectrum, poses fresh challenges for IUCAF. In the USA, this has produced initiatives by the FCC to consider new ways of assessing "harmful interference", such, for instance, as by introducing the concept of an interference temperature. Another current issue is the push in the USA and the EU to allow the operation of unregistered low-power ultra-wide bandwidth devices across spectrum that is already allocated to a variety of other services and which preliminary studies show to be potentially very harmful for radio astronomy. Times are achanging and IUCAF must needs adapt. One possible mode to tackle some of these ills is IUCAF's advocacy of an increase in the number of Radio Quiet Zones, specifically those for the next generation of giant instruments, ALMA and SKA.

Robinson, B. J., Ann.Rev.Astron.Astrophys, 1999, 37, 65-96

The ITU structure and the ITU Study Groups

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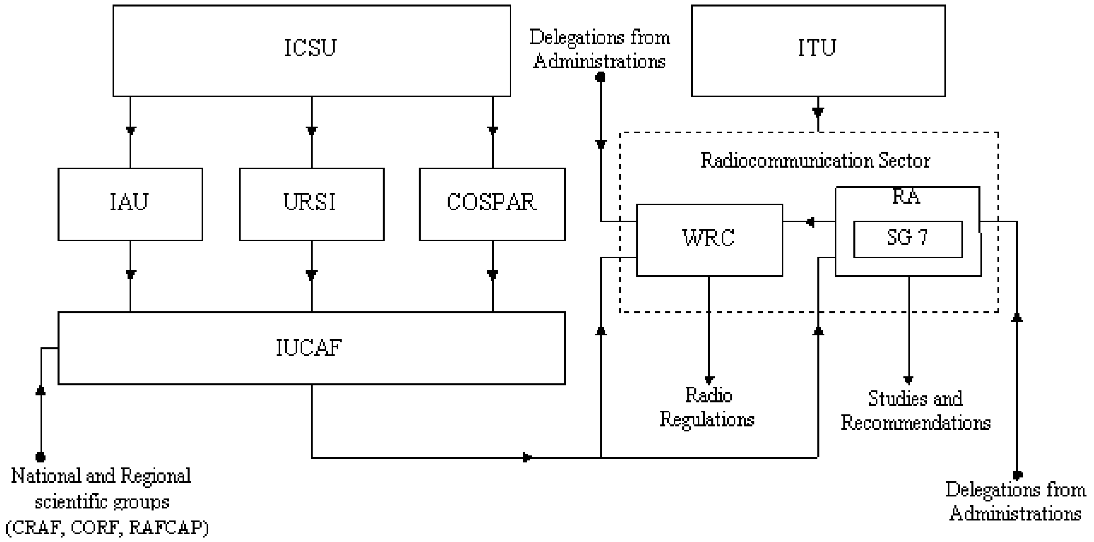
1. The Radiocommunication Sector and World Radiocommunication Conferences of the ITU

This document is concerned principally with aspects of radio astronomy that are relevant to frequency coordination, that is, the usage of the radio spectrum in a manner regulated to avoid interference by mutual agreement between the radio services. On an international scale, the regulation of spectrum usage is organized through the International Telecommunication Union (ITU), whose web page is at http://www.itu.int/). The ITU is a specialized agency of the United Nations Organization.

Fig. 1: Inter-relationships between international agencies involved in frequency coordination for the radio astronomy service.



where (in alphabetical order):

CORF	Committee on Radio Frequencies
COSPAR	Committee on Space Research
CRAF	Committee on Radio Astronomy Frequencies
IAU	International Astronomical Union
ICSU	International Council of Scientific Unions
ITU	International Telecommunication Union
IUCAF	Inter-Union Commission for the Allocation of Frequencies for Radio Astronomy and Space Science
RA	Radiocommunication Assembly
RAFCAP	Radio Astronomy Frequency Committee in the Asia-Pacific region
SG 7	Study Group 7
URSI	International Union of Radio Science
WRC	World Radiocommunication Conference

The Radiocommunication Sector (ITU-R; http://www.itu.int/ITU-R/), which is a part of the ITU, was created on 1 March 1993 to implement the new ITU structure. Other parts of the ITU are the ITU-T (Telecom Standardization Sector) and the ITU-D (Telecom Development Sector). The Radiocommunication Sector includes World and Regional Radiocommunication Conferences, Radiocommunication Assemblies, the Radio Regulations Board, Radiocommunication Study Groups, the Radiocommunication Advisory Group and the Radiocommunication Bureau headed by the elected Director. The Radiocommunication Assembly and the Radiocommunication Bureau replaced the former International Consultative Committee on Radio (CCIR) and its Secretariat, which performed similar functions.

The ITU Radio Regulations, which provide the basis for the planned usage of the spectrum, are the result of World Radiocommunication Conferences (WRCs) that are held at intervals of a few years. At such conferences, the aim is to introduce new requirements for spectrum usage in a form, which is as far as possible, mutually acceptable to the representatives of participating countries. The results of each WRC take the form of a treaty to which the participating administrations are signatories. As in most areas of international law, the enforcement of the regulations is difficult, and depends largely upon the goodwill of the participants.

Radiocommunication Study Groups are set up by a Radiocommunication Assembly. They study questions and prepare draft recommendations on the technical, operational, and regulatory/procedural aspects of radiocommunications. These ITU-R Study Groups address such issues as the preferred frequency bands for the various services, the threshold levels of unacceptable interference, sharing between services, the desired limits on emissions, etc. These groups are further organised into Working Parties and Task Groups, which deal with specific aspects of Study Group work. As of 2002, the ITU-R Study Groups and associated Working Parties are as follows:

Study Group 1	Spectrum management
WP 1A	Spectrum engineering techniques
WP 1B	Spectrum management methodologies
WP 1C	Spectrum monitoring
TG 1/7	**Protection of passive service bands from unwanted emissions**

JTG 1-6-8-9	Multimedia applications (Resolution 737 (WRC-2000))

Study Group 3	Radio wave propagation
WP 3J	Propagation fundamentals
WP 3K	Point-to-area propagation
WP 3L	Ionospheric propagation
WP 3M	Point-to-point and Earth-space propagation
Study Group 4	Fixed-satellite service
WP 4A	Efficient orbit/spectrum utilization
WP 4B	Systems, performance, availability and maintenance of FSS, Satellite news gathering (SNG) and outside broadcast via satellite
JWP 4-9S	Frequency sharing, between the FSS and the FS
JTG 4-7-8	Sharing in the band 13.75 – 14 GHz (Resolution 733 (WRC-2000))
JTG 4-7-8-9	5 GHz band allocations (Resolution 736 (WRC-2000))

Study Group 6	Broadcasting service (terrestrial and satellite)
WP 6A	Programme assembling and formatting
WP 6E	Terrestrial delivery
WP 6M	Interactive and multimedia broadcasting
WP 6P	Content production / postproduction
WP 6Q	Performance assessment and quality control
WP 6R	Recording for production, archival and play-out; film for television
WP 6S	Satellite delivery
TG 6/6	Recommendation for a digital broadcasting standard below 30 MHz
TG 6/7	Planning parameters for digital broadcasting at frequencies below 30 MHz
TG 6/8	Preparation for the Regional Radiocommunication Conference 2004 (RRC-04)
TG 6/9	Digital cinema

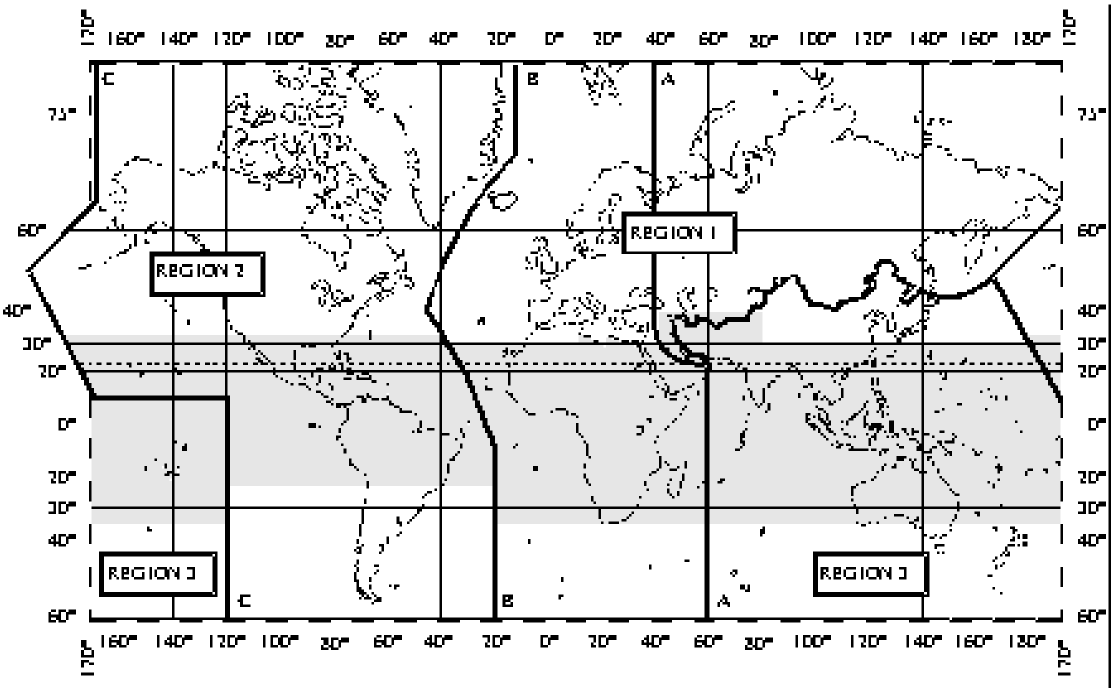
Study Group 7	**Science services**
WP 7A	Time signals and frequency standard emissions
WP 7B	Space radio systems
WP 7C	Earth-exploration satellite systems and meteorological elements
WP 7D	**Radioastronomy**

WP 7E	Inter-service sharing and compatibility
Study Group 8	Mobile, radiodetermination, amateur and related satellite services
WP 8A	Land mobile service excluding IMT-2000
WP 8B	Maritime mobile service including Global Maritime Distress and Safety System (GDMSS); aeronautical mobile service and radiodetermination service
WP 8D	All mobile-satellite services and radiodetermination-satellite service
WP 8F	International Mobile Telecommunications – 2000 and systems beyond IMT-2000
JRG 8A-9B	Wireless access systems
Study Group 9	Fixed service
WP 9A	Performance and availability, interference objectives and analysis, effects of propagation and terminology
WP 9B	Radio-frequency channel arrangements, radio system characteristics, interconnection, maintenance and various applications
WP 9C	Systems below 30 MHz (HF and others)
WP 9D	Sharing with other services (except for the FSS)
JRG 6S-9D	Frequency sharing between the FS and BSS (sound)
SC	Special Committee on Regulatory / Procedural Matters
CCV	Coordination Committee for Vocabulary
CPM	Conference Preparatory Meeting

Radio astronomy (WP 7D) falls within ITU-R Study Group 7, Science Services, which also includes space sciences, time signals and frequency standards. In the work of the Study Group, the search for extraterrestrial intelligence (SETI), radar astronomy as practiced from the surface of the Earth, and space-based radio astronomy are usually included with radio astronomy.

International meetings of the **Study Groups** and **Working Parties** occur at approximately two-year intervals, and are attended by delegations from many countries. The **Task Groups** are usually set up for a limited period of time to carry out specific tasks, and meet at intervals according to their needs.

Appropriate **Questions** are assigned to the Study Groups, which provide responses, generally in the form of **ITU-R Recommendations. The ITU-R Recommendations provide a body of technical, operational, and regulatory/procedural information that has been agreed upon by the participating administrations.** This information is used to provide technical inputs to WRCs, and many of the results of the work of the Study Groups are thereby incorporated into the Radio Regulations. Aside from this, the ITU-R Recommendations and Reports are, in themselves, generally regarded as authoritative guidelines for spectrum users. This is particularly true of the ITU-R Recommendations, which are widely followed, and are revised and published on a four-year cycle by the ITU.



The shaded part represents the Tropical Zones as defined in Nos. 5.16 to 5.20 and 5.21.

5-01

Fig. 2: The Three ITU Regions of the World.

2. The Radio Regulations and frequency allocations

International frequency allocations are carried out at WRCs, which are attended by representatives of more than 180 administrations from all over the world. For the purpose of allocation, the world is divided into three regions (see 5. 2 through 5.22 of the RR): **Region 1** includes Europe, Africa and northern Asia; **Region 2** includes North America and South America; **Region 3** includes southern Asia and Australasia. For any particular frequency band, the allocations may be different in different regions. Bands are often shared between two or more services. Generally speaking, the allocations are primary or secondary. A service with a secondary allocation is not permitted to cause interference to a service with a primary allocation in the same band. **The frequency allocations are contained in Article 5 of the Radio Regulations. Most are shown in a table of allocations; however, additional allocations are contained in numbered footnotes to the table.**

Within individual countries, spectral-allocation matters are handled by government agencies. The agencies vary greatly from one administration to another. In many countries, the administration of the radio spectrum is part of the work of a larger agency, which may also administer other items such as postal and telephone services, transportation, commerce, etc. Such agencies play major roles in the preparation of the national positions that are advocated at WRCs. Administrations participating in the WRC treaties retain sovereign rights over the spectrum within their national boundaries, and can deviate from the international regulations to the extent that this does not cause harmful interference within the territories of other administrations. In the setting up of the Radio Regulations, many administrations have claimed exceptions in certain bands in order to cover particular national requirements.

3. Frequency allocations and related issued with radio astronomy

In Article 1, Section 1 of the Radio Regulations, **radio astronomy is defined as astronomy based on the reception of radio waves of cosmic origin.** In the table of frequency allocations, frequency bands which offer the greatest protection to radio astronomy are those for which the radio astronomy service has a **primary allocation** that is shared only with other passive (non-transmitting) services. Next in degree of protection are the bands for which radio astronomy has a primary allocation while it shares this status with one or more active (transmitting) services. Less protection is afforded where bands are allocated to radio astronomy on a **secondary basis.**

The following footnotes are related to primary and secondary allocations:

5.23 *Primary and secondary services*
5.24 1) Where, in a box of the Table in Section IV of this Article, a band is indicated as allocated to more than one service, either on a worldwide or Regional basis, such services are listed in the following order:
5.25 *a)* services the names of which are printed in "capitals" (example: FIXED); these are called "primary" services;
5.26 *b)* services the names of which are printed in "normal characters" (example: Mobile); these are called "secondary" services (see Nos **5.28** to **5.31**).
5.27 2) Additional remarks shall be printed in normal characters (example: MOBILE except aeronautical mobile).
5.28 3) Stations of a secondary service:
5.29 *a)* shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date;
5.30 *b)* cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date;
5.31 *c)* can claim protection, however, from harmful interference from stations of the same or other secondary service(s) to which frequencies may be assigned at a later date.
5.32 4) Where a band is indicated in a footnote of the Table as allocated to a service "on a secondary basis" in an area smaller than a Region, or in a particular country, this is a secondary service (see Nos **5.28** to **5.31**).

5.33 5) Where a band is indicated in a footnote of the Table as allocated to a service "on a primary basis", in an area smaller than a Region, or in a particular country, this is a primary service only in that area or country.

For many frequency bands, the protection is by footnote rather than by direct table listing. The footnotes are of several types. For an exclusive band allocated only to passive services, the footnote points out that all emissions are prohibited in the band (see **5.340**). Other footnotes are used when radio astronomy has an allocation in only part of the band appearing in the table (see for example, **5.149**). A different form of footnote is used for bands or parts of bands which are not allocated to radio astronomy, but which are nevertheless used for astrophysically important observations. It urges administrations to take all practicable steps to protect radio astronomy, when making frequency assignments to other services. Although such footnotes provide no legal protection, they have often proven valuable to radio astronomy, when coordination with other services is required.

5.149 In making assignments to stations of other services to which the bands:

13 360-13 410 kHz,
25 550-25 670 kHz,
37.5-38.25 MHz,
73-74.6 MHz in Regions 1 & 3
150.05-153 MHz in Region 1
322-328.6 MHz,
406.1-410 MHz,
608-614 MHz in Regions 1 & 3
1 330-1 400 MHz,
1 610.6-1 613.8 MHz,
1 660-1 670 MHz,
1 718.8-1 722.2 MHz,
2 655-2 690 MHz,
3 260-3 267 MHz,
3 332-3 339 MHz,
3 345.8-3 352.5 MHz,
4 825-4 835 MHz,
4 950-4 990 MHz,
4 990-5 000 MHz,
6 650-6 675.2 MHz,
10.6-10.68 GHz,
14.47-14.5 GHz,
22.01-22.21 GHz,
22.21-22.5 GHz,
22.81-22.86 GHz,
23.07-23.12 GHz,
31.2-31.3 GHz,
31.5-31.8 GHz in Regions 1 & 3
36.43-36.5 GHz,
42.5-43.5 GHz,
42.77-42.87 GHz,
43.07-43.17 GHz,
43.37-43.47 GHz,
48.94-49.04 GHz,
76-86 GHz,
92-94 GHz,
94.1-100 GHz,
102-109.5 GHz,
111.8-114.25 GHz,
128.33-128.59 GHz,
129.23-129.49 GHz,
130-134 GHz,
136-148.5 GHz,
151.5-158.5 GHz,
168.59-168.93 GHz,
171.11-171.45 GHz,
172.31-172.65 GHz,
173.52-173.85 GHz,
195.75-196.15 GHz,
209-226 GHz,
241-250 GHz,
252-275 GHz

are allocated, administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference. Emissions from spaceborne or airborne stations can be particularly serious sources of interference to the radio astronomy service (see Nos **4.5** and **4.6** and Article **29**) (WRC-2000).

5.208A In making assignments to space stations in the mobile-satellite service in the bands 137-138 MHz, 387-390 MHz and 400.15-401 MHz, administrations shall take all practicable steps to protect the radio astronomy service in the bands 150.05-153 MHz, 322-328.6 MHz, 406.1-410 MHz and 608-614 MHz from harmful interference from unwanted emissions. The threshold levels of interference detrimental to the radio astronomy service are shown in Table 1 of Recommendation ITU-R RA.769-1 (WRC-97).

5.225 *Additional allocation:* in Australia and India, the band 150.05-153 MHz is also allocated to the radio astronomy service on a primary basis.

5.250 *Additional allocation*: in China, the band 225-235 MHz is also allocated to the radio astronomy service on a secondary basis.

5.304 *Additional allocation:* in the African Broadcasting Area (see Nos **5.10** to **5.13**), the band 606-614 MHz is also allocated to the radio astronomy service on a primary basis.

5.305 *Additional allocation:* in China, the band 606-614 MHz is also allocated to the radio astronomy service on a primary basis.

5.306 *Additional allocation:* in Region 1, except in the African Broadcasting Area (see Nos **5.10** to **5.13**), and in Region 3, the band 608-614 MHz is also allocated to the radio astronomy service on a secondary basis.

5.307 *Additional allocation:* in India, the band 608-614 MHz is also allocated to the radio astronomy service on a primary basis.

5.340 All emissions are prohibited in the following bands:

1 400-1 427 MHz,	
2 690-2 700 MHz,	except those provided for by Nos **5.421** and **5.422**,
10.68-10.7 GHz,	except those provided for by No **5.483**,
15.35-15.4 GHz,	except those provided for by No **5.511**,
23.6-24 GHz,	
31.3-31.5 GHz,	
31.5-31.8 GHz,	in Region 2,
48.94-49.04 GHz,	from airborne stations,
50.2-50.4 GHz[2],	except those provided for by No **5.555A**,
52.6-54.25 GHz,	
86-92 GHz,	
100-102 GHz,	
109.5-111.8 GHz,	
114.25-116 GHz,	
148.5-151.5 GHz,	
164-167 GHz,	
182-185 GHz,	except those provided for by No **5.563**,
190-191.8 GHz,	
200-209 GHz,	
226-231.5 GHz,	
250-252 GHz.	

5.341 In the bands 1 400-1 727 MHz, 101-120 GHz and 197-220 GHz, passive research is being conducted by some countries in a programme for the search for intentional emissions of extraterrestrial origin.

5.372 Harmful interference shall not be caused to stations of the radio astronomy service using the band 1 610.6-1 613.8 MHz by stations of the radiodetermination-satellite and mobile-satellite services (No **29.13** applies).

5.376A Mobile earth stations operating in the band 1 660-1 660.5 MHz shall not cause harmful interference to stations in the radio astronomy service (WRC-97).

5.379A Administrations are urged to give all practicable protection in the band 1 660.5-1 668.4 MHz for future research in radio astronomy, particularly by eliminating air-to-ground transmissions in the meteorological aids service in the band 1 664.4-1 668.4 MHz as soon as practicable.

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[2] **5.340.1** The allocation to the Earth exploration-satellite service (passive) and the space research service (passive) in the band 50.2-50.4 GHz should not impose undue constraints on the use of the adjacent bands by the primary allocated services in those bands (WRC-97).

5.385 *Additional allocation:* the band 1 718.8-1 722.2 MHz is also allocated to the radio astronomy service on a secondary basis for spectral-line observations (WRC-2000).

5.402 The use of the band 2 483.5-2 500 MHz by the mobile-satellite and the radiodetermination-satellite services is subject to the coordination under No **9.11A.** Administrations are urged to take all practicable steps to prevent harmful interference to the radio astronomy service from emissions in the 2 483.5-2 500 MHz band, especially those caused by second-harmonic radiation that would fall into the 4 990-5 000 MHz band allocated to the radio astronomy service worldwide.

5.413 In the design of systems in the broadcasting-satellite service in the bands between 2 500 MHz and 2 690 MHz, administrations are urged to take all necessary steps to protect the radio astronomy service in the band 2 690-2 700 MHz.

5.443 *Different category of service:* in Argentina, Australia and Canada, the allocation of the bands 4 825-4 835 MHz and 4 950-4 990 MHz to the radio astronomy service is on a primary basis (see No **5.33**).

5.443B *Additional allocation:* The band 5 010-5 030 MHz is also allocated to the radionavigation-satellite service (space-to-Earth) (space-to-space) on a primary basis. In order not to cause harmful interference to the microwave landing system operating above 5 030 MHz, the aggregate power flux-density produced at the Earth’s surface in the band 5 030-5 150 MHz by all the space stations within any radionavigation-satellite service system (space-to-Earth) operating in the band 5 010-5 030 MHz shall not exceed –124.5 dB (W/m^2) in a 150 kHz band. In order not to cause harmful interference to the radio astronomy service in the band 4 990-5 000 MHz, the aggregate power flux-density produced in the 4 990-5 000 MHz band by all the space stations within any radionavigation-satellite service (space-to-Earth) system operating in the 5 010-5 030 MHz band shall not exceed the provisional value of –171 dB (W/m^2) in a 10 MHz band at any radio astronomy observatory site for more than 2% of the time. For the use of this band, Resolution **604** (WRC-2000) applies (WRC-2000).

5.458A In making assignments in the band 6 700-7 075 MHz to space stations of the fixed-satellite service, administrations are urged to take all practicable steps to protect spectral-line observations of the radio astronomy service in the band 6 650-6 675.2 MHz from harmful interference from unwanted emissions.

5.511A The band 15.43-15.63 GHz is also allocated to the fixed-satellite service (space-to-Earth) on a primary basis. Use of the band 15.43-15.63 GHz by the fixed-satellite service (space-to-Earth and Earth-to-space) is limited to feeder links of non-geostationary systems in the mobile-satellite service, subject to coordination under No **9.11A.** The use of the frequency band 15.43-15.63 GHz by the fixed-satellite service (space-to-Earth) is limited to feeder links of non-geostationary systems in the mobile-satellite service for which advance publication information has been received by the Bureau prior to 2 June 2000. In the space-to-Earth direction, the minimum Earth station elevation angle above and gain towards the local horizontal plane and the minimum coordination distances to protect an Earth station from harmful interference shall be in accordance with Recommendation ITU-R S.1341. In order to protect the radio astronomy service in the band 15.35-15.4 GHz, the aggregate power flux-density radiated in the 15.35-15.4 GHz band by all the space stations within any feeder-link of a non-geostationary system in the mobile-satellite service (space-to-Earth) operating in the 15.43-15.63 GHz band shall not exceed the level of –156 dB(W/m^2) in a 50 MHz bandwidth, into any radio astronomy observatory site for more than 2% of the time (WRC-2000).

5.551G In order to protect the radio astronomy service in the band 42.5-43.5 GHz, the aggregate power flux-density in the 42.5-43.5 GHz band produced by all the space stations in any non-geostationary-satellite system in the fixed-satellite service (space-to-Earth) or in the broadcasting-satellite service (space-to-Earth) system operating in the 41.5-42.5 GHz band shall not exceed –167 dB (W/m^2) in any 1 MHz band at the site of a radio astronomy station for more that 2% of the time. The power flux-density in the band 42.5-43.5 GHz produced by any geostationary station in the fixed-satellite service (space-to-Earth) or in the broadcasting-satellite service (space-to-Earth) operating in the band 42-42.5 GHz shall not exceed –167 dB (W/m^2) in any 1 MHz band at the site of a radio astronomy station. These limits are provisional and will be reviewed in accordance with Resolution **128** (Rev.WRC-2000) (WRC-2000).

5.555 *Additional allocation:* the band 48.94-49.04 GHz is also allocated to the radio astronomy service on a primary basis (WRC-2000).

5.556 In the bands 51.4-54.25 GHz, 58.2-59 GHz and 64-65 GHz, radio astronomy observations may be carried out under national arrangements (WRC-2000).

5.562A In the bands 94-94.1 GHz and 130-134 GHz, transmissions from space stations of the Earth exploration-satellite service (active) that are directed into the main beam of a radio astronomy antenna have the potential to damage some radio astronomy receivers. Space agencies operating the transmitters and the radio astronomy stations concerned should mutually plan their operations so as to avoid such occurrences to the maximum extent possible (WRC-2000).

5.562B In the bands 105-109.5 GHz, 111.8-114.25 GHz, 155.5-158.5 GHz and 217-226 GHz, the use of this allocation is limited to space-based radio astronomy only (WRC-2000).

5.562D *Additional allocation*: In Korea (Rep. of), the bands 128-130 GHz, 171-171.6 GHz, 172.2-172.8 GHz and 173.3-174 GHz are also allocated to the radio astronomy service on a primary basis until 2015 (WRC-2000).

5.565 The frequency band 275-1 000 GHz may be used by administrations for experimentation with, and development of, various active and passive services. In this band a need has been identified for the following spectral-line measurements for passive services:

- radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, 426-442 GHz, 453-510 GHz, 623-711 GHz, 795-909 GHz and 926-945 GHz;
- Earth exploration-satellite service (passive) and space research service (passive): 275-277 GHz, 294-306 GHz, 316-334 GHz, 342-349 GHz, 363-365 GHz, 371-389 GHz, 416-434 GHz, 442-444 GHz, 496-506 GHz, 546-568 GHz, 624-629 GHz, 634-654 GHz, 659-661 GHz, 684-692 GHz, 730-732 GHz, 851-853 GHz and 951-956 GHz.

Future research in this largely unexplored spectral region may yield additional spectral lines and continuum bands of interest to the passive services. Administrations are urged to take all practicable steps to protect these passive services from harmful interference until the date when the allocation Table is established in the above-mentioned frequency band (WRC-2000).

World Radiocommunication Conferences

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1. Introduction

World Radiocommunication Conferences (WRCs), called World Administrative Radio Conferences (WARCs) until 1993, are important to most countries. They are convened regularly by the International Telecommunication Union (ITU), a specialized agency of the United Nations, to update the regulations governing the use of the radio spectrum according to changes in technology and to allow the introduction of new services. They accomplish this by reallocating spectrum to the various radio services, and by updating other articles of the regulations.

WRCs are large events. The last one, WRC-00, was attended by more than 2000 delegates, over 80 companies and some 300 observers, from more than 150 countries. An excellent account of a WRC as experienced by an astronomer can be found at:

http://dsnra.jpl.nasa.gov/freq_man/wrc97.html

2. A brief history of radio astronomy participation in World Radio Conferences

The history of WRCs is closely related to that of the International Telecommunication Union (ITU). The origins of the ITU go back to 1865, when 20 founding member states established the *International Telegraph Union (ITU),* by signing the First International Telegraph Convention. The First International Radiotelegraph Conference, held in Berlin in 1906, established the first International Radiotelegraph Convention. The Annex to this Convention contained the first regulations governing wireless telegraphy. Expanded and revised by numerous radio conferences since, they are known today as the *Radio Regulations (RR).* The 1927 Radiotelegraph Conference, held in Washington, D.C., established the International Radio Consultative Committee (CCIR) to assist with recommendations for technical standards for the various radio services. Finally, the 1932 Madrid Conference, combined the *International Telegraph Convention* of 1865 and the *International Radiotelegraph Convention* of 1906, to form the *International Telecommunication Convention, and* changed the name of the Union to *International Telecommunication Union*, by which it is still known today.

The history of the modern ITU begun with the Atlantic City Conference, held in 1947, convened with the aim of developing and modernizing the organization. At this meeting the ITU became a UN specialized agency and the International Frequency Registration Board (IFRB) was established. These institutions were tasked with coordinating the increasingly complicated task of managing the radio-frequency spectrum and the Table of Frequency Allocations that was introduced in 1912 in the wake of the *Titanic* disaster. An Extraordinary Administrative Conference for space communications was held in Geneva in 1963 to allocate frequencies to the various space services for the first time. General WARCs or G-WARC that allowed reallocation of the spectrum across the board were held in 1959 and 1979 in Geneva. In addition, limited conferences that dealt with requirements of specific services were held between these G-WARCs (e.g. the 1983 and 1987 Mobile-WARCs that dealt with requirements of the mobile services). Until 1993, WARCs were held on an "as needed" basis. Since 1993 to date they have been held regularly, at 2-3 year intervals, with a variety of unrelated topics on their Agenda.

The need for exclusive bands allocated to radio astronomy was discussed first at the 1950 Zurich URSI General Assembly. Radio astronomy was recognized as a "radio service" at the 1959 G-WARC, when the 1400-1427 MHz band was allocated to radio astronomy for observations of the recently discovered HI line. Charles Seeger represented the radio astronomy community at this meeting, which lasted for four months! The international radio astronomy community recognized that to sustain and enlarge the gains of the 1959 WARC, it would have to get organized, and the Inter-Union Committee for the Allocation of Frequencies (IUCAF) was formed shortly after WARC-59, to prepare the radio astronomy positions for the 1963 Space WARC. IUCAF surfaced for the first time at the 1963 Space WARC, and managed to obtain secondary allocations for the 1.6 GHz OH lines that were discovered while the Conference was meeting. The next WARC, at which allocations up to 275 GHz were made to the various services for the first time was held in 1971, in Geneva. Radio astronomers managed to get table allocations for the 1665 and 1667 MHz OH lines, for ammonia at 23.7 GHz and for HCN at 86.3 and 88.6 GHz at this meeting. They also obtained footnote allocations for observations of another 7 spectral lines, and the conference adopted a Recommendation on the Shielded Area of the Moon that reserved it for radio astronomy purposes.

By the 1979 G-WARC the radio astronomy community realized that it had a large stake in World Administrative Radio Conferences, and 14 radio astronomers spent some or all of the 6 week long conference in Geneva. This massive participation had good results:16 bands were allocated to radio astronomy in the table, the highest one at 116 GHz. Another 18 radio astronomy allocations by footnote were added above 140 GHz. The conference also approved Recommendation 66, that gave expression to the preoccupation of astronomers about unwanted emissions, particularly from space-borne platforms, that still survives, albeit in a heavily modified form. After the G-WARC, the participation of astronomers in the WARCs diminished temporarily. Only 1 astronomy representative attended the 1987 Mobile WARC and the 1988 Orbital WARC. Complacency couldn't last long, however. The 1992 WARC, held in Spain at Malaga-Torremolinos, had a very full agenda, and considered allocations to satellite services that were close to or overlapped bands of interest to radio astronomers. The 1452-1492 MHz band was allocated to satellite broadcasting and the 1613.8- 1626.5 MHz band was allocated to the mobile satellite service on a secondary basis at this WARC. While the 1610.6-1613.8 MHz radio astronomy allocation was upgraded simultaneously to primary status, and a footnote was adopted to protect the radio astronomy service from harmful interference, the IRIDIUM satellite system that utilizes this allocation for its downlink, became the most difficult problem for radio astronomers for many years.

WRC-95 and WRC-97 were attended by 9 and 14 members of the radio astronomy community, respectively. Central to the agendas of these WRCs was the increasing demand for satellite spectrum, and because of this, they posed large challenges for radio astronomers. For example, WRC-97 allocated the 40.5-42.5 GHz band to the Fixed Satellite Service, adjacent to the 42.5-43.5 GHz primary radio astronomy band. To defend radio astronomy bands from spillover emissions, astronomers demanded protection of the bands through specific pfd limits that would protect their observations. The first footnote limiting unwanted emissions spilling over into a radio astronomy band was adopted at WRC-97. Astronomers also succeeded in attaching resolutions to the more controversial satellite allocations, requiring that the impact on radio astronomy and possible mitigation methods be studied. The most recent WRC (WRC-00), attended by 17 astronomers, approved the rearrangement of the 71-275 GHz spectrum range for the benefit of astronomers and other passive scientists.

3. The ITU framework

Why should radio astronomers pay attention to the ITU and to WRCs? The International Telecommunication Union (ITU), an independent organization of the United Nations, regulates uses of the radio spectrum internationally, through the Radio Regulations (RR). The RR, that deals with all aspects of radiocommunications and cover the use of the radio frequency spectrum by all radiocommunication services, constitute an international treaty. The international Table of Allocations is one part (Article 5) of the RR. As defined by the ITU, radiocommunication involves the use of the spectrum up to 3 000 GHz. At present allocations cover only up to 275 GHz, but this limit is likely to increase in the near future. Countries are sovereign with regard to the use of the radio spectrum within their own borders and are under no obligation to adopt or follow the international table.

WRCs may have a large impact on radio astronomy in a variety of ways:

- Directly, through the allocation process by:
  - Mandating In-Band Sharing
  - Adopting Adjacent Band Allocations (Satellite Downlinks)
  - Adding Footnotes to the Table of Allocations
- Establishing (or not establishing) Standards (e.g. Spurious Emissions, Frequency Tolerances, etc.)

The impact may also be indirect, for example:

- Through studies that may affect the status of radio astronomy in various bands or regions of the spectrum,
- Imposition of other regulations (e.g. coordination zones around radio observatories, earth stations, etc.),
- Placing issues of interest to radio astronomy (or related issues) on the agenda of future WRCs

4. How do WRCs work?

The scope of a WRC is limited by its agenda. Each WRC develops and formally adopts a draft agenda for the next conference, and a provisional agenda for the one after. Both draft Agendas are contained in WRC Resolutions that must be formally approved by the ITU Council, which meets annually and that can, and often does revise the agenda. For example, it has on occasions dropped agenda items, to reduce the conference workload and attendant costs, or added items considered urgent by the members. Since 1993, WRC agendas have, as a rule, contained numerous unrelated issues, that are considered urgent by the members, sometimes leading to quite a fight about what issues should be on the Agenda of a forthcoming Conference.

The preparatory process for a WRC starts immediately upon the conclusion of the previous one, based upon the provisional agenda just established and usually also under pressure from unresolved issues. Preparatory efforts are channeled towards the Conference Preparatory Meeting (CPM) that is charged with preparing a report containing the "technical" basis for the various agenda items. The first CPM meeting, held immediately after the WRC, determines the contents and organization of the Report, based on the agenda just established. The studies mandated in WRC resolutions are carried out (or not!) in the various study groups in the year(s) between WRCs.

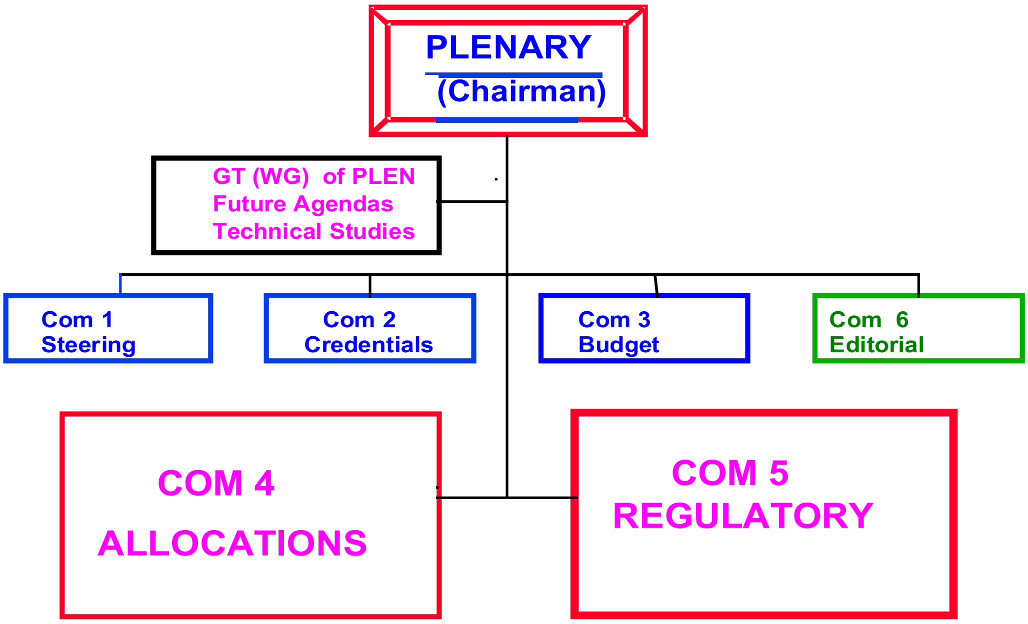
Member administrations in good standing are entitled to submit proposals to the WRC, usually up to a certain deadline a few months before the beginning of the Conference, to allow time to translate them into the languages required by the ITU Convention (English, French, and Spanish) and distribute them to member administrations. Notwithstanding enormous pressures to submit proposals in a timely fashion, they are often received up to the beginning of the Conference and even later.

As noted already, a few thousand delegates may attend a WRC and it is clearly impractical to discuss or debate any issue in such a large group. As a rule, a Conference structure is agreed upon among the major participants, to carry forward the work. The usual committee structure is shown in Fig. 1.

Committees 1 through 3 deal with formal matters, such as scheduling the daily work of the Conference, accreditation of the delegations and the budget. The main task of the committee is to make sure that the meaning of the English, French and Spanish text is identical. The substantive work is done in the two main committees, dealing with allocations and regulatory issues. These committees are further split in various sub-committees, dealing with the various agenda items. The breakdown of the allocation committee during WRC-00 is shown in Figure 2, which also indicates the issues of interest to radio astronomers by order of importance ranging from essential to marginal or mild interest.

After being introduced, proposals are assigned to the various subcommittees and agreement on details is then worked out in sub-subcommittees or drafting groups. The process of breaking a proposal down into its various elements continues until a manageable size, in terms of issues and of delegations willing to dedicate resources to it, is reached. The fact that subgroups are often nested 5-6 levels deep, and that many discussions take place in parallel, explains the necessity for large delegations as well as a large astronomy participation. As a rule issues are resolved by consensus, which often requires many meetings to work out even a minimal agreement, which is sometimes characterized as the "state of equal unhappiness of all parties". Once agreement is reached, the consensus is elevated to the parent group for further discussion (hopefully minimal) and approval. The process of elevating approved documents to higher and higher-level groups continues until a given proposal/issue reaches the Plenary for final approval. When consensus cannot be reached, the issue is returned to the parent group, where further attempts may be made for resolution at a higher level. Votes, while certainly a possibility, are usually avoided. They tend to polarize a Conference, making progress on all issues more difficult. They are taken only as a last recourse, in cases where attempts to reach a consensus solution failed, and the issue cannot be deferred. Otherwise, the Conference may settle for a partial solution or the issue may be passed on to the next Conference, possibly along with a Resolution (or Resolutions) requiring further studies within the ITU-R.

Fig. 1 Typical WRC Committee Structure



Much depends on a Chairperson's ability to conduct meetings, and nudge or if necessary, force the group towards some common ground.

A good example of an issue of great interest to radio astronomy where consensus was reached relatively early and easily was the realignment of allocations in the 71-250 GHz spectral range, adopted by WRC-00. There were good reasons for a successful outcome:

- Astronomers coordinated the proposals very closely and carefully worldwide, during the process leading up to the WRC. This resulted in nearly identical proposals by the three large regional groups within the ITU (CITEL, CEPT and APT) and minimized potential opposition.

- The astronomy proposals were also carefully coordinated with the remote sensing community, the other major interest group involved, as well the Amateur community, that was also very interested in the process.

- Very few systems above 71 GHz are operational, so no costly equipment needed to be relocated in spectrum

- There were as yet few active commercial requirements in this spectral region, even though that situation is rapidly changing!

- Flexibility was shown by the astronomy community in developing the proposals, including willingness to give up access to some spectral lines in return for others.

An issue involving radio astronomy, where consensus could not be reached is that of protection of radio astronomy allocations at 42.5-43.5 GHz (7-mm continuum) and the 42.821 GHz, 43.122 GHz and 43.423 GHz SiO lines (listed in RR 5.149 and in Rec. ITU-R RA.314) and the 42.159 GHz SiO line (not listed in either of the above). The band and the spectral lines it contains need to be protected from unwanted emissions of

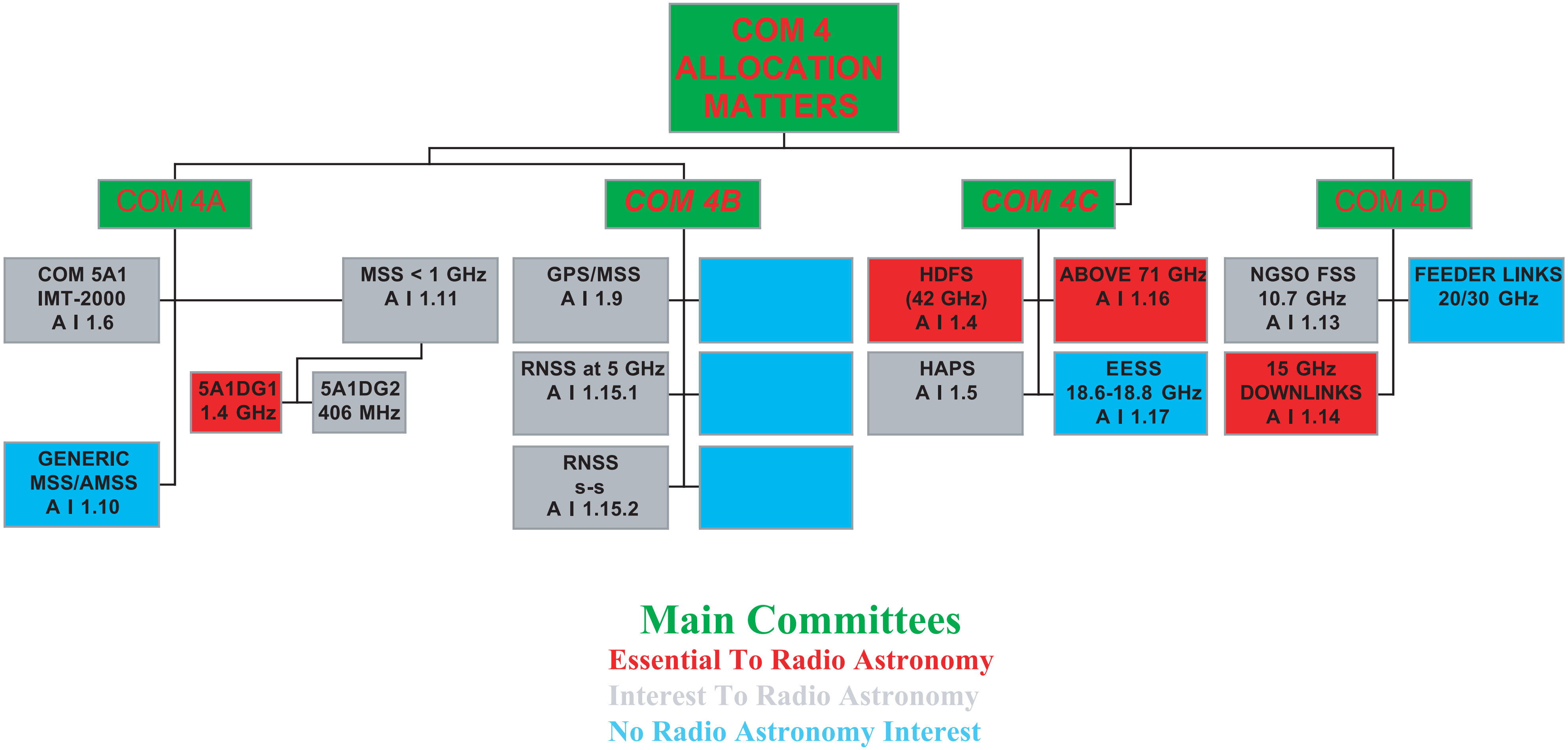


Fig. 2 : Breakdown of an Allocation Committee.

potential satellite downlinks that intend to operate in the adjacent lower band. This issue illustrates the difficulties encountered when satellite downlinks and radio astronomy are allocated in close proximity. It has been the subject of various Resolutions and studies since WRC-97, that first allocated the 40.5-42.5 GHz band to the Fixed Satellite Service, was on the agenda of WRC-00 and is once again on the Agenda of the upcoming WRC-03.

The achievements of a WRC are contained in its "Final Acts", a document that updates the Radio Regulations. Administrations may and frequently do except themselves from complying with some of the provisions of the Final Acts, reserving their position on those that they find objectionable. The Final Acts are eventually be ratified by Administrations (in the U.S they are subject to approval by the Senate, a process that may take a long time).

5. References

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Robinson, B. J. "Frequency Allocation: The First Forty Years", Ann. Rev. Astron. Astrophys., 1999, 37-65

Kuiper, T. B. H.,"WRC-97, Geneva, Nov. 2-7", at:
http://dsnra.jpl.nasa.gov/freq_man/wrc97.html

The website of the ITU:
http://www.itu.int/

is a particularly useful source of reference for WRC related issues.

ITU-R Recommendations of Particular Importance to Radio Astronomy

A. Richard Thompson

NRAO

The ITU-R recommendations can be broadly described as a series of documents that specify the requirements of the various radio services with regard to the frequencies and other parameters of transmission, propagation, reception, etc., and also include studies pertaining to coordination with other services. The documents are written in a formal manner, and each one must be approved by all ITU-R study groups before it is adopted. Thus the recommendations provide a record of agreements that have been reached, upon which decisions of the ITU-R can be based. The formal nature of the recommendations, and the requirement that they be approved by all study groups of the ITU-R, help to maintain a basis for continuing progress in situations where opinions can differ widely. While the term "recommendation" indicates that the conclusions reached are not strictly mandatory, within the ITU-R the recommendations carry heavy weight and results from many of them become incorporated into the radio regulations.

Recommendations are assigned numbers, and the full reference to a recommendation is, for example: Recommendation ITU-R RA.769-1. Here, for brevity, we shall just use RA.769. RA indicates that this is a document in the radio astronomy series, 769 indicates the particular recommendation, and 1 indicates the number of revisions. In referring to a recommendation the revision number is often omitted, in which case the reference is intended to apply to the latest revision. The form of each recommendation is a series of statements under the heading *considering*, followed by statements under the heading *recommends*. These statements generally do not include detailed considerations or mathematical equations, and such supporting material, when necessary, is given in one or more annexes. The recommendations are intended to be complete in themselves, and do not contain references to other documents or papers unless these are on file with the ITU-R. Below the title of each recommendation a question number appears. This refers to a question document stating the problem to be addressed, which must be approved at the start of any study leading to a recommendation. Periodic review of the questions ensures that studies are completed in a timely manner.

At the present time there are ten recommendations in the radio astronomy series. In what follows, these are presented in an order in which it is convenient to review them. The notes given on each one are necessarily brief and intended to cover the main points only. References to the Handbook refer to the ITU-R Handbook on Radio Astronomy, 1995 edition. Six other recommendations that are important in considerations relating to the protection of radio astronomy are also briefly discussed.

RA.314-8 Protection for frequencies used for radioastronomical measurements

This recommendation specifies the spectrum requirements for radio astronomy. Most services have a recommendation of this type, outlining the preferred frequency bands for their particular operation. The *considerings* of RA.314-8 include: the existence of lists of important spectral lines approved by the IAU (International Astronomical Union); the need to take account of Doppler shifts in the line frequencies; the need for bands for continuum observations which should be spaced with frequency ratios of approximately 2:1; the range of frequencies used in radio astronomy (given as 2 MHz to 800 GHz); and the use of lunar occultations and VLBI as high resolution techniques. The *recommends* include: attention to protection of the frequency bands for observations of spectral lines in Tables 1 and 2 and the continuum bands in Table 3. These tables, which are included in the recommendation, can also be found in the Handbook as Table 2 (p. 13), Table 3 (p. 14), and Table 1 (p. 11), respectively. Table 1 is a list of lines below 275 GHz and the suggested minimum bandwidths which are based on Doppler shifts of up to ±300 km/s for lines from sources within the Galaxy, and up to 1000 km/s for lines strong enough to be observed in external galaxies. Table 2 is a list of important lines in the range 275-900 GHz, that is, above the limit for which allocations of the spectrum have been made. Table 3 lists the bands in which continuum observations are usually made. RA.314-8 was the first radio astronomy recommendation to be approved, and for many years it was revised after each 3-yearly meeting of the IAU to update the lists of most important lines.

The next two recommendations, RA.769 and RA.1513, are of particular importance because they include discussions of basic criteria that are used in determining the levels of protection required for radio astronomy.

RA.769-1 Protection criteria for radioastronomical measurements

This recommendation contains estimates of the threshold levels of power flux density and spectral power flux density at which interference becomes detrimental to radio astronomy. The *considerations* include: that the sensitivity of radio astronomical receiving equipment greatly exceeds that of communication and radar systems; that at frequencies below 40 MHz long distance propagation of interference (by ionospheric reflection) occurs; that choice of observatory site or local protection (shielding) does not help protect against satellite transmissions; and that long observing times are sometimes needed. The *recommends* include choice of sites as free as possible from interference; reduction of unwanted emissions falling within radio astronomy bands, particularly from spacecraft, aircraft, and balloons; and avoidance of allocations which result in interfering transmitters within line of sight of an observatory.

Calculations of threshold levels and tables listing the results are given in the annex to the recommendation. Because of the importance of these results the analysis is reviewed in some detail below. To make the calculations it is necessary to define a criterion for the interference threshold and a value for the collecting area of the sidelobes through which the interference is received.

Criterion for the threshold of detrimental interference. Calculations of interference thresholds date back to an early CCIR Report (No. 224-1) which appeared in 1967. The criterion established at that time, and used continuously since then, is that the threshold of detrimental interference is the level that produces a voltage at the receiver output equal to 1/10 of the rms noise. This is usually considered with respect to measurements of the total power received in a single antenna. The detrimental threshold can be more generally stated as the level at which the rms error of the measurements is increased by 10%. One can visualize this effect as increasing by 10% the length of the error bars on measurements of the strength of a radio source, which might be plotted as a function of some other astronomical parameter. Note also that in the absence of interference a 10% increase in rms uncertainty is equivalent to a loss of 20% in observing time. Under these conditions useful measurements are still possible, but the data are noticeably degraded.

Effective area for interference reception. Since the main beam of a radio astronomy antenna usually subtends a solid angle of order 10^{-3} ster or less, the probability of interference being received in the main beam is small enough that we consider interference entering only through the sidelobes. In the calculations of interference thresholds in the early CCIR report, a collecting area corresponding to a sidelobe gain of 0 dBi was chosen for the interference reception. A model of antenna sidelobes in recommendation SA.509 (Space applications and meteorology series) has sidelobe gain (in decibels relative to an isotropic radiator) equal to $32 - 25 \log \phi$ dBi where ϕ is the angle measured from the main beam axis, for $1° < \phi < 47.8°$. For $\phi > 47.8°$, the gain is -10 dBi. With this model the 0 dBi level occurs at $\phi = 19.1°$. Note that if we compute the threshold level of pfd or spfd based on reception with sidelobe gain of 0 dBi, then the threshold of interference in the radio astronomy receiver will be exceeded if the interference is received through sidelobes with gain greater than 0 dBi, that is, for values of ϕ less than 19.1°. Thus if a threshold-level signal is incident in a direction that lies within a cone of half-angle equal to 19.1° centered on the axis of the main beam, the power received will exceed the detrimental interference criterion. If we call the solid angle of this cone Ω, then a rough measure of the probability of receiving interference within the 19.1° cone is Ω divided by the 2π steradians above the horizon from which interfering signals may be received. For $\phi = 19.1°$, $\Omega/2\pi = 5.5\%$. For more recent antenna designs a sidelobe model of 29-25 log ϕ has been proposed (see, e.g. S.580, Fixed satellite series). With this model the zero-dBi value of ϕ is 14.5°, and the corresponding value of $\Omega/2\pi$ is 3.2%. Yet another recent sidelobe model (see, S.1428-1, Fixed satellite series) uses 34-30 log ϕ, for which the zero-dBi angle is 13.6° and the corresponding value of $\Omega/2\pi$ is 2.8%. An upper limit on the percentage of time that interference above the detrimental threshold can be tolerated is specified as 5% in the aggregate in RA.1513 (discussed below). The three values of $\Omega/2\pi$ discussed above are in reasonable accord with this figure, and thus lend support to the choice of the 0 dBi sidelobe level as appropriate for the calculation of the power flux density corresponding to the detrimental threshold. The collecting area of an antenna in a direction for which the gain is 0 dBi is $\lambda^2/4\pi$, where λ is the wavelength, or $c^2/4\pi f^2$, where f is the frequency.

Detrimental thresholds. For an interfering signal with spfd S_H, the interference-to-noise (voltage) ratio at the output of the receiver is

$$\frac{interference}{rms\ \ noise} = \left[\frac{S_H\left(c^2/4\pi f^2\right)\Delta f}{k\left(T_A+T_R\right)\,\Delta f}\right]\sqrt{\Delta f\ t} \qquad (1),$$

where Δf is the receiver bandwidth, k is Boltzmann's constant (1.38×10^{-23} JK^{-1}), T_A is the antenna noise temperature, T_R is the receiver noise temperature, and t is the averaging time at the receiver output. Within the square brackets in Eq. (1) the numerator is equal to the power received from an interfering signal of spfd S_H through a collecting area of $c^2/4\pi f^2$, in bandwidth Δf. The denominator is equal to the equivalent noise power at the receiver input, which is k times the sum of contributions from the antenna and the receiver expressed as temperatures and multiplied by the bandwidth. Thus the expression within the square brackets represents the ratio of the interference power to the noise power in the receiving amplifiers. The combined interference and noise are processed by a power-linear detector (output voltage proportional to input power) and averaged over a time interval t. The time averaging reduces the noise by the square root of ($\Delta f\ t$). Thus Eq. (1) represents the ratio of the voltages of the interference and rms noise, after averaging. Then if we equate the right-hand side of Eq. (1) to 0.1, we can solve for the threshold value of interference,

$$S_H = \frac{0.4\,\pi\,k\ f^2\left(T_A+T_R\right)}{c^2\sqrt{\Delta f\ t}} \qquad (2)$$

S_H is in units of spfd ($\mathrm{Wm^{-2}Hz^{-1}}$), and Eq. (2) is given in the Handbook as Eq. (10) on p. 19. In terms of pfd ($\mathrm{Wm^{-2}}$) we can write,

$$F_H = S_H \Delta f = \frac{0.4\,\pi\,k\,f^2\left(T_A + T_R\right)\sqrt{\Delta f}}{c^2\sqrt{t}} \qquad (3).$$

Equations (2) and (3) are used to determine S_H and F_H for bands allocated to radio astronomy. For continuum observations we take f to be the center frequency of the band and Δf the allocated bandwidth. T_A and T_R are chosen to represent a high performance system. For t a value of 2000 s is used, which is typical of a short duration observation. Note that for a continuum observation the square root of ($\Delta f\ t$) in (2) is typically of order 10^5 or more, whereas for a communication system it may be of order unity. Thus interference thresholds for radio astronomy are lower by ~50 dB or more than corresponding interference thresholds for many transmitting services. Threshold levels of S_H and F_H from (2) and (3) are given in Table 1 of RA.769. A footnote to the tables indicates how the values are adjusted for longer averaging times. For spectral line observations the value of Δf is chosen to be typical of the resolution bandwidth used for observations in the particular band, and results are given in Table 2 of RA.769. Tables 1 and 2 are reproduced in the Handbook as Tables 4 and 5 (pp. 20 and 21). A plot of the values of S_H as a function of frequency is given by the lowest curve in Fig. 4 of the Handbook (p. 23). Values of S_H increase with f to a power that is a little greater than 2, resulting from the decreasing collecting area of the sidelobes with frequency and the gradually increasing values of T_A and T_R. The curve also varies in an irregular manner because of the variation in bandwidth from one allocated band to another.

Detrimental threshold for interferometers and synthesis arrays. Two effects reduce the response of interferometers and synthesis arrays to interference. These are related to the fringe oscillations that occur when the outputs from two antennas are combined, and to decorrelation resulting from the relative delays of interfering signals received in two widely spaced antennas. The treatment of these effects (Thompson 1982; Thompson, Moran, and Swenson 1986, 2001) is more complicated than that for single antennas discussed above. This is not included in RA.769, but a brief qualitative description is given. The response to a radio source observed using an interferometer (i.e., two spaced antennas and a receiving system that combines their received signals) is modulated by a sinusoidal fringe function as a result of the change in the relative path lengths to the antennas as the source moves across the sky. Interference received from a transmitter in a fixed location does not suffer such an effect. In the signal processing an instrumental phase variation is introduced to remove the fringe oscillations from the (wanted) astronomical signal, and this has the effect of transferring the fringe oscillations to the (unwanted) interference. Then if the averaging time t is comparable to, or greater than, the fringe period the response to the interference is reduced by the averaging. In effect, the interferometer discriminates against signals that do not show the variations in relative phase at the antennas predicted for the sidereal motion of the source under investigation. In general the greater the spacing between the antennas, measured in wavelengths, the more rapid are the fringe oscillations and the greater is the discrimination against interfering signals. Synthesis arrays used in radio astronomy are ensembles of two-element interferometers and respond to interference in this way. In Fig. 4 of the Handbook (p. 23) detrimental threshold values for two synthesis arrays, the VLA and MERLIN, are plotted as functions of frequency.

In the case of VLBI (very long baseline interferometry) fringe frequencies are so high that the oscillations that represent interfering signals at the output of a correlator are effectively removed by the time averaging. If the interference is strong enough, however, it can introduce gain errors, for example through the action of automatic level control in the receiver. This results in the introduction of an error in the form of a multiplicative factor. To limit this effect the criterion used specifies that the interference power in the receiver, before the detector or correlator stage, should not exceed 1% of the noise power. The corresponding threshold is given by equating the expression in square brackets on the right-hand side of Eq. (1) to 0.01. Detrimental thresholds for VLBI, based on this condition, are given in Table 3 of RA.769, which is reproduced in the Handbook as Table 6 (p. 23), and are also shown in Fig. 4 of the Handbook. The detrimental thresholds for VLBI are roughly 40 dB higher than for total power measurements with single antennas. For calibration purposes a VLBI observation may also include measurements of the power received in a single antenna, for which the threshold values in Tables 1 and 2 of RA.769 apply (see lecture by J. D. Romney).

Like the threshold values for single antennas, the interference thresholds for synthesis arrays and VLBI also increase with frequency (approximately as $f^{2.5}$ for synthesis arrays and as f^2 for VLBI). This effect results largely from the variation of the sidelobe collecting area with frequency. For a given frequency, the interference thresholds also increase progressively through the sequence of single antennas, closely spaced synthesis arrays, more widely spaced synthesis arrays, and VLBI. The values in the figure are calculated for the case of a source of interference in a fixed location. Discrimination against such interference increases with the angular resolution of the system, since the ability to discriminate against sources of radiation that do not share the sidereal motion of the source under observation depends upon the angular resolution. Although synthesis arrays and VLBI arrays have higher thresholds for interference, these instruments are most useful for studying sources with small angular structure, while single antenna telescopes fulfill an essential role in the observation of more extended sources.

Geostationary Orbit. Radiation at the threshold level will cause interference above the detrimental criterion if the radio astronomy antenna presents sidelobes of gain greater than 0 dBi in the direction of an interfering transmitter. If the sidelobes are represented by the 32-25 log ϕ model, this implies that a radio astronomy antenna should not be pointed closer than 19° to a transmitter radiating at such a level. This consideration is particularly important in the case of interference from geostationary satellites, since a band of sky centered on the geostationary orbit could become blocked to radio astronomy. It is noted in RA.769 that the geostationary orbit moves in declination as seen from observatories at different latitudes. Observatories in mid-latitudes of the northern and southern hemispheres can jointly cover the whole sky if observations can be made to within 5° of the geostationary orbit (see Fig. 5 on p. 26 of the Handbook). With the 32-25 log ϕ model, it would be necessary to observe with the +15 dBi sidelobe level on the geostationary orbit.

RA.1513 Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy service on a primary basis

This recommendation is concerned with the percentage of time lost to interference that radio astronomers are able to accept, that is, the percentage of time that interference levels can exceed the detrimental thresholds in RA.769. The *considerings* include: the requirement for extreme sensitivity and precision in research in radio astronomy; the need to make observations of certain phenomena, such as comets or occultations by the Moon, at times that cannot be arbitrarily chosen; that interference in the form of unwanted emissions from several services or systems may occur in the same radio astronomy band; and that the specification of an acceptable percentage of time for which interference may exceed the threshold levels is necessary for certain studies such as those using the Monte Carlo method. The *recommends* include: that in any band with a primary allocation to the radio astronomy service, a criterion of 5% be used for the aggregate data loss; that a criterion of 2% be used for the data loss due to interference from any one network; and that the percentage of data loss be determined as the percentage of 2000 s integration periods in which the average spfd at the radio telescope exceeds the level defined in RA.769.

RA.1513 contains an annex with further discussion of several points. Some examples of aggregate percentage data loss accepted by other services that fall within the coverage of Study Group 7 are given in Table 1 of the annex. As radio astronomy has matured, the usefulness of data that is limited in accuracy by the presence of interference has declined. Interference at the threshold levels of RA.769 effectively blocks the region of sky within 19° of the main beam axis from observations with useful sensitivity (assuming that the sidelobes follow the 32-25 log ϕ model), and that this region subtends a solid angle of 0.344 ster., which is 5.5% of the sky above the horizon. Consideration of sky blockage can be useful in evaluating the percentage of time lost in cases involving non-GSO satellites when full data are not available. However, to take fuller account of the parameters of a satellite system, a method based on the concept of equivalent power flux density can also be used. For interference in which the level fluctuates strongly because of time-varying propagation conditions, a value of 10% has generally been used to specify a percentage of time required in propagation calculations. This does not conflict with RA.1513 because such conditions are generally of limited duration.

Monte Carlo Method. This approach is useful in situations in which there are a number of parameters that each take a range of values. The result of interest is computed for a large number of trials, each of which uses randomly chosen values for the parameters. However, the values for any parameter must be consistent with its expected statistical variation. For example, consider a radio observatory in an area also occupied by ground-based mobile transmitters. Trials would involve random choice of transmitter locations, but these locations would conform to the expected density of units active at any given time. Random choice would also apply to the pointing of the radio telescope. In a large number of trials some near worst-case examples are likely to occur, in which the radio telescope points close to the direction of a nearby transmitter. It is therefore necessary to have a figure for the acceptable probability of detrimental interference, as provided by RA.1513. If the number of trials were infinitely large, then the percentage of times that the detrimental limit was exceeded would be a true measure of the probability of occurrence of detrimental interference. Since the number of trials is necessarily limited, the interpretation of the results requires consideration of their statistical probability, which involves the Bernoulli distribution. For example, if it is required that, with 90% certainty, the probability of detrimental interference does not exceed 2%, then with 400 trials the number of detrimental results should not exceed 1%, or with 10,000 trials the detrimental results should not exceed 1.8%. See *On 2% by Monte Carlo* by J. E. B. Ponsonby.

The next two recommendations, RA.1031 and RA.1272, are concerned largely with sharing situations, that is, cases where a band is allocated to another service as well as to radio astronomy. Sharing is possible if there is sufficient attenuation along the path between a radio astronomy observatory and each transmitter of the other service, which usually implies that there is no line-of-sight path between the radio astronomy observatory and the transmitter. Coordination zones can be used to provide protection in situations of this type.

RA.1031-1 Protection of the radioastronomy service in frequency bands shared with other services

This recommendation concerns sharing of bands with other services. The *considerings* include: that the power levels received by radio astronomy are generally much lower that those used in other radio services; that preferred bands are given in RA.314; that protection criteria are given in RA.769; and that frequency sharing is generally impossible for transmitters within line of sight of an observatory. The *recommends* include: that consideration be given to protection of radio astronomy sites by the use of coordination zones; and that the size of the coordination zone be calculated taking account of the criteria in RA.769, specific characteristics of the sharing service, propagation models such as those in recommendations P.452, P.526, and P.617 (P indicates Propagation series), and the percentage of time for which the detrimental thresholds can be exceeded.

The annex to RA.1031 contains some discussion of separation distances, the large distances required for sharing within the line of sight, and the use of coordination zones. A coordination zone associated with a radio astronomy station is defined as the area for which the sum total of emissions from transmitters outside its boundary does not exceed the threshold levels of detrimental interference measured at the radio astronomy antenna. Because of the number of factors involved, the boundaries of the coordination zones should be established individually for each radio astronomy site, as required.

RA.1272 Protection of radio astronomy measurements above 60 GHz from ground based interference

This recommendation is concerned with observations of atomic and molecular spectral lines in the millimeter wavelength range above 60 GHz (i.e. above the oxygen absorption band of the atmosphere), in bands used by other services. These are bands in which radio astronomy has a shared allocation or no allocation. RA.1272 essentially extends the considerations in RA.1031 to include frequencies above 60 GHz for cases in which radio astronomy has no allocation. Observation under such conditions becomes practicable in part because interference thresholds in RA.769 increase with frequency. The *considerings* include: that a large number of important spectral lines are found above 60 GHz, and many of these do not fall within radio astronomy bands; that Doppler shifts spread the frequencies of radio lines well outside radio astronomy bands in many cases; that SIS (superconductor-insulator-superconductor) mixers provide sensitive receiver stages but are very susceptible to saturation; and that the oxygen bands and other factors that increase the atmospheric attenuation at millimeter wavelengths facilitate sharing with ground-based transmitters. The *recommends* include: that coordination zones be established around mm-wave observatories for all frequencies above 60 GHz, where practicable, following the procedure outlined in RA.1031.

The next three recommendations, RA.517, RA.617, and RA.1237, are all concerned with interference in the form of unwanted emissions from transmitters in other bands. The dates when they were first approved are 1978, 1986, and 1997, which shows that these problems have been ongoing for many years and acceptable solutions are hard to find.

RA.517-2 Protection of the radioastronomy service from transmitters in adjacent bands

This recommendation deals specifically with interference from transmitters in adjacent bands. The *considerings* include: that the Radio Regulations, specifically RR No. 344[1], do not provide the needed protection for radio astronomy with regard to adjacent bands; and the possible future increase in the level of usage of bands adjacent to radio astronomy bands, particularly by airborne and satellite transmitters. The *recommends* include; that all practical, technical means, for example the use of filters, be adopted in both transmitters and radio astronomy receivers; that attempts should be made to limit the edge of the necessary band adjacent to a radio astronomy band (i.e. limit emissions close to the allocated band edge); and that in future assignments in bands adjacent to radio astronomy bands, account should be taken of the special risks to radio astronomy.

Band-edge problems are discussed further in the annex. They can arise by three mechanisms. (1) The response of the radio astronomy receiver outside the radio astronomy band may not be sufficiently low. (2) Non-linear responses of the receiver, together with the occurrence of two or more strong signals near the band edge, can give rise to intermodulation products that fall within the receiver passband. (3) Transmitters may produce modulation sidebands that fall outside of their allocated band and into a radio astronomy band. The particular problem of transmitters on satellites or aircraft is noted. Also, for radio astronomy at millimeter wavelengths, sites must be chosen at high elevations rather than for avoidance of interference. Figure 1 of the annex shows the position of the geostationary orbit on the sky as seen from the latitudes of various radio astronomy observatories on the Earth. This figure is reproduced in the Handbook as Fig. 5 (p. 26). The annex also contains a table of services in adjacent bands that could cause harmful interference to the radio astronomy service.

RA.611-2 Protection of the radioastronomy service from spurious emissions

This recommendation deals with spurious emissions from other services. The current definition of spurious emissions, as unwanted emissions that fall outside a bandwidth of ±2.5 times the necessary bandwidth for the system concerned, is not mentioned in the recommendation, which was last revised in 1992. The *considerings* include: that the use of certain modulation techniques with inadequate filtering of spurious products can affect radio astronomy bands far removed from the wanted emission band; that Appendix 8 of the Radio Regulations establishes maximum permitted levels of spurious emissions; that

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[1] RR 344 states "For the purpose of resolving cases of harmful interference, the radio astronomy service shall be treated as a radiocommunication service. However, protection from services in other bands shall be afforded to the radio astronomy service only to the extent that such services are afforded protection from each other."

the technical criteria concerning interference to radio astronomy are the threshold levels of interference in Tables 1 and 2 of RA.769. The *recommends* include: that the radio astronomy service should continue to place observatories in locations with good natural protection and make all practical efforts to minimize sidelobe gains; and that for the special case of geostationary satellites, to the maximum extent possible, interference from spurious emissions should be at levels low enough to allow radio astronomy observations to be made when observing as close as 5° to the geostationary orbit. With regard to this last point, Fig. 1 of the annex is the same as Fig. 1 of the annex of RA.517 and Fig. 5 of the Handbook. This shows that observatories in the northern hemisphere could cover all declinations north of 0° if they could work to within 5° of the geostationary orbit. Similarly, observatories in the southern hemisphere could cover all declinations south of 0° if they could work to within 5° of the geostationary orbit. Thus observation to within 5° of the geostationary orbit would enable astronomers to work around sky blockage at the orbit. Note that this point is also made in the annex or RA.769.

The discussion in the annex of RA.611 also notes that harmonic radiation, intermodulation of two or more strong signals, and inadequately filtered digitally-modulated signals (including spread spectrum) can affect radio astronomy bands far removed from the carrier frequency. In particular, biphase phase-shift keying (2-PSK) modulation, which produces a power spectrum of $(\sin x/x)^2$ form, can be a very serious problem if left unfiltered. The annex also includes a table of services that could cause harmonic interference to the radio astronomy service, that is, services with strong transmissions at frequencies of which harmonics fall within an allocated radio astronomy band.

RA.1237 Protection of the radio astronomy service from unwanted emissions resulting from applications of wideband digital modulation

This recommendation is concerned with interference in the form of unwanted radiation from wideband digital modulation. The *considerings* include: that transmitters, particularly those in space stations, are increasingly employing direct sequence spread spectrum (DSSS) and other wideband digital modulation techniques that can produce extensive unwanted emission sidebands; that spectrally efficient digital modulation techniques are known which produce intrinsically low levels of unwanted emissions; and that from the viewpoint of the victim service there is no practical distinction between spurious and out-of-band interference. The *recommends* include: that all practicable steps be taken to reduce the levels of sidebands that fall outside the allocated bands of services employing digital transmissions; and that in establishing limits in bands for which the radio astronomy service has a primary allocation, note should be taken of the threshold levels of interference specified in RA.769.

The discussion in the annex notes that experience for more that two decades has shown that most of the seriously damaging interference to radio astronomy has resulted from unwanted emissions from satellites. The distinction between out-of-band and spurious emissions, as defined in RR Article 1, is not entirely clear, since it states that out-of-band emissions result from the modulation process and are immediately outside the necessary bandwidth. However, digital modulation and spread spectrum are examples of modulation with sidebands that can extend widely outside the necessary bandwidth. Limits in RR Appendix 8, specified in terms of power into a transmission line, could be more helpful if the response of the transmitting antenna were taken into account. Also, for interference calculations the levels of unwanted emissions are required in absolute terms, not as decibels relative to the main transmission. Calculation of the spfd at an observatory for the case of line-of-sight transmission is discussed. The DSSS-modulated emissions of the GLONASS satellite system have proved to be a particularly serious case of sideband interference. For DSSS the sideband power spectrum falls off at only 6 dB per octave. Elimination of the sidebands of spread spectrum by means of filters at the carrier frequency may not be practicable if the spread spectrum carrier is close to the radio astronomy band. However, modulation techniques such as Gaussian-filtered minimum-shift keying can provide effective spectrum shaping. Other topics discussed include possible interference to radio astronomy bands below 1 GHz and the transmissions of digital audio broadcasting in the 1452-1492 MHz band. Table 1 of the annex summarizes the threshold values in Tables 1 and 2 of RA.769. Table 2 of the annex gives the orbital period and spreading loss for satellites at various heights.

The final two recommendations in the RA series, RA.479 and RA.1417, are concerned with protection of radio-quiet areas of space.

RA. 479-4 Protection of frequencies for radioastronomical measurements in the shielded zone of the Moon

This recommendation is concerned with protection of the radio environment in the shielded zone of the Moon. The shielded zone is smaller than the remote hemisphere of the Moon to allow for shielding of the line of sight from satellites in Earth orbits of radius up to 100,000 km, and taking account of the libration of the Moon. The remaining invisible portion of the Moon's surface is that which lies more than 23.2° beyond the mean limb of the Moon as seen from the center of the Earth. The shielded zone of the Moon consists of the shielded area of the Moon's surface together with an adjacent volume that is shielded from interference originating within a distance of 100,000 km from the center of the Earth. The *considerings* include: that resolution B16 of the 1994 General Assembly of the IAU recommends that radio communication transmissions in the shielded zone of the Moon be limited to the band 2-3 GHz, but that an alternate band at least 1 GHz wide be identified for future operations on a time-coordinated basis; and that Article 26, Nos 2532-2635 of the Radio Regulations recognizes the necessity of maintaining the shielded zone of the Moon as an area of great potential for observations by the radio astronomy service and by passive space research, and consequently of maintaining it as free as possible from transmissions. The *recommends* include: that in taking account of the need to provide for radio astronomy in the shielded zone of the Moon, special attention be given to those frequency bands in which observations are difficult or impossible from the surface of the Earth; that the frequency spectrum in the shielded zone should be used in keeping with the guidelines in Annex 1 of the recommendation; and that special attention be given to emissions into the shielded zone from deep-space platforms or transmitters near or on the Moon.

Annex 1 states that the entire radio frequency spectrum in the shielded zone is designated for passive services except for those bands required by the space operations, space research, and similar services that are required to support space research. Also included are any frequencies allocated in the future for radiocommunication and space research transmissions (i.e., data transmissions etc.) within the lunar shielded zone. Annex 1 also reviews the frequency usage for radio astronomy. The 30 kHz-30 MHz range is difficult or impossible to use from the Earth because of the ionosphere and the intense usage for communications, but could be important for observations of a range of phenomena. The 30-300 MHz range is important for the red-shifted HI line and continuum observations. The 300 MHz - 3 GHz range contains the important lines of deuterium, HI and OH, which are only protected over a limited range of Doppler shifts from the Earth. The 3-20 GHz range contains a number of astrophysically important lines that are not adequately protected on Earth, including lines of methyladyne, formaldehyde, methanol, and cyclopropenylidene. In the 20-300 GHz range absorption in the Earth's atmosphere becomes important, with absorption bands of water lines near 22 and 183 GHz, and of oxygen near 60 and 120 GHz. The dryness and lack of atmosphere on the Moon are ideal for astronomical observations in this range.

The prime consideration for the use of the shielded zone is the avoidance of radio interference generated on or near the Earth. It is stated that as a first requirement all frequencies below 2 GHz should be accessible to radio astronomy. Also, alternate bands are necessary for those active transmissions absolutely indispensable for space operations, to enable total access. Systems developed and used for data transmission or other active purposes in the shielded zone of the Moon should allow for enough frequency redundancy to ensure that, if a new discovery is made in a band used by them, operations may be vacated and moved to a different band to enable passive research. For continuum observations the existing primary and secondary radio astronomy allocations should be rigorously protected on the Moon, to allow direct comparison with terrestrial measurements and for VLBI using stations on the Earth and the Moon. However, the bandwidths for use on the Moon should not be restricted to the bandwidths allocated for measurements from Earth. Annex 2 of RA.479 is resolution B16 of the XXIIth General assembly of the IAU.

RA.1417 A radio-quiet zone in the vicinity of the L2 Sun-Earth Lagrange point

This recommendation is concerned with the protection of radio quiet conditions in the vicinity of the L2 Sun-Earth Lagrangian point, which is used as a location for existing and planned astronomical observatories. The L2 Lagrangian point of the Sun-Earth system is approximately 1.5 x 10^6 km from the Earth in the anti-solar direction, on a line joining the barycentres of the Earth and the Sun. The *considerings* include: that the vicinity of the L2 point is a relatively radio quiet point because of its great distance from the Earth; that quasi-stable orbits having radii up to about 250,000 km are possible in the vicinity of the L2 point; that the low levels of spfd in the vicinity of the L2 point from the quiet Sun and from transmitters on the Earth and in space between the Earth and the geostationary orbit, would permit highly sensitive radio astronomy observations to be made; and that viewed from the L2 point almost all sources of interference will lie within a cone no more than 3.2° across, as determined by the diameter of the geostationary orbit. The *recommends* include: that administrations, in making frequency assignments that may affect missions near the L2 point, should protect a volume of space of radius 250,000 km centered on the L2 point of the Sun-Earth system as a coordination zone of low electromagnetic emission, where all radio transmissions originating in the coordination zone are confined to specified bands of frequencies and limited transmitter powers.

The annex includes a diagram showing the relative positions of the Sun, the Earth, and the L2 point, and a table of some current and planned missions to the L2 point.

Six more ITU-R recommendations that are of particular importance in considering levels of protection to radio astronomy are briefly mentioned below. They are in the space applications and meteorology (SA) series, the fixed satellite service (S) series, and the spectrum management (SM) series.

SA.509.2 Generalized space research earth station and radio astronomy antenna radiation pattern for use in interference calculations, including coordination procedures

The generalized pattern is the sidelobe model mentioned in the discussion of RA.769 above, in which the gain is 32-25 log ϕ where ϕ is the angle measured from the main beam axis, for $1° < \phi < 47.8°$, and -10 dBi for $\phi > 47.8°$. This applies to antennas of diameter greater than 100 wavelengths and frequencies between 1 and 30 GHz. The annex shows a comparison of the model with the measured pattern for the Lovell Mk1A radio astronomy antenna (76.2 m diameter) at 1420 MHz.

S.1428-1 Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 and 30 GHz

This recommendation defines a more complex antenna response model than RA.509, which varies with the antenna diameter measured in wavelengths and includes the main beam. It may be useful as a model for a radio astronomy antenna when making detailed calculations of the interference levels from satellites. The recommendation gives no details of the basis for the sidelobe model that is proposed. However, the model includes an enhancement of gain centered at an angle of 100° from the axis of the main beam, which suggests spillover from a prime-focus feed.

SM.328-10 Spectra and bandwidth of emissions

This document contains definitions of terms used in spectrum management and methods of calculation of transmitted spectra. It contains seven annexes that are concerned with different types of signals and modulation. Annex 6 is concerned with digital phase modulation, unwanted sidebands from which are a particularly serious problem for radio astronomy. Methods of modulation are described, such as Gaussian minimum shift keying, that are designed to minimize unwanted emissions. Annex 7 is concerned with reduction of interference due to unwanted emissions at transmitters. SM.328 is an important reference document but is too long to be considered further here.

SM.329-9 Spurious emissions

This recommendation is basically concerned with placing limits on spurious emissions. It includes discussions of the definition of the spurious domain and other relevant terms. Five categories of limits are included (see section 3.3), of which category A is generally the least stringent and most widely used. The category A limits are given in Table 2. For space services they generally specify an attenuation below the power supplied to the (transmitting) antenna transmission line of $43 + 10 \log P$ dBc, or 60 dBc, whichever is less stringent, where P is the mean power in watts at the antenna transmission line. For $P < 17$ dBW (50 W) the corresponding limit on the spurious emission power is -43 dBW (50 μW). For all space services the spurious emission limit applies to a 4 kHz reference bandwidth, that is, -43 dBW corresponds to a mean level of -79 dBW Hz^{-1}. For other services the reference bandwidth is greater, and for frequencies above 1 GHz it is 1 MHz. Thus in terms of power spectral density the limits for space services are generally 24 dB (a factor equal to 1 MHz/4 kHz) less stringent than for other services. The Category A limits are insufficient to protect radio astronomy from detrimental interference from GEO and non-GEO satellites within the line of sight, in most cases**.** Methods of measurement are discussed in Annex 2. Annex 3 is concerned with threshold levels of interference for radio astronomy and for space services using passive sensors, and includes the detrimental threshold levels from Tables 1 and 2 of RA.769.

SM.1540 Unwanted emissions in the out-of-band domain falling into adjacent allocated bands

This recommendation recognizes that OoB (out-of-band) emissions (that is, unwanted emissions that fall at frequencies closer to the center of the necessary band than the inner boundaries of the spurious domain) may fall within the adjacent band and cause interference to the neighboring service. Various methods are considered, such as limiting the power in the outer channels of a multichannel transmitting system, where appropriate, to avoid unacceptable interference into the neighboring band.

SM.1541 Unwanted emissions in the out-of-band domain

This recommendation contains annexes that give OoB masks, that is, spectral profiles for unwanted emissions in the out-of-band domain that specify the maximum permitted levels as a function of frequency measured from the center of the allocated band. In general, the permitted levels are higher than those in the spurious domain, and they fall towards the Category A spurious level at the out-of-band/spurious boundary. Thus the limits specified in this recommendation are, in general, not sufficiently stringent to protect radio astronomy from detrimental interference from satellites within the line of sight. Discussions of the application of the masks and of methods of measurement of OoB emissions are given.

References

ITU Handbook on Radio Astronomy, Radiocommunication Bureau, 1995 (first ed.).

Thompson, A. R., *"The Response of a Radio Astronomy Synthesis Array to Interfering Signals"*, IEEE Trans. Antennas and Propagation, AP-30, 450-456, 1982.

Thompson, A. R., J. M. Moran, and G. W. Swenson, Jr*., "Interferometry and Synthesis in Radio Astronomy"*, Wiley, New York, 1986, reprinted by Krieger, Malabar, 1991, second ed. Wiley, 2001 (see Ch. 14 of first ed., or Ch. 15 of second ed.).

NOTIFICATION OF RADIO ASTRONOMY STATIONS WITHIN THE ITU

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ITU Radio Regulation **11.12** states, "Any frequency to be used for reception by a particular radio astronomy station may be notified if it is desired that such data be included in the Master Register." In preparations for WRC-03 there are indications that in some instances the protection of radio astronomy stations will be predicated on them being notified to the ITU before a specified date. In the CPM report to WRC-03, under agenda item 1.32 (which concerns frequencies around 42.5 GHz), the following text is contained in a possible footnote, "These values shall apply at any radio astronomy station that has been notified to ITU, either before [end of WRC-03], or before the date of receipt of the advance publication information (API) of the space station to which the limits are to apply. For other radio astronomy stations, notified after these dates, agreement may be sought with administrations authorizing the space stations."[1]

Using the ITU's SRS from March 2002, a review of the notification of USA radio astronomy stations to the ITU indicates the following:

- the first USA radio astronomy service (RAS) station was notified to the ITU in January 1958 (Hamilton, MA)
- the last USA RAS station was notified in October 1975 (VLA, NM)
- much of the information in the current ITU database is suspect
- it appears that the current information contained in the ITU database does not accurately reflect actual RAS usage

It is expected that other administrations operating radio astronomy sites will also determine that they have not been diligent in notifying their requirements to the ITU. Each administration, or their radio astronomy communities, will have to review the database to determine if the information is sufficient to cover its requirements.

The notification of radio astronomy assignments to the ITU is done through an electronic

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[1] See CPM Report to the WRC-03, Chapter 4, § 4.5.

process. The “SpaceCap” software can be downloaded from the ITU website at

http://www.itu.int/ITU-R/software/space/spacecap/index.html

Only a limited amount of information needs to be submitted to the ITU for radio astronomy assignments (see appendix). But this information needs to be forwarded by radio astronomers to the administration on whose territory their radio astronomy sites lie, whereupon that administration must then submit it to the ITU.

In conclusion, it is evident that the radio astronomy community needs to become much more active in the notification of their assignments to the ITU, including reviewing existing notifications, and updating unregistered requirements. This would seem to require the use of minimal resources to achieve worldwide recognition of the needs of radio astronomers, and will quite possibly allow their operations to continue to be protected by the ITU’s Radio Regulations.

APPENDIX

APPENDIX 4 DATA REQUIREMENTS FOR NOTIFICATION OF RADIO ASTRONOMY ASSIGNMENTS[2]

1. Administration
2. Name of Station
3. Country (Location of Station)
4. Geographic Coordinates (Longitude and Latitude)
5. Antenna type/characteristics
6. Assigned Frequency Band
7. Operating Administration or Agency
8. Class of Observations
9. Assigned Frequencies

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[2] More detailed information can be found in the ITU Radio Regulations, Appendix 4, Annex 2A (Characteristics of satellite networks’ earth stations or radio astronomy stations)

Satellite Coordination

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1. What is Coordination?

The International Telecommunication Union allocates frequency bands to services at World Radio Conferences. In general, any one frequency band is shared between several different services. Article 5 of the Radio Regulations contains the detailed information for each frequency band. The Radio Regulations also lay out complex procedures to ensure that when new systems start to use the frequency bands allocated to them, there is minimum disruption to existing systems of all services sharing the same frequency bands. Coordination is among these procedures.

Before an administration allows an operator to commence operation of a new system, other administrations likely to be affected must be informed and agree to technical and operational parameters, perhaps with conditions. To this end the ITU maintains a master list of officially registered systems and stations, with their characteristics, in the Master International Frequency Register. Radio telescopes need to be registered there and so do satellite systems and any radio system which affects or is affected by the radio systems of another country. Any officially registered station or system is to be protected from the incoming new system by the process of coordination. Once coordination is completed the new system can be registered on the Master Register. The new system then acquires its own protected status, even if not yet implemented, and further incoming systems must coordinate with it and protect it. Radio telescopes not registered in the Master Register have no official status and cannot claim protection.

Coordination is a critical process for satellite systems. Unless it is sucessful a proposed new system is not guaranteed protection, which may mean that the satellites never fly. But coordination is also critical for radio astronomy. It is our one official chance to protect our science and our facilities against new satellite systems. The decisions we make during coordination will affect not only our own local time and place, but will set the mould for future generations of radio astronomers. We need to be aware of this when entering into satellite coordination. We must also be vigilant, because we normally only get one chance in the coordination game. GLONASS slipped through the safety net of coordination because almost nobody objected to it (on behalf of radio astronomy) at the appropriate time.

The following sections look at the regulatory machinery of satellite coordination and discuss some of the issues for radio astronomy.

2. The Regulatory Process

Chapter III of the Radio Regulations describes “Coordination, notification and recording of frequency assignments and Plan modifications”. The relevant articles are the following:

- Article 7	Application of the procedures
- Article 8	Status of frequency assignments recorded in the Master International Frequency Register
- Article 9	Procedures for effecting coordination with or obtaining agreement of other administrations
- Article 10	Not used
- Article 11	Notification and recording of frequency assignments
- Article 12	Seasonal planning of the HF bands allocated to the broadcasting service between 5 900 kHz and 26 100 kHz
- Article 13	Instructions to the Bureau
- Article 14	Procedure for the review of a finding or other decision of the Bureau

Articles 7 and 8 set out the priority gained by coordination: only coordinated systems have priority. Note in particular the strong language of **8.5**: “If harmful interference to the reception of any station whose assignment is in accordance with No. **11.31** is actually caused by the use of a frequency assignment which is not in conformity with No. **11.31**, the station using the latter frequency assignment must, upon receipt of advice thereof, immediately eliminate this harmful interference.” Articles 13 and 14 are concerned with the appeal process, if the coordination process fails to reach agreement. Ultimately an administration has the right to raise the matter at a World Radiocommunication Conference.

The details of the coordination process are spelled out in Article 9. The first stage is Advance Publication, in which the general characteristics of the satellite system, such as frequency bands, orbit type and service area are published. The information should be published not earlier than five years and preferably not later than two years before the planned date of bringing it into use. The information to be provided is set out in Appendix 4. This information is published by the ITU in weekly International Frequency Information Circulars. Any admininstration which considers that its existing or planned systems may be affected has four months to register its interest and its concerns with the ITU. If no comments are received within this time it is assumed that the administration has no objections to the planned system.

The next stage is the request for coordination. The date of receipt of this request effectively establishes the priority date for the new system. Using more detailed information on the satellite system the administrations identified in the first stage enter into detailed bilateral discussions, estimate the likely interference and hopefully reach some agreement on how the new system can be brought into operation. During this process the parameters of the new satellite system may be modified so as to mitigate interference, for example by changing the coverage area or sidelobe performance of the satellite antenna, by reducing power levels, by frequency planning or even by changing orbital location.

Particularly important is Footnote **9.50.1** "In the absence of specific provisions in these Regulations relating to the evaluation of interference, the computational methods and the criteria should be based on the relevant ITU-R Recommendations agreed by the administrations concerned. In the event of disagreement on a Recommendation or in the absence of such a Recommendation, the methods and criteria shall be agreed between the administrations concerned. Such agreement shall be concluded without prejudice to other administrations." The first sentence of this footnote shows that if both parties agree then Rec.RA.769 can form the basis of the interference evaluation. I have had this happy experience myself several times. In more difficult cases a private deal may be needed. The last sentence indicates that such a deal applies only to the affected parties, and has no wider implications for other coordination parties and other bilateral coordination discussions. In practice this is not so easy to achieve. The deal struck between Iridium and US radio astronomers at the NRAO was carried abroad and used in a strong way to try to force similar deals with radio astronomers around the world.

Once coordination is completed the final details of the new system, and the fact that coordination has been agreed with the relevant adminstrations, are officially notified to the ITU and the system is entered in the Master Register, which establishes its priority over any subsequent systems. Details of this are in Article 11. If the coordination process is not concluded within five years (plus a possible extension of two years) then the ITU will cancel the provisional entry and terminate the coordination process.

3. More Regulatory Details

Some of the detailed information that the ITU requires for coordination purposes is set out in Appendix 4 "Consolidated list and table of characteristics for use in the application of the procedures of Chapter III", which has four annexes:

- Annex 1A: Lists of characteristics of stations in the terrestrial services
- Annex 1B: Table of characteristics to be submitted for stations in the terrestrial services
- Annex 2A: Characteristics of satellite networks or earth or radio astronomy stations
- Annex 2B: Table of characteristics to be submitted for space and radio astronomy services

Radio telescopes need to be registered in this way in order to be protected by the ITU machinery. The process is cumbersome and not well suited to the flexible use we make of radio telescopes in our research, but it must be respected or we lose any priority over incoming satellite systems.

Within Annex 2A, A.17 "Compliance with aggregate power flux-density limits", we find a group of power flux density limits that trigger coordination. Three of these concern the protection of radio astronomy from satellite systems:

(a) NGSO satellites in the RNSS operating in the band 5010 - 5030 MHz, aggregate pfd into the band 4990 - 5000 MHz (**5.443B**);

(b) NGSO satellites in the FSS operating in the band 41.5 - 42.5 GHz, aggregate pfd into the band 42.5 - 43.5 GHz (**5.551G**); and

(c) NGSO satellites operating in the FSS in the band 15.34 - 15.63 GHz, aggregate pfd into the band 15.35 - 15.4 GHz (**5.511A**).

What is most surprising and significant about these three triggers is that they trigger coordination between systems that operate in *different* frequency bands: satellites in one band and radio telescopes in a different band. Normally coordination is between systems that operate in the *same* frequency band. The issue here is how to protect the sensitive radio astronomy service against unwanted emissions from the satellite transmitters that spread into nearby frequency bands.

Further triggers for coordination are spelled out in Appendix 5 "Identification of administrations with which coordination is to be effected or agreement sought under the provisions of Article 9". The very extensive Table 5-1 lists technical conditions for coordination, such as bandwidth overlap, orbital position relative to existing system, pfd into a certain frequency band and coordination area of earth station covers the territory of another administration. The coordination area around an earth station is to be calculated according to the methods set out in Appendix 7, which runs to 96 pages and includes models of antenna gain and propagation models. In principle, something similar could be used to set out coordination areas around radio observatories, if administrations agreed.

Article 21, concerning sharing between terrestrial and space services in frequency bands above 1 GHz, gives limits of power flux density from space stations (in Section V, and Table 21-4). Here we see that higher pdf is allowed at higher elevation angles! This is appropriate for protection of most terrestrial services, which transmit and receive horizontally, but it is not so good for radio astronomy, with telescopes looking up into the heavens.

Article 22 concerning space services introduces the concept of equivalent power flux density (epfd) as a tool for controlling interference from NGSO satellite systems into GSO satellite systems. This tool is one that the satellite operators developed for use when coordinating with each other, and that is why they are keen to bring it into their discussions with radio astronomers.

In passing, Section V of Article 22 concerns Radio astronomy in the shielded zone of the Moon. Footnote **22.22.1** gives the ITU definition of the shielded zone, while **22.22**, **22.23**, **22.24** and **22.25** spell out the agreed protection. According to Footnote **22.22.2** the level of harmful interference is to be determined by agreement between the administrations concerned, with the guidance of the relevant ITU-R Recommendations.

4. Reaching Agreement

Interference issues may be resolved in coordination discussions by one or both parties accepting technical or operational conditions or restrictions. Technical conditions could include limiting transmitter power or power flux density, limiting power in certain sensitive frequency channels, limiting satellite coverage (e.g. beam shaping), or adding filters to transmitters. Operational conditions could include frequency planning of a satellite network, restricting the pointing directions of an earth station (or a radio telescope), or some form of time sharing or time coordination. For example the cloud radar at 94 GHz is planned to operate with time-sharing, to avoid the situation where the radar transmits directly into the main beam of a working mm-wave radio telescope.

In general, coordination discussions start from pessimistic assumptions about interference generation and reception. These are needed to trigger the coordination process. Then the analysis is gradually refined, using actual parameters rather than generic or envelope (worst case) parameters. This is the perspective from which a satellite operator will approach radio astronomy. Our coordination triggers are not worst case, but the satellite people don't know that.

Recall that satellite operators have a lot of experience of trying to coordinate with each other, where there are realistic possibilities for doing deals, trading, and reaching win-win compromises. They are used to beating each other down. Radio astronomers need to defend each of their requirements robustly in such a discussion. It may not be accepted that Rec. RA.769 automatically applies to your radio astronomy station. You may have to explain how the different assumptions concerning system noise temperature, integration time, resolution bandwidth and sidelobe levels apply to your station. You may be called on to consider all kinds of possible mitigation factors, such as polarization discrimination, site shielding, digitization loss, etc. And it is a one-way discussion. You will never get agreement for better protection than the levels of Rec.RA.769, even if you show that you need it.

5. Computerising the Process

Coordinating with a constellation of satellites is a complex problem for which we now have complex methods of solution. The aggregate power flux density (units of W m^{-2} Hz^{-1}) produced at a radio telescope by a constellation of satellites is the flux density averaged over all possible directions of arrival equally. This corresponds to the case of an isotropic antenna.

The equivalent power flux density (epfd) from a constellation of satellites is defined mathematically in Article **22.5C1**. It is a direction-weighted average, taking into account the off-axis discrimination of each transmitter and a reference victim antenna, each assumed to be pointing in its nominal operational direction(s). Epfd was developed for GSO-NGSO sharing studies. It is now the favoured approach for treating radio telescopes, using a Monte Carlo method to simulate a range of observing situations. The epfd cannot usually be measured directly, but must be calculated (estimated) using complex computer software.

The philosophy behind the Monte Carlo approach is that worst-case situations are rare. Most of the time one or other of the sharing requirements may be relaxed. Hence this approach finds favour with people wanting to bring new systems into operation as it eases their coordination burden. The Monte-Carlo approach is now widely used for dealing with moving and intermittent interferers (such as mobile transmitters on the ground, in aircraft, or in orbit) and also for dealing with interference produced by unwanted emissions. A great many input parameters need to be agreed by all parties before the work can commence (emission masks, antenna patterns, sometimes operational details, etc.). Some of the parameters are commercially sensitive, since so much depends in the business world on being first with a new type of product. So it is hard to get the input parameters needed in the simulation. Furthermore the software to calculate epfd is expensive and complicated.

The first application of the Monte Carlo approach to radio astronomy was in the case of frequency sharing around 1.6 GHz between radio astronomy stations and mobile earth stations (Earth-space transmitters). A new ITU-R Rec.M.1316 was developed based on the Monte Carlo methodology, and endorsed by Resolution 125 (WRC-97) as a way to facilitate coordination. Res. 125 also invites ITU-R to submit a report to a future competent conference on the effectiveness of using Rec.M.1316. As yet, nobody has provided experimental data to confirm or deny the value of the Monte Carlo approach to sharing with radio astronomy.

6. Paper Satellites

One of the issues that provides an unspoken background to many satellite coordination discussions is that of paper satellites. Until the 1980s most satellite systems filed with the ITU had been designed and would fly. In 1988 a Pacific-based company Tongasat began applying for orbital slots in the GSO that it could not possibly use in the foreseeable future. An amusing account is available on the internet at *http://www.mendosa.com/tongasat.html.* A fully coordinated satellite system is an asset that might be sold. Soon others got the same idea to stake claims cheaply and get rich quickly. Nowadays there is a massive over-filing at the ITU, and not only at the longitude of Tonga. Unfortunately each filed system has to be processed by the ITU and coordinated by administrations. The coordination burden increases as the square of the number of satellite systems. A tenfold increase in filings leads to a hundredfold increase in the coordination burden. This is one reason why satellite operators spend so much time in coordination discussions with each other.

The issue of paper satellites is politically very sensitive. Developing countries want to claim and defend their share of the geostationary orbit for future use. Some are also concerned that the developed countries will use up or pollute radio spectrum resources before the developing nations can bring their orbital slots into use.

Despite attempts at reform, no means has been found to reach a consensus, and the ITU backlog is still increasing.

7. Adjacent-band problems

Satellite coordination matters loom large at WRC-03, through the issue of adjacent band coordination that was mentioned earlier (Section 3). Resolution 128 "Protection of the radio astronomy service in the 42.5-43.5 GHz band" applies to WRC-03 agenda item 1.32, which is one of the most complex of the whole WRC. The fixed satellite service achieved a worldwide allocation in the band 41.5-42.5 GHz at WRC-2000, but under the conditions set out in footnote **5.551G**, which include a limit on the aggregate pfd produced in the adjacent radio astronomy band 42.5-43.5 GHz, that contains astrophysically important spectral lines of SiO. The provisional pfd limit is to be reviewed at WRC-03, and mitigation techniques are to be identified by the ITU–R, including measures that may be implemented at the satellite transmitters to reduce unwanted emissions into the radio astronomy band, and measures that may be implemented at the radio astronomy stations to reduce the susceptibility to such interference.

In addition there is the issue of priority. Radio astronomers are not unreasonable to ask that future radio telescopes be protected against satellites operating in an adjacent, i.e. different, frequency band. Yet satellite operators with their background claim that such a demand places an undue burden on the future development of *their* service in their own band. They do not accept the obligation to keep the adjacent band free of interference. In preparation for WRC-03 there are moves within ITU to extend the concept of priority to this adjacent band situation, so that only radio telescopes notified to the ITU before the end of WRC-03 will be protected in future. This is a disturbing move that we are strongly resisting.

Agenda item 1.15 presents similar problems. It concerns the radio navigation satellite service, which achieved a new allocation (space-Earth) at 5010-5030 MHz at WRC-2000, at the expense of a similar footnote **5.443B** which protects the radio astronomy service against unwanted emissions into the nearby band 4990-5000 MHz, to a certain aggregate pfd level. Res.604 calls for the provisional pfd limit to be reviewed at WRC-03, and interestingly suggests that calculated aggregate pfd values should be provided when filing new systems in the band 5010-5030 MHz. The administration sponsoring the new RNSS system (Galileo) is arguing strongly that only those radio astronomy stations notified to ITU before the end of WRC-03 should receive protection. This would seriously compromise the future development of radio astronomy.

Iridium and Radio Astronomy in Europe

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1. Introduction

I describe here how the Iridium mobile satellite system was coordinated with radio astronomy in Europe. It was a difficult episode that we all need to learn from. Negotiations began in 1991, when Motorola approached me about the possibility of a small delegation visiting Jodrell Bank, to discuss the Iridium satellite system and ways of minimizing any possible interference to radio astronomy, in particular in the frequency band 1610.6-1613.8 MHz. Iridium planned to use the frequency band 1616-1626.5 MHz to provide mobile communications anywhere on the globe, via a constellation of 66 satellites. The Iridium system is unique in using the same frequencies for uplinks and downlinks, through time division, with a 90-millisecond duty cycle. Individual messages are transmitted in bursts, in separate time and frequency channels, a combination of TDMA (time division multiple access) and FDMA (frequency division multiple access).

The visit in August 1991 was very friendly and productive. It included a one-day plenary meeting with representatives of British Aerospace and Motorola, as well as smaller meetings. Key issues to emerge from the discussions were possible interference from the Iridium downlink (unwanted emissions into the radio astronomy band), and the possibility of using a beacon transmitter at the radio observatory to inhibit transmissions from Iridium mobile terminals whenever they were close enough to detect the beacon. It was also clear, to the radio astronomers at least, that the downlink issue was pan-European, and would need to be negotiated at European level, simply because of the large area served by each satellite. I suggested that Motorola and Iridium take the matter up with the CEPT (European Conference of Postal and Telecommunications Administrations) and with CRAF (Committee on Radio Astronomy Frequencies of the European Science Foundation). It was many years before these suggestions bore fruit, as summarized in Table 1.

Table 1. Short History of Iridium in Europe

Date	Milestone
1991 August	Visit by Iridium to Jodrell Bank
1991 October	Iridium presentation to ITU-R WP7D in Geneva
1992 November	WARC-92 allocates Iridium downlink (secondary)
1994 June	NRAO sign MOU with Iridium
1995-1997	Iridium tries to reach an MOU in the UK
1995-1997	European discussions in SE28(CEPT)
1998 July	ESF signs a pan-European MOU with Iridium

In October Iridium were back in Europe to present the results of further studies to ITU-R WP7D in Geneva. They said they were confident that they could protect radio astronomy to the levels specified in Recommendation ITU-R RA.769, namely –238 dBW/m^2/Hz (Robinson 1991). On the strength of these and other arguments, WARC-92 allocated the band 1613.8-1626.5 MHz to the mobile satellite service, on a primary basis for the uplink and on a secondary basis for the downlink. At the same time, WARC-92 upgraded the radio astronomy allocation at 1610.6-1613.8 MHz to primary status and modified Footnote **733E** (nowadays Footnote **5.372)** to read:

> "Harmful interference shall not be caused to stations of the radio astronomy service using the band 1610.6-1613.8 MHz by stations of the radio-determination-satellite service and mobile-satellite services (No. **2904** applies)."

Things went quiet in Europe after the frequency band had been allocated. However we were somewhat taken aback to learn in 1995 that Iridium had signed a Memorandum of Understanding (MOU) with NRAO in June of 1994, and more surprised still to learn that the concept of a blanker had been accepted by US radio astronomers as a way of mitigating interference from the pulsed downlink. The existence of this MOU and the technical details it contained were to strongly colour the exercise of coordinating Iridium in Europe. European radio astronomy had a lot to lose at 1612 MHz, yet European radio astronomers were placed in the extraordinary position of having to defend their right to observe up to 100% of time without a blanker.

2. European Radio Astronomy at 1612 MHz

The frequency band 1610.6-1613.8 MHz is used heavily in Europe to observe the spectral line of OH at 1612.231 MHz, which is one of the characteristic emissions of OH-IR sources. The large reflector at Nançay in France has discovered hundreds of OH-IR sources, and is engaged in long-term monitoring of their OH emission. Approximately 30% of the available observing time is devoted to OH monitoring programmes, which became feasible again following the first stages of the GLONASS "clean-up". There have also been extensive OH monitoring programmes at other European observatories, including Dwingeloo, Effelsberg and Jodrell Bank.

The MERLIN interferometer and the European VLBI Network (EVN) have unique capabilities for imaging OH-IR sources, through their combination of long baselines and large collecting area. MERLIN provided the first images of the circumstellar shells of OH 1612-MHz masers around OH-IR sources (Booth et al. 1981). The combination of interferometer maps with phase-lags obtained from single-telescope monitoring can be used to estimate accurate distances to OH-IR sources by simple geometry (comparing the angular diameter of the OH shell with the front-to-back light travel time). This technique is potentially of great fundamental importance in astronomy.

The EVN measured the first proper motions of circumstellar OH 1612-MHz masers, showing the stellar mass-loss in real time, while EVN also pioneered the measurements of the circumstellar magnetic field through Zeeman splitting of the 1612-MHz spectral line (Kemball 1992). OH-IR sources were used by Lindqvist et al.(1992) as test particles orbiting in the Galactic nucleus, to measure the mass distribution within 100 pc of the Galactic Centre to estimate the mass of the central black hole. The 1612-MHz line is studied in other regions such as star-forming clouds and comets. And finally the band 1610.6-1613.8 MHz is used for continuum measurements, for example multifrequency synthesis with MERLIN (using measurements at 1612, 1665 and 1720 MHz to synthesise extra interferometer baselines).

In summary, the 1612-MHz frequency band is of great importance in Europe, and is widely used. It was essential to look for an overarching regional agreement with Iridium, since any downlink transmissions accepted over one small European country would impact on radio astronomy in many other European countries. Nevertheless Iridium tried very hard to get bilateral agreements first, particularly in the UK. It also tried many times to get a non-disclosure agreement. Although these are normal in industry and commerce, such an agreement would have effectively isolated Jodrell Bank from the rest of CRAF.

3. Technical Discussions within SE28

Technical discussions on the European sharing issues with Iridium started within the CEPT project team SE28 in late 1995. The matters to be resolved included not only sharing with radio astronomy, but also the protection of GLONASS, the protection of Inmarsat above 1626.5 MHz, and the future sharing between Iridium and other MSS systems such as Geostar which use CDMA (code division multiple access) spread spectrum coding for uplinks from user terminals.

Sharing between the MSS uplink and radio astronomy was a challenging problem that raised a number of new issues. The concept of a beacon at the observatories was eventually abandoned. Instead, direct position measurements of user terminals were to be used to determine whether they were far enough away from observatories to be allowed to transmit without restriction. The method developed by SE28 to determine the coordination zone using Monte Carlo simulations eventually found its way into the ITU-R as Recommendation M.1316. The question of how much data loss is acceptable to the radio astronomy service had not been firmly dealt with hitherto, since the 10% criterion recommended for propagation calculations does not automatically correspond to 10% of data loss. Again the approach developed in SE28 found its way into the ITU-R, this time as Recommendation RA.1513.

Sharing between the MSS downlink and radio astronomy turned out to be the “killer problem”, the most difficult to resolve. Unwanted emissions from the Iridium satellites are primarily due to intermodulation between the different frequency channels. The level of unwanted emissions rises very sharply with increasing density of user traffic, in ways that Motorola were able to predict. According to their calculations, emission levels of –238 dBW/m^2/Hz would be achieved for only a few hours per day when most users were asleep. During peak traffic periods the emission levels were expected to be more than 20 dB higher! European radio astronomers faced the prospect of having only about four hours of clear time per day. Could the interference be mitigated?

4. Mitigation Factors

The blanker proposed by Motorola was the first of a long series of mitigation factors that were proposed, considered, weighed, and ultimately rejected. The discussions occupied three years, on the UK front and a similar time within SE28. From our side we suggested that filters might be fitted to future Iridium satellites, but since the Iridium beams are formed using active antennas the number of filters required was declared to be unrealistically large. We suggested that user traffic might be capped at peak hours if radio astronomy observations could be done at no other time, but we were told that was impossible for shareholders to accept. We pointed to the regulatory position, but to no avail.

On their side, Motorola and Iridium took the view that radio astronomy protection criteria were to be closely scrutinized down to the last tenth of a decibel. Each assumption of Recommendation ITU-R RA.769 was argued over, starting with the radio telescope sidelobe pattern, the elevation coverage, actual system noise temperatures, possible polarization discrimination, detector sensitivity factor, and post-detection processing such as baseline subtraction. It was argued that the Iridium unwanted emissions would be so broadband in nature that we would be able to subtract them along with receiver noise.

In addition there was the question of whether the radio astronomy observations could wait until periods of low MSS user traffic. On this point the Nançay instrument gave a firm answer: *"Non!"* Being a transit instrument it could only observe each source at a particular time of day that varied through the year at sidereal rate. Monitoring programmes require regular observations, so necessarily in a year there would be at least two months when the source was only available during peak MSS traffic. It was proposed to use the blanker to observe in such cases, but this was rejected as too high a rate of data loss. We also discussed more exotic solutions, such as adaptive cancellation, which were deemed to be too expensive for the radio astronomy community at large. That is probably still the case nowadays. Nobody, to my knowledge, has demonstrated a realistic way to cancel 4 rapidly moving satellites simultaneously!

One reason why the Motorola engineers were so knowledgeable about possible mitigation factors is that they had got hold of my preliminary report on the GLONASS experiment. This was a confidential hand-produced document sent to only a few people in Russia, the USA, and Australia. I will know next time to number the copies.

In view of the lengthy debates we had, it is interesting to note several unforeseen developments. Far from being smooth, the Iridium emission showed spikes due to a "broadcast signal" that had not been included in the simulations or mentioned before we saw them. Transmissions over Europe commenced in July 1998 and occupied the whole band available to the hardware, 1616-1626.5 MHz, although only the band 1621.5-1626.5 MHz had been agreed with CEPT. This was put right after a few quick exchanges, but the hardware can be switched back at any time. Finally, the user traffic predictions turned out to be over-optimistic, given the rapid growth of GSM in Europe.

5. Agreement between Iridium and ESF/CRAF

When a technical solution could not be found in SE28, the debate moved into the political arena. The European Commission wanted to have a coordination agreement despite the technical issues. Direct negotiations between CRAF and Iridium were organized by the European Radiocommunications Committee under the auspices and guidance of the Milestone Review Committee. The CRAF delegation was led by Titus Spoelstra, the CRAF Frequency Manager. CRAF insisted on a pan-European agreement, and after further months of hard debate the so-called Framework Agreement was reached and signed in August 1998. The European Science Foundation, the umbrella organization for CRAF, signed on behalf of European radio astronomy. The full text can be found on the CRAF web pages (at *http://www.astron.nl/craf/framagr.htm*). Half of the agreement describes what is to be done in the case of dispute!

The crucial part of the Framework Agreement is its first clause:

> "§1. From 1 January 2006, European radioastronomers shall be able to collect measurement data consistent with the recommendation ITU-R RA.769-1."

The Framework Agreement also sets out the plan for an interim agreement to cover the period up until 2006. Parameters to be agreed for the interim period were left as variables:

- an interference level of X dBW/m^2/Hz for 24 hours per day;
- an interference level of –238 dBW/m^2/Hz for Y consecutive hours per day;
- an interference level of –238 dBW/m^2/Hz for an additional T hours per year.

The Interim Agreement reached the following year is subtler than the Framework Agreement. The key breakthrough in the second phase of negotiations was the concept of "*le weekend*". The issue of protecting the Nançay monitoring programme was solved by having two quiet weekend days per month, giving the chance to observe for 48 hours at any right ascension. Furthermore it was agreed that every weekend would be moderately quiet, to a level of –224 dBW/m^2/Hz, allowing monitoring observations of bright sources, plus aperture synthesis observations over full tracks. The fully quiet level of –238 dBW/m^2/Hz would be available for 7 hours every day of the week (Y=7). The full text of the Interim Agreement is given in Appendix A.

It is generally accepted that the CRAF agreements are far more favourable to radio astronomy than previous agreements reached with Iridium.

6. Personal Observations

Looking back, there are many lessons for us to learn from these events. I was struck from the beginning by the contrast with the GLONASS-IUCAF negotiations, where leading OH astronomers discussed the issues with the chief GLONASS engineer and the head of GLONASS operations. The top people have more scope to negotiate. In the Iridium case we were never allowed to meet the top people, but were left to the mercy of corporate lawyers.

When the chips were down regulatory arguments did not help us, nor did technical arguments: Iridium was always going to fly. In practice the secondary service was able to dictate to the primary service when we could operate without interference. It is fortunate for us that the expected levels of user traffic did not materialize.

The media took a strong interest in the David vs. Goliath aspect of the situation, from the most respected scientific journals (e.g. Feder 1996; Abbot 1999) down to daily newspapers, radio and television. In my view, the publicity did radio astronomy no harm.

In practice, non-disclosure agreements were used for gagging people. Our US colleagues did not feel able to tell us about the MOU until we learned of it from Iridium/Motorola. So whereas GLONASS united astronomers, Iridium divided them.

In practice the MOUs with Iridium have been of limited use to us. I can see no direct scientific benefit. This is in contrast with the GLONASS case, where things have changed for the better as a direct result of the GLONASS-IUCAF agreement.

Finally, I keep asking myself, where was IUCAF? Iridium sidestepped IUCAF. We must try very hard to avoid that situation in future.

7. References

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Appendix A: The ESF/CRAF- Iridium Interim Agreement

Agreement for the Period 1st May 1999 to 1st January 2006 between Iridium LLC and ESF/CRAF to co-ordinate the operations of the Iridium System and Radio Astronomy Sites that are Parties to the Framework Agreement, in order to temporarily accommodate unwanted emissions from the Iridium satellites into the band 1610.6-1613.8 MHz

Iridium LLC (hereafter "Iridium") and the European Science Foundation, acting for itself and in the name and on behalf of the ESF Associated Committee for Radio Astronomy Frequencies ("CRAF") (collectively, the "Parties"), hereby enter into this Agreement to govern the operations of the Iridium System and various radio astronomy sites in Europe for the period from 1st May 1999 to 1st January 2006.

CRAF represents the entities which operate radio telescopes that observe in the 1610.6-1613.8 MHz band in the following countries: France, Germany, Italy, Netherlands, Poland, Spain, Sweden and U.K.;

PREAMBLE

1. WHEREAS, the Iridium® System is composed of a constellation of 66 non-geostationary satellites, plus orbiting spares, which have been launched and are in orbit and operational;

2. WHEREAS, Iridium LLC and its European Gateway Operators have been authorised to use the Iridium® System to provide mobile telecommunications services in Europe using the 1621.35-1626.5 MHz band, according to CEPT ERC Decision 97(03), CEPT ECTRA Decision 97(02), MRC Recommendations and any decisions of administrations,

3. WHEREAS, the Iridium® System operates near the band in which the radio astronomy service observes signals from various sources, including signals produced by interstellar clouds of the hydroxyl radical, i.e. from 1610.6-1613.8 MHz;

4. WHEREAS, the status of allocations to services are given by the ITU Radio Regulations, including its provisions and footnotes;

5. WHEREAS, the Parties entered into an Agreement on 11th August 1998 (hereafter the "Framework Agreement"), which specified that the Parties would negotiate before 1st March 1999 an Agreement for the interim period 1st March 1999 to 1st January 2006;

6. WHEREAS, the Parties have agreed to extend the 1st March 1999 date to 1st May 1999;

7. WHEREAS, the term “Observatories” will mean all radio astronomy stations operating at 1610.6-1613.8 MHz that are parties to this agreement;

8. WHEREAS, the Parties anticipate that the current uses of the band 1610.6-1613.8 MHz by the Observatories, and the current uses of the band from 1621.35-1626.5 MHz by Iridium are not static and may change over time;

AGREEMENT

NOW, THEREFORE, the Parties agree to the following:

(1) The Parties agree that Iridium will provide protection to the Observatories as described below. Iridium agrees to meet spectral power flux density levels (“Interference Levels”) for the Iridium® System downlink signals within the 1610.6-1613.8 MHz band during the periods specified below:

(a) A level of -238 dB(W/m^2/Hz) for:

(i) 7 contiguous hours per day, 7 days a week, for the following radio astronomy sites: Nançay, France; Effelsberg, Germany; Westerbork, The Netherlands; and Jodrell Bank, UK;

(ii) Up to 7 contiguous hours per day, 7 days a week subject to notification of need for the following radio astronomy sites: Medicina, Noto and Sardinia, Italy; Torun, Poland; Yebes and Robledo, Spain; and Onsala, Sweden;

(iii) 2 weekend days per month, for radio astronomy sites referred to in (i);

(iv) Up to 2 weekend days per month subject to notification of need for radio astronomy sites referred to in (ii);

(v) Up to a total of 30 additional hours per year subject to notification of need for the radio astronomy stations referred to in (i) and (ii);

(b) A level of –224 dB(W/m^2/Hz) every weekend for the radio astronomy stations referred to in (a)(i) and (a)(ii);

(c) Iridium will choose the contiguous 7 hours per day referred to in (a)(i) and (a)(ii) above upon at least 90 days notice. Iridium will also choose the 2 weekend days each month referred to in (a)(iii) and (a)(iv) above upon at least 90 days notice. Under exceptional circumstances notice may be given 2 weeks in advance. The chosen hours and weekend days will be the same for all the Observatories.

(d) The Parties agree that CRAF will notify Iridium LLC, pursuant to (1)(a)(ii), (iv) and (v), in writing at which dates and times the Iridium out-of-band emissions shall not exceed certain levels specified in (1)(a)(ii), (1)(a)(iv) and (1)(a)(v) above. This notification shall be provided no more than once a month and at least 30 days in advance of the date when protection is needed, except that up to two times per calendar year, two weeks notice will be sufficient. The notification document shall be properly certified through the signature of a CRAF designated responsible person. CRAF may send copies of the notifications to FCC and CEPT (ECTRA/ERC) for information.

(e) The Parties agree to evaluate the effectiveness of the agreed upon procedures and may share the appropriate information in this regard with the other party.

(f) The Parties further agree to a workplan to explore existing factors, new techniques and system improvements which will remove the need for operational restraints from the Iridium system as of 1st January 2006. These will include, but are not limited to (1) development of an understanding of actual interference effects from Iridium to radio astronomy observations, (2) changes which could be made to the future generation Iridium spacecraft to reduce unwanted emissions into the radio astronomy band 1610.6-1613.8 MHz, and (3) changes which could be made to reduce the susceptibility of radio astronomy observations to interference. The details of the technical areas which will be investigated, and a schedule for these investigations, are described in Annex 1 hereto.

(2)(a) In accordance with the Framework Agreement, each of the Parties may communicate to the other party the desire to enter into negotiations with a view to amend, to revise, and to adapt this Agreement or its update, including the addition of European radio astronomy stations who also wish to accede to this agreement. Any such request shall include an explanation of the reasons for further negotiations, details of specific changes sought, and a proposed date for beginning negotiations. Such a request shall be sent to the other party no earlier than one year after the entering into force of this Agreement or its update. If a request is made, the Parties shall meet in order to negotiate in good faith the requested amendments, revisions and adaptations. The negotiation process will start at a date, which must be agreed within 2 months after the request has been received by the other party.

(b) This Agreement shall remain effective until the Parties have reached agreement on an update.

(c) Representatives from the CEPT (ECTRA/ERC) may be invited to attend negotiations.

(3) In case of dispute, §§ 7-9 of the Framework Agreement shall apply.

(4) This Agreement shall be binding on successors in interest to the Parties.

The persons executing this Agreement hereby certify that they are authorised to sign this document on behalf of their respective organizations, including the organizations that operate the radio astronomy sites mentioned in WHEREAS (7) of this document.

ACCEPTED AND AGREED:

Iridium LLC	**European Science Foundation**
Name: James G. Ennis	Name: ____________________
Title: Deputy General Counsel	Title: ______________________
Signature: ______________	Signature: __________________
Date: __________________	Date: ______________________

Annex 1

Initial Workplan for
Investigation of Iridium/Radio Astronomy Interference Compatibility Improvement

This document is not meant to be exhaustive or restrictive and may be added to in the future as necessary and agreed between the parties.

Introduction

The following document is meant to serve as the starting point for a collaborative work effort between CRAF and Iridium, as called for in the ESF/Iridium Framework Agreement. It is understood between both ESF/CRAF and Iridium that ITU-R Recommendation 769-1, which was used as a basis for establishing the protection for radio astronomy in that Framework Agreement, was not developed with a consideration to non-GSO satellite systems. As such, the Framework Agreement acknowledged that there may be certain existing factors beyond those of Recommendation 769-1, or other additional ways for reducing the susceptibility of radio astronomy observations to interference, or ways to reduce the unwanted emission levels from Iridium satellites that would help to eliminate the effect of Iridium unwanted emissions to radio astronomy. The Framework Agreement calls for the parties to work together to quantify the merit of possibilities before 1 January 2006 and the following document outlines a program for this work. This document is not meant to be exhaustive or restrictive and may be added to in the future as necessary and agreed between the parties.

Initial Areas to be Examined:

a. Existing factors

- Antenna pattern considerations (effect of sidelobe levels below 0 dBi, polarisation effects, main beam, etc.)
- Spectral and statistical nature of the interference (noise-like properties; effect of integration, etc.)

b. Further interference susceptibility reduction techniques

- Possible applications of the blanker (including possible selective use)

- Interference characterisation and subtraction based on Iridium duty cycle and/or measured Iridium intended emissions
- Other techniques as agreed upon by the parties

c. Satellite unwanted emission reduction

- Possible improvements that could be made to next generation Iridium satellites to reduce level of unwanted emissions.

Technical Approach:

a. Existing factors

Objective – to determine the extent to which, and manner in which, real-world Iridium interference manifests itself in radio astronomy observation data

Antenna Pattern Considerations

- assess relationship between actual interference SPFD and increase in ΔT (as defined in ITU-R Rec. 769-1) as a function of antenna main beam off-axis angle
- assess overall effects of polarisation discrimination between Iridium and radio astronomy antennas

Spectral and Statistical Nature of the Interference

- assess the extent to which Iridium out-of-band emissions exhibit noise-like characteristics
- determine the effectiveness of existing radio astronomy integration techniques at removing fluctuations caused by Iridium unwanted emissions

b. Further interference susceptibility reduction techniques

Objective – to investigate the possible development of practical techniques that could reduce the impact of Iridium unwanted emissions and be deployed at radio astronomy sites

- conduct overall assessment of prior state of the art in order to determine possible applicability to current interference situation
- create models of interference in order to establish thorough understanding of the nature of the interference signal
- using the interference models as a basis, derive and evaluate potential interference subtraction or reduction methods
- estimate the potential effectiveness of all techniques through simulation and practical measurement programs

c. Satellite unwanted emission reduction

Objective - to investigate practical possible improvements that could be made to next generation Iridium satellites to reduce level of unwanted emissions.

- Iridium/Motorola investigate different areas of potential improvement to Iridium next generation satellites and report the result of this investigation.

d. Implementation of Results:

For each of the existing factors, additional techniques or satellite improvements that are deemed to be practical and effective, agreement must be reached on:

- how to apportion the benefit of the solution (i.e. what portion of the benefit is to be applied to the case of Iridium interference)

For each additional technique that is deemed to be practical and effective, agreement must be reached on:

- how the solution would be implemented in practice ;
- who will pay for any such implementation including any hardware or software development costs, system hardware modifications at particular sites, manpower for implementing any solution at particular sites, etc.

e. Annual Planning Exercise

Objective - to provide a periodic review of the forecasted radio astronomy observation requirements in order to assess the extent to which those requirements are addressed by the current flexible time sharing agreement and the extent to which those requirements could be addressed by any agreed interference susceptibility reduction techniques or existing factors relative to ITU-R Rec. 769-1.

Timeframes and milestones:

Feb.22, 1999: strawman workplan agreed

Jan. 1, 2000: detailed workplan for work elements pertaining to existing factors relative to ITU-R Rec. 769-1

Aug. 1, 2000: quantification of possible reduction of unwanted emission levels of next generation of Iridium satellites

Jan. 1, 2001: detailed workplan for work elements pertaining to further interference susceptibility reduction techniques

Jan. 1, 2002: preliminary conclusions on existing factors relative to ITU-R Rec. 769-1 based on practical measurements.

Jan. 1, 2004: preliminary conclusions on further interference susceptibility reduction techniques based on analysis and simulation.

Jan. 1, 2006: final conclusions based on practical measurements.

GLONASS and Radio Astronomy

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1. Introduction

Like many radio astronomers of my generation, I became involved in frequency protection because of GLONASS. I had begun studying OH masers in 1981. It was a very exciting time in maser research. The MERLIN interferometer at Jodrell Bank had just made the first maps of OH maser shells around OH-IR sources (Booth et al. 1981). The OH 1612-MHz maser is one of the few tools we have for studying these pulsating red giants, which are hidden from optical telescopes by the thick envelopes of gas and dust that they shed. Just one year later the Soviet Union launched the first satellites of their Global Navigation Satellite System GLONASS. The GLONASS satellites transmit one of their main navigational signals in a frequency band that directly overlaps the OH 1612-MHz rest frequency. As interest in OH-IR sources increased, so too did the number of GLONASS satellites, and so did the levels of interference to radio astronomy at 1612 MHz. By 1985 the interference had become a severe problem at radio observatories around the world, and the source of the interference had been clearly identified (Pankonin et al. 1985). A whole branch of radio astronomy was under threat (Cohen 2000).

My own research had moved on to OH megamasers. We were using a wideband acousto-optical spectrometer to search for the redshifted OH lines. The moment we took our first spectra with AOS we saw GLONASS (Figure 1). Compared with OH megamasers, the GLONASS signal was gigantic! Yet GLONASS was a military secret, and it was many years before IUCAF was able to establish a dialogue with its operators (Robinson 1999). Table 1 summarises some of the historical developments.

Table 1. Historical Landmarks

1968	Discovery of OH-IR sources (Wilson & Barrett 1968)
1979	OH 1612-MHz line given secondary allocation at WARC-79
1982	First GLONASS satellite launched (military); First OH megamaser discovered (Baan *et al.* 1982)
1983	Coordination of GLONASS begins
1985	Interference identified (Pankonin *et al.* 1985); IRAS catalogue published, with ~10^4 OH-IR candidates
1991	First IUCAF-GLONASS meeting
1992	Worldwide experiment to test possible solutions; Radio astronomy band made primary at WRC-92
1993	ITU-R WP7D reviews the joint experiment; GLONASS-IUCAF Agreement signed in Moscow
2006	Projected completion of clean-up plan

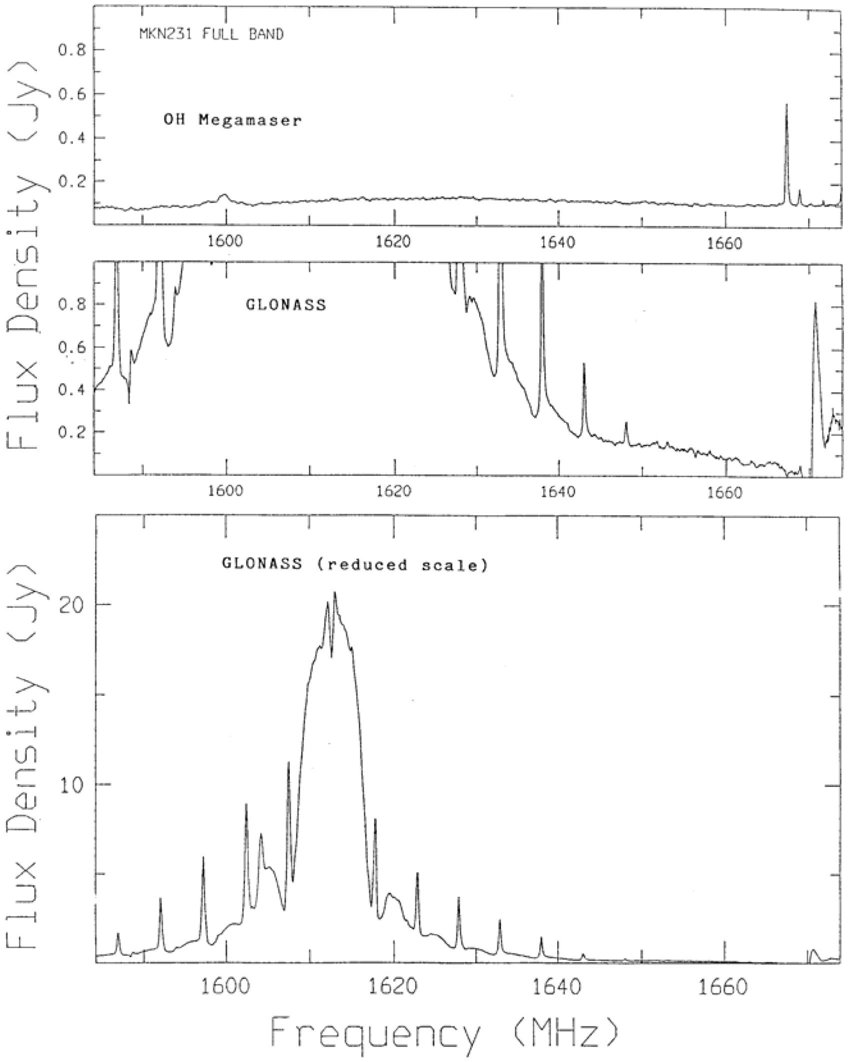

Fig. 1. Example of GLONASS interference in comparison with the OH megamaser emission from Markarian 231 at ~1600 MHz. The upper panel shows a GLONASS–free spectrum. The centre panel shows a spectrum with GLONASS interference plotted on the same scale, while the lower panel shows the same data plotted on a reduced scale. The spectra were taken at Jodrell Bank in 1986, with the 76-m Lovell Telescope and an acousto-optical spectrometer.

2. The GLONASS system

GLONASS employs a constellation of satellites in three orbital planes, with 8 orbital positions per plane. The orbital period is 11.294 hours, so that each satellite completes exactly two and one eight orbits per day. One of the main navigational signals is transmitted at one of 25 possible centre frequencies, given by ν = 1602.0000 + 0.5625 *n* MHz, where the channel number *n* ranges from 1 to 24, with channel 0 reserved for engineering tests. Channels 16-21 fall directly in the radio astronomy band 1610.6-1613.8 MHz, which is used to observe the OH 1612-MHz line.

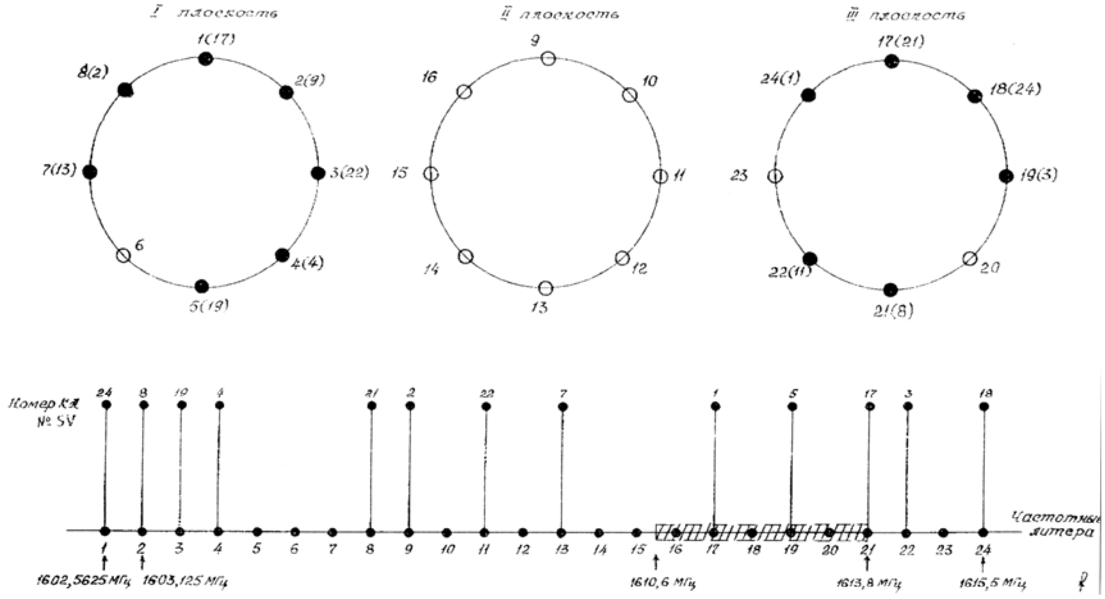

Fig. 2. GLONASS orbital occupancy and frequency plan in November 1992, at the time of the GLONASS-Radio Astronomy joint experiment.

The navigational signal is phase-modulated with a low-precision code switched at 0.511 MHz and a high-precision code switched at 5.11 MHz. The abrupt nature of the switching produces sinc-squared sidebands at both these frequencies. In addition there are "null spikes" that appear at the nulls of the 5.11-MHz pattern. Figure 1 shows the combined effect of several GLONASS satellites on radio astronomy data. The GLONASS emissions are picked up through far sidelobes of the radio telescope at ~0 dBi gain. The artefacts in the radio astronomical spectra have levels of ~5 K, that are equivalent to ~5 Jy for a 100-m telescope, but ~50 Jy for a 30-m telescope. The interference is spread over more than 100 MHz.

3. The joint experiment

The GLONASS administration was willing to help radio astronomy once the interference situation had been explained to them by IUCAF. They proposed a joint GLONASS-Radio Astronomy experiment to verify the levels of interference, and to test different ways of reducing the interference. The Soviets wanted the 76-m Lovell Telescope at Jodrell Bank to be the representative radio telescope for the experiment. They were keen to come to Jodrell Bank to witness the experiment, probably on account of the long historical association we have had with Soviet space scientists and radio astronomers. At an IUCAF meeting in Manchester I agreed to coordinate the experiment. My first move was to widen the experiment and bring in other observatories. In the event 12 radio observatories in 8 countries participated.

The experiment was carried out from 23.00 UT November 19th 1992 (02.00 November 20th Moscow time) to 19.50 UT November 21st 1992 (22.50 Moscow time). During the experiment 13 GLONASS satellites were operating. Initially the frequencies were as shown in Figure 2. During the experiment 9 satellites were moved in frequency and/or their navigation signals were switched off, while 4 satellites remained unchanged. Three frequency configurations were tested:

1. Central frequencies of navigation signals removed from the radio astronomy band (1610.6-1613.8 MHz);
2. Central frequencies of navigation signals restricted to frequency channels 12 or lower;
3. Central frequencies of navigation signals restricted to frequency channels 6 or lower.

Twelve radio astronomy observatories participated, as listed in Table 2: 10 made radio astron-omical measurements, while 6 measured the satellite transmissions directly and monitored the times of the satellite manoeuvres. Some observatories also took measurements before the official start of the experiment and during the restoration of the GLONASS system immediately after the experiment. The Jodrell Bank measurements were witnessed by the GLONASS chief engineer, Valery Tubalin, and by Slava Slysh.

Data from the participating stations were sent to Jodrell Bank during the experiment by fax and by email. Dr. Tubalin was particularly impressed with the quality of the monitoring data from the Leeheim tracking station in Germany, which gave

Table 2. Radio telescopes that participated in the joint experiment.

Observatory	No. of hours	No. of sources	Type of observation	Bandwidth
Jodrell Bank (UK)	104	21 13 sat.	Spectral line autocorrelator and acousto-optical, plus satellite monitor	5.0 and 1.25 MHz 90 MHz
Arecibo (USA)	15	8	Spectral line	20.0 and 2.5 MHz
Effelsberg (Germany)	24	1	Spectral line	25.0 and 6.25 MHz
Hartebeesthoek (South Africa)	24	10	Spectral line	5.12, 2.56, 1.28 and 0.64 MHz
Leeds University (UK)	60	13 sat.	Satellite navigation messages	
Leeheim (Germany)	60	13 sat.	Satellite measurements and monitor	100.0 and 3.2 MHz
Nançay (France)	100	40 13 sat.	Spectral line plus radio interference surveillance	1.6 and 6.4 MHz
NRAO Greenbank (USA)	57	9	Spectral line plus satellite measurements	5.0, 2.5, 1.25 and 0.625 MHz
Parkes (Australia)	39	112	Spectral line	8.0 and 0.5 MHz
Penticton (Canada)	170	2	Spectral line plus satellite measurements	2.0 MHz 50.0, 20.0, 4.25, 0.25 and 1.25 MHz
VLA (USA)	6	4	Interferometer, Phased Array	6.25 and 1.56 MHz
Westerbork (Netherlands)	83	8	Interferometer	5.0 MHz

gave precise spfd values for each satellite. At the end of the experiment data from all the participating observatories were sent to Jodrell Bank for evaluation. Figure 3 gives an example of data from the VLA, showing how GLONASS interference affects synthesis imaging. The source should appear as a single point at the centre of the field, but it is hidden by the artefacts produced by imaging the radio interference. Figure 4, which is based on Jodrell Bank data, shows that although the GLONASS satellites transmit only on one circular polarization (RHC), radio astronomical spectra are equally affected in both circular polarizations, since the GLONASS signals arrive through many different sidelobes. The only polarization selectivity comes when GLONASS is in the main beam (RHC) or seen directly by the feed in the "spillover ring" at an angular separation of 100° (LHC).

As had been agreed, I sent a preliminary report on the experiment to the GLONASS administration within 2 months. This was probably the toughest deadline of my career. The joint experiment was subsequently evaluated by ITU-R Working Party 7D in April 1993. Working Party 7D recommended firstly that the GLONASS frequency configuration 2 from the experiment (n ≤ 12) be adopted as soon as practicable and noted that this could be achieved by reuse of frequencies on opposite sides of the same orbit. The full WP7D report is given in Appendix A.

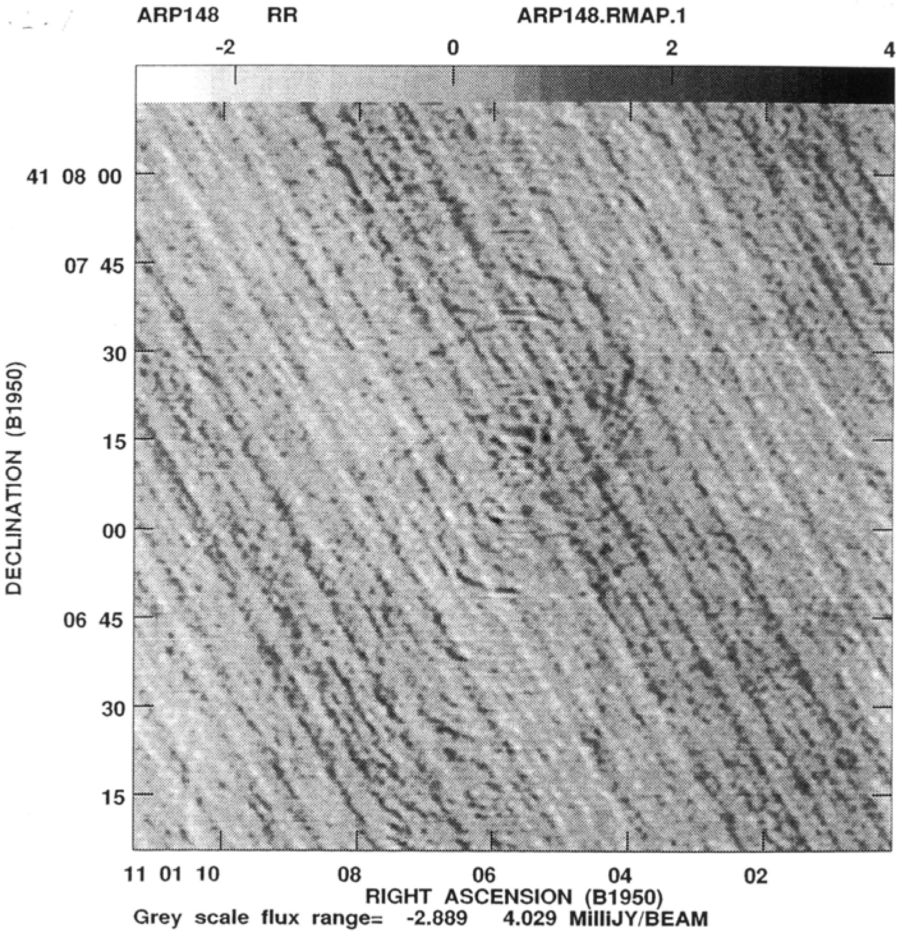

Fig. 3. Results from the VLA during the joint experiment, showing imaging artefacts due to GLONASS interference (courtesy of Vivek Dhawan).

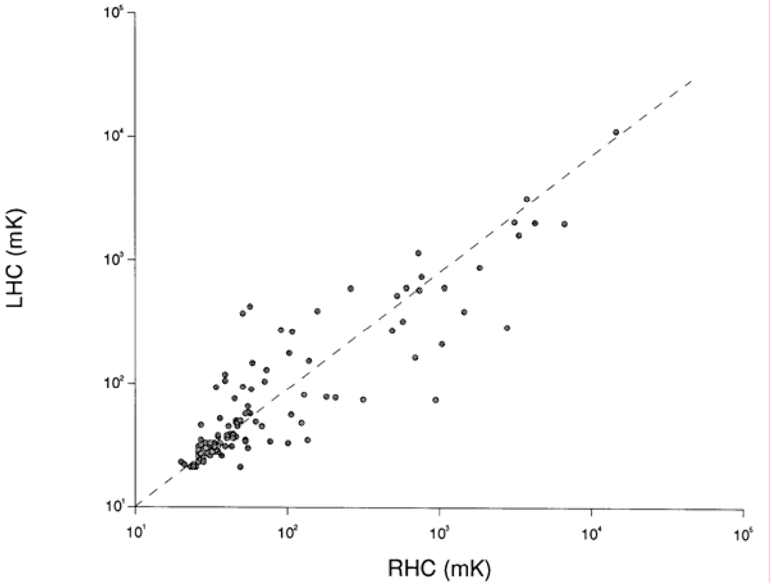

Fig. 4. Effects of GLONASS on spectra of LHC and RHC polarizations show no systematic difference, even though GLONASS transmits RHC. The data shown here are the rms noise levels of spectra taken at Jodrell Bank using the Lovell Telescope and a 1024-channel autocorrelator interference.

4. The GLONASS - IUCAF Agreement

In September 1993 the GLONASS administration reached a bilateral agreement with the Australian administration, and as a show of good faith changed the frequency plan of GLONASS without warning. Satellites with frequency channels between n=16 and n=21 were moved out of the radio astronomy band, as in phase 1 of the joint experiment. By good fortune, Jodrell Bank was observing OH at the time, and we were able to thank the Russians within a matter of days for reducing our interference levels. The political importance of this was vital when IUCAF went to Moscow at the end of October 1993 for further negotiations.

The IUCAF delegation was headed by Willem Baan, and the GLONASS delegation was headed by General Vladimir Durnev (although Col. Viktor Gorev led the actual negotiations). The meeting reached an historic agreement, the full text of which is reproduced in Appendix B. The agreement sets out a step-by-step plan to achieve compatibility between GLONASS and radio astronomy. The first steps follow phases 1, 2 and 3 of the joint experiment, with satellite frequencies being moved further and further away from the radio astronomy band. Future steps include the fitting of filters to satellites to suppress the GLONASS sidebands.

Strictly speaking the GLONASS-IUCAF agreement is not a coordination agreement, since those can only be reached by administrations. Nevertheless the agreement with IUCAF, squarely based on the results of the joint experiment, has served as a model for coordination agreements subsequently reached between GLONASS and many other administrations.

Fig. 5. Willem Baan signing the GLONASS-IUCAF accord in Moscow, 4th November 1993. Jim Cohen and John Ponsonby from the IUCAF delegation are standing behind. General Vladimir Durnev, head of the GLONASS delegation, is seated holding his papers; the lady is Nina Labusova, the translator.

5. Current Status and Prospects

GLONASS has followed the step by step plan agreed in Moscow. Since 1993 there have been no satellites with a centre frequency in the radio astronomy band. Since 2000 there have been no satellites with their main emissions in the radio astronomy band. The last launch was on 1st December 2001. We have yet to see evidence of filters fitted on new satellites, but IUCAF has been reliably informed that the next launch will include a satellite fitted with filters.

Unfortunately the situation is now complicated by newcomers, notably Iridium. A new GLONASS administration is in place. IUCAF is gathering information on current levels of interference from GLONASS, with a deadline 1st Nov 2002. This will form the basis for further negotiations and a possible further joint experiment.

6. References

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Wilson W.J. and Barrett A.H., 1968, *Science*, 161, 778-779.

Appendix A: Technical Evaluation of the GLONASS-Radio Astronomy Joint Experiment by Working Party 7D (Radio Astronomy) of ITU-R.

Documents	Document 7D/TEMP/17-E
Radiocommunication	5 April 1993
Study Groups	English only
Period 1990-1994	

Working Party 7D

PREMLIMINARY DRAFT REPORT

EVALUATION OF THE JOINT GLONASS-RADIOASTRONOMY EXPERIMENT

The members of Working Group 7D of the Radiocommunication Sector (formerly CCIR) have considered the observatory reports on the Joint GLONASS – Radio Astronomy Experiment held 20-22 November 1992. Reports considered in detail were those for single dish observations from Arecibo, Dominion Radio Astrophysical Observatory, Effelsberg, Jodrell Bank, Greenbank 140 ft, and Parkes, the interferometric data from the Very Large Array and Westerbork Synthesis Radio Telescope, and monitoring data from the Leeheim Station.

On the basis of the available data, the members of Radiocommunication Sector WP 7D conclude that:

1. GLONASS emissions display broad sidebands with frequency structure of widths 0.511 and 5.11 MHz due to low precision and high precision navigation code modulations, together with narrow monochromatic spikes which occur in the nulls of the 5.11 MHz sidebands. During the experiment accurate power flux densities were measured for all satellites by the Leeheim monitoring station. An example of these data is shown in Figure 1.

2. During the Joint Experiment GLONASS satellite transmissions were restricted in frequency to centre frequencies outside the radio astronomy band 1610.6 – 1613-8 MHz (phase 1), to centre frequencies ≤ 1608.75 MHz (phase 2) and to centre frequencies ≤1605.375 MHz (phase 3). During phases 2 and 3 of the experiment the interference levels suffered by radio astronomy observatories in the band 1610-6 – 1613.8 MHz were reduced by more than 20 dB. This effect is illustrated by Figure 2.

3. During phases 2 and 3 of the experiment useful data were obtained for most observations of strong Galactic 1612 MHz OH-IR sources, which generally have narrow bandwidths (≤500 kHz). The usefulness of the observational data depends on the strength of the source, as well as the spectral profile of its emissions.

4. Observations of weak Galactic 1612 MHz OH-IR sources produced some useful data during phases 2 and 3 of the experiment. The usefulness depends on the proximity of occupied GLONASS channels to the radio astronomy band, the frequencies of the narrow spikes in the GLONASS sidebands relative to the frequency of the astronomical source, and the spectral structure of the emissions from the source. The success rate was higher in phase 3 of the experiment.

5. Observations of broadband Galactic and extragalactic sources (bandwidths ≥ 1 MHz) were strongly affected by emissions from GLONASS satellites with centre frequencies above 1605.375 MHz. The usefulness of these data is low due to the weakness and spectral width of the emissions from the astronomical sources.

6. The narrow monochromatic spikes which occur in the nulls of the GLONASS 5.11 MHz sidebands were detected over a wide range of frequencies. In particular they were detected in the 1660 – 1670 MHz radio astronomy band at power flux densities exceeding the thresholds for harmful interference to spectral line measurements. These spikes may mimic astronomical signals from narrow band maser sources.

7. During phase 3 of the experiment the power flux densities of emissions from individual GLONASS satellites in the radio astronomy band 1610.6 – 1613.8 MHz were below the thresholds for harmful interference to spectral line observations using long baseline and very-long-baseline interferometers. Some useful data were also obtained using long baseline interferometers during phase 2 of the experiment.

In order to reduce the interference experienced by the radio astronomy service due to GLONASS emissions, the members of Radiocommunication Sector WP 7D recommend that:

1. As an urgent first step, the GLONASS system be confined to the lower twelve frequency channels of the present configuration (centre frequencies ≤1608.75 MHz). This may be achieved by the reuse of frequencies by satellites on opposite sides of the same orbit.

2. As a second step, the twelve frequency channels of the GLONASS system be shifted down in frequency to channels six and lower (centre frequencies ≤ 1605.375 MHz).

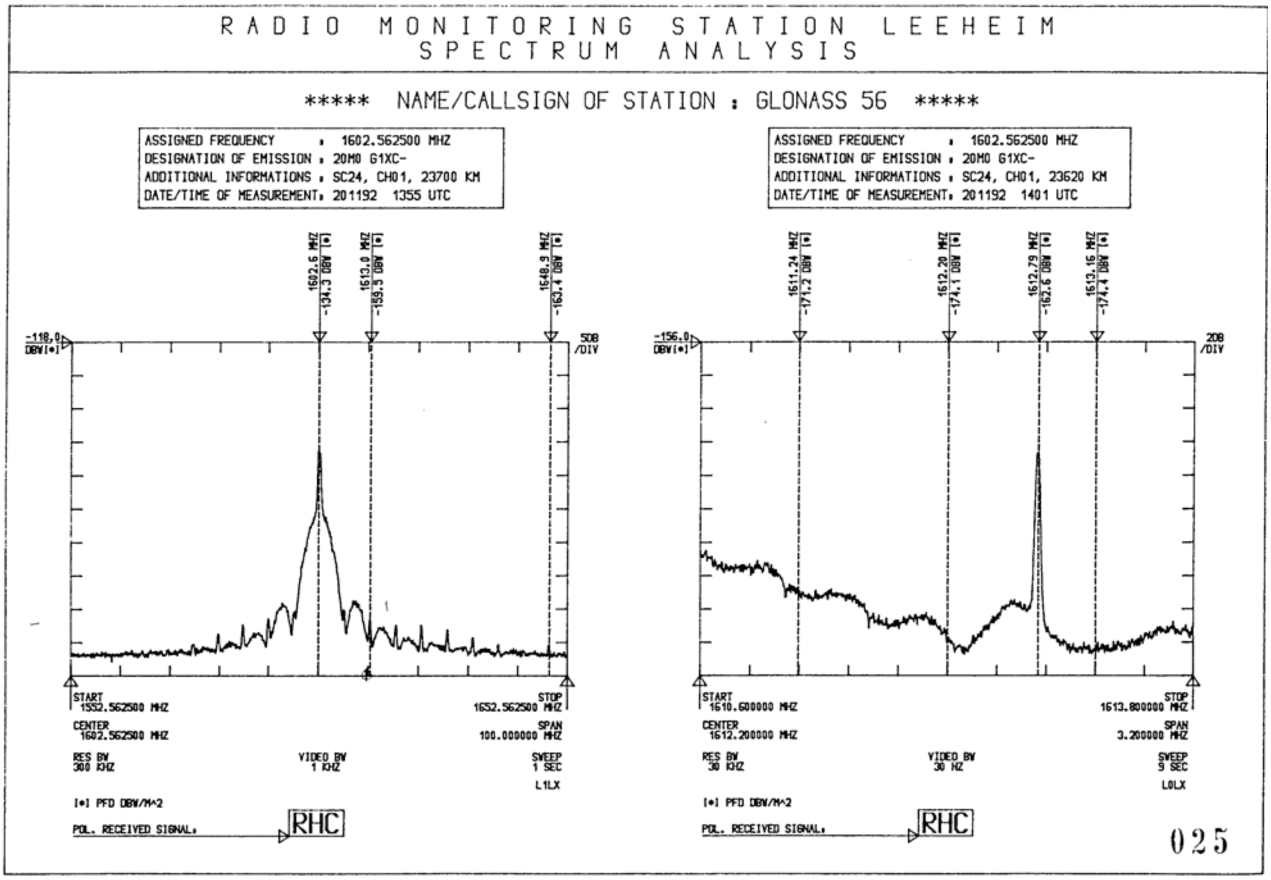
3. As soon as practicable, the GLONASS system employ filtering above the first sideband of the highest frequency channel used.

4. Radio observatories continue to monitor the effects of GLONASS emissions in the radio astronomy bands, in order to assist in the evaluation of changes made to the GLONASS system.

5. IUCAF representatives and the GLONASS administration continue their efforts to find an equitable solution to the interference problem.

The following members of Working Party 7D participated in the evaluation:

Willem Baan (Arecibo Observatory, USA), Yuri Borodaenko (Russian Space Agency, Russia), R. James Cohen (University of Manchester, Jodrell Bank, United Kingdom), Robert Cooper (Radiocommunications Agency, United Kingdom), Tomas Gergely (National Science Foundation, USA), Hans Kahlmann (Netherlands Foundation for Research in Astronomy, The Netherlands), Robert S. Roger (Dominion Radio Astrophysical Observatory, Canada), Klaus Ruf (Max Planck Institut für Radioastronomie, Germany), A. Richard Thompson (National Radio Astronomy Observatory, USA), John B. Whiteoak (Australia Telescope National Facility, Australia).



RADIO MONITORING STATION LEEHEIM
SPECTRUM ANALYSIS

***** NAME/CALLSIGN OF STATION : GLONASS 56 *****

ASSIGNED FREQUENCY : 1602.562500 MHZ
DESIGNATION OF EMISSION : 20M0 G1XC-
ADDITIONAL INFORMATIONS : SC24, CH01, 23700 KM
DATE/TIME OF MEASUREMENT: 201192 1355 UTC

START 1552.562500 MHZ
STOP 1652.562500 MHZ
CENTER 1602.562500 MHZ
SPAN 100.000000 MHZ
RES BW 300 KHZ
VIDEO BW 1 KHZ
SWEEP 1 SEC
L1LX
[*] PFD DBW/M^2
POL. RECEIVED SIGNAL: RHC

ASSIGNED FREQUENCY : 1602.562500 MHZ
DESIGNATION OF EMISSION : 20M0 G1XC-
ADDITIONAL INFORMATIONS : SC24, CH01, 23620 KM
DATE/TIME OF MEASUREMENT: 201192 1401 UTC

START 1610.600000 MHZ
STOP 1613.800000 MHZ
CENTER 1612.200000 MHZ
SPAN 3.200000 MHZ
RES BW 30 KHZ
VIDEO BW 30 HZ
SWEEP 9 SEC
L0LX
[*] PFD DBW/M^2
POL. RECEIVED SIGNAL: RHC

025

Figure 1. Power flux density of emissions from GLONASS spacecraft number 24 as measured by the Leeheim Monitoring Station during the joint experiment. The left hand panel shows measurements made over a 100 MHz bandwidth centred on the assigned frequency of the satellite emissions, with a resolution bandwidth of 300 kHz. The centre frequency of the satellite emissions was 1602.5625 MHz in this case. The right hand panel shows the power flux density falling in the radio astronomy band 1610.6 – 1613-8 MHz, measured with a resolution bandwidth of 30 kHz. The peak pfd level of the emissions in the radio astronomy band is –212 dBWm^{-2}Hz^{-1}, which lies well above the threshold for harmful interference to single telescope spectral line measurements (-238 dBWm^{-2}Hz^{-1}), but below the threshold for harmful interference to very-long-baseline interferometry (-208 dBWm^{-2}Hz^{-1}), as given in Recommendation 769, Tables 2 and 3.

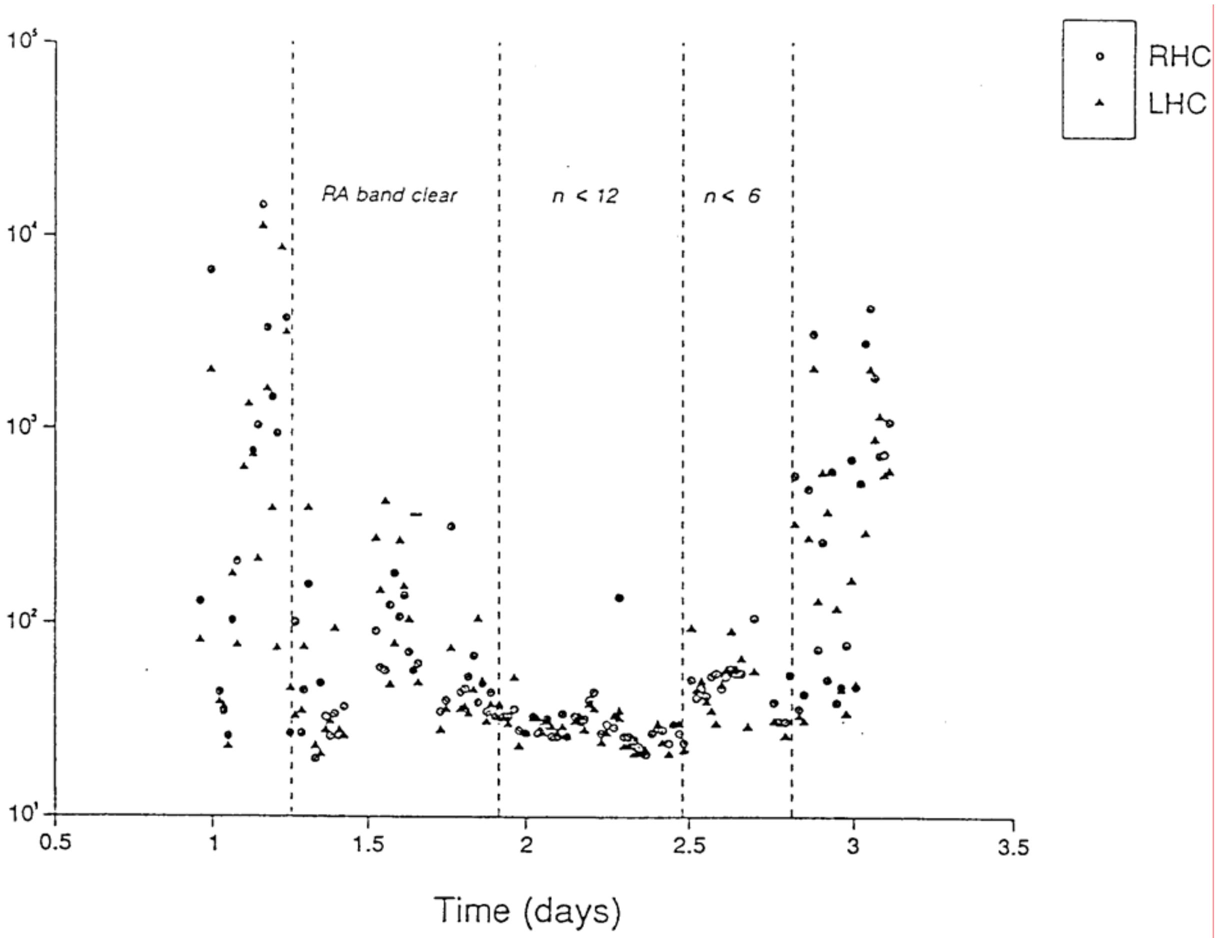


Figure 2. The effects of the GLONASS emissions on radio astronomy spectral line measurements are shown as a function of time during the course of the joint experiment. The measurements were made at Jodrell Bank, with a resolution bandwidth of 17.3 kHz and an integration time of 1200 s. The quantity RMS3 is the rms noise level in the measurements after subtracting a third order polynomial baseline. The rms noise was measured across those parts of the radio astronomy band believed to be free of spectral line emission from the astronomical source. Data for LHC and RHC are shown separately. The different phases of the experiment are indicated by the dashed vertical lines. Phase 2 corresponds to n ≤ 6. The rms noise decreased by 20 dB during phases 2 and 3 of the joint experiment. Note that the receiver noise increased by 3 dB when the galactic centre was observed at times 1.5 – 1.7 day and 2.5 – 2.7 day, so the rms noise values at these times were also increased by 3 dB.

Appendix B: GLONASS-IUCAF Agreement
(presented to WRC-93 as document CMR-93/43-E)

AGREEMENT

between the GLONASS Administration and IUCAF concerning frequency usage by GLONASS-M and the Radio Astronomy Service

The delegation of the GLONASS Administration and the delegation of the Inter-Union Commission on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), meeting in Moscow on 2-4 November 1993,

Considering

- the conclusions of their meetings in Moscow in October 1991, June 1992 and November 1993;
- the results of the Joint GLONASS-Radio Astronomy Experiment in November 1992, and the technical evaluation of the experiment by Working Party 7D of the Radiocommunication Sector of the ITU in April 1993;
- the organizational and technical measures implemented by the GLONASS Administration in September 1993;
- the bilateral agreements reached in September 1993 between the administration of the Russian Federation and the administrations of Australia and Japan, and the summary record of the meeting in October 1993 between the administrations of the Russian Federation and the United States of America;

and noting

- the impact of the GLONASS-M satellite system on radio astronomical measurements in the bands 1610.6-1613.8 MHz and 1660-1670 MHz, and the continuing implementation of the GLONASS-M satellite system; and
- the technical difficulties in achieving electromagnetic compatibility between the GLONASS-M system and the Radio Astronomy Service;

agree that:

1. the GLONASS Administration shall continue to exclude the main emission of the 1M02G7X class (GLONASS: narrow band) from the band 1610.6-1613.8 MHz, and from 1999 will exclude the main emission of 10M2G7X class (GLONASS-M: broad band);
2. during the period 1994-1998 filters will be installed on the newly developed GLONASS-M spacecraft to reduce the levels of out-of-band emissions in the frequency band 1660-1670 MHz below the levels specified in CCIR Report 224;

3. the GLONASS Administration undertakes to communicate to IUCAF any changes in the orbital parameters and frequencies of the GLONASS system, as soon as practicable, in order to assist in the planning of radio astronomy observations to avoid the interference caused by GLONASS.

4. IUCAF undertakes to communicate information on the GLONASS system to the radio astronomy community, to advise the radio astronomy community on optimal times to observe, and to coordinate further joint experiments as needed to evaluate the compatibility of the GLONASS system with the Radio Astronomy Service. The coordination will be done by the IUCAF coordinator at Arecibo Observatory in the first instance;

5. GLONASS Administration undertakes to investigate the optimal assignment of frequencies among the GLONASS-M satellites, within the constraints of existing technical limitations, so as to minimize the impact on the radio astronomical observations;

6. the GLONASS administration agrees to investigate the ways of reducing out-of –band emissions in the frequency band 1610.6-1613-8 MHz to the levels indicated in CCIR Report 224, and to communicate their proposed solution of this problem at a future meeting;

7. a solution of the interference problem caused by the main emission of class 10M2G7X and out-of-band emissions of GLONASS transmitters in the frequency band 1610.6-1613.8 MHz will be achieved only if the frequency plans of the GLONASS-M systems are modified. IUCAF agrees to assist in the coordination of the necessary changes with the interested administrations and with the ITU.

Both delegations believe that the implementation of the above agreements is a sufficient basis to achieve compatibility between the GLONASS system and the Radio Astronomy Service, and that coordination between GLONASS, GLONASS-M and the Radio Astronomy Service is possible. This information shall be communicated to the ITU and to interested administrations within one month.

The agreement is written in Russian and in English, and both versions have equal standing. The agreement will come into force at the moment of signing.

On behalf of the GLONASS Administration	On behalf of IUCAF
General Vladimir I. Durnev	Dr Willem A. Baan
Head of GLONASS delegation	Head of IUCAF delegation

Moscow, 4th November 1993

Interference in VLBI Observations

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Abstract

This lecture addresses the effects of interfering signals on the specific observational technique known as Very Long Baseline Interferometry, VLBI. Sections 1 and 2 present some background on interferometry in general, and on VLBI, which will be essential to an understanding of the impact of interference in these techniques. The purported "immunity" of VLBI observations to interference, an essential point that applies in both practical and regulatory senses, is then discussed in Section 3. The special regulatory status that has been assigned to VLBI as a result is considered in Section 4. The lecture concludes in Section 5 by describing the impact of interference on some of the auxiliary measurements essential for calibration of VLBI results.

1. Interferometry

Operating in the long-wavelength region of the electromagnetic spectrum, radio astronomy has been driven since its inception by a quest for higher angular resolution. Practical limits on the size of single, filled-aperture telescopes led quickly to the development of interferometric observing systems, in which a large effective aperture is "synthesized" by combining signals from multiple smaller filled-aperture elements. This technique increases both the total collecting area of the instrument, and the angular resolution. The latter aspect led to the development of VLBI, and will be emphasized here. The angular resolution achieved by an interferometer system is inversely proportional to the maximum geometric extent of the array of individual elements.

An essential detail of an interferometer's operation is that signals from the individual elements must be shifted in delay and phase to re-align the wavefronts arriving from the desired direction, before the signals can be combined. This has the effect of dispersing and washing out interfering signals arriving from any other direction. Thus, the angular-resolution scale to which the interferometer is sensitive is also the range of directions about the observed source from which interference can have a direct impact.

Indeed, an interferometer can be said to be even less sensitive to interference than a filled-aperture telescope with the same synthesized beam. The reason is that the angular discrimination just described applies at *all* frequencies (albeit with varying effectiveness). Single-dish telescopes, in contrast, are also affected by interference received directly into their electronic signal channels. This interference can arrive from directions far outside their main antenna beam.

2. VLBI: Very Long Baseline Interferometry

VLBI is simply the extension of the interferometric technique to continental or global distance scales. This technique was developed in the 1970s. NRAO operates the world's only dedicated VLBI instrument, the Very Long Baseline Array, VLBA. Other VLBI arrays, both formally and informally organized, also exist on a part-time basis.

The large distances intrinsic to VLBI require two specialized implementation details. First, the distances and bandwidths are (currently) too great to transmit the observed signals to the central correlation site in real time. Instead, the signals must be recorded, with precise time tags; the recorded media are shipped in bulk to the correlation center, where the signals are later reproduced from the recordings. Further, and similarly, the distances are also too great to transmit the reference signal that allows all interferometer elements to observe precisely the same band of frequencies. Each antenna must have its own independent, precise frequency standard, which in current practice is typically an atomic clock such as a hydrogen maser.

Since the individual antennas operating as part of a VLBI array generally require a full complement of a typical radio observatory's infrastructure, they are usually referred to as "stations". This usage will be followed henceforth in this lecture.

3. Interference "Immunity" of VLBI

The fundamental consideration that makes VLBI observations unique with respect to interference also arises directly from the large distances separating the stations: interfering signals almost always are independent at the individual stations. This is true whether the interference arises from a local, ground-based source, from an aircraft, or even from a satellite. (A few exceptional cases are noted below.)

Such independent interference signals generally do not appear in the VLBI interferometer's output. One reason is shared with local or "connected-element" interferometers: signals arriving from directions offset from the observed radio source by more than an angular-resolution scale are dispersed or washed out in the interferometer instrumentation. But perhaps more fundamentally, the independent interference signals are not correlated with each other, unlike the signals that arrive at the different stations from the radio source.

The principal exception to this "immunity" occurs when the interference is sufficiently strong that the gain of the receiving system is compressed. In such a case, the VLBI output signal would be reduced without (in the absence of specialized measures) a corresponding increase in the calibration factors. It is also possible in principle, but unlikely, that simultaneous, coherent (i.e., non-independent) interfering signals could arise from certain satellite systems; one such event actually may have been observed.

4. Regulatory Status of VLBI

The fundamental ITU Recommendation on "Protection Criteria Used for Radioastronomical Measurements", the famous Rec. RA.769, recognizes that some interference immunity exists even for local, connected-element interferometers:

> ... compared to a single radio telescope, the interferometer has a degree of immunity to interference which, under reasonable assumptions increases with the array size expressed in wavelengths.

However, Rec. 769 recommends special treatment only for VLBI:

> The greatest immunity from interference occurs for interferometers and arrays in which the separation of the antennas is sufficiently great that the chance of occurrence of correlated interference is very small (e.g. for very long baseline interferometry (VLBI)).

and specifies an alternative level of protection:

> The tolerable interference level is determined by the requirement that the power level of the interfering signal should be no more than 1% of the receiver noise power.

These levels, specified in terms of SPFD, are 40-55 dB higher than for non-VLBI observations.

The few other ITU Recommendations that specifically mention VLBI only apply to very special cases, such as Space VLBI (observations using one – or in principle more – radio telescopes in space) or the Shielded Zone of the Moon.

A special regulatory concept of VLBI *observatories*, derived from the RA.769 category of VLBI *observations*, appears in some other ITU documents. These are observatories that perform *only* VLBI observations; so far, this class is limited to the ten stations of NRAO's VLBA instrument. (Some other VLBI-only stations do exist, but do not operate in any bands allocated to the Radio Astronomy Service.) This distinction is significant only with respect to the site-dependent protection agreements that are becoming increasingly common. In such agreements, VLBI observatories are entitled only to the protection levels specified for VLBI in RA.769.

5. Impact of Interference on VLBI Calibration

Several types of calibration and other auxiliary measurements must be performed by treating the stations of a VLBI array as individual antennas. Most important among these are measurements of antenna gain and pointing. To a large extent, such measurements can be – indeed, often must be – done in ways that mitigate any possible adverse effects of interference, by observing relatively strong sources and by observing at nearby frequencies free of interference.

An important exception is the "template method" of gain calibration sometimes used in observations of spectral lines. This approach monitors the strength of emission or absorption features in the total-power spectrum from each individual station. It is useful when the gain cannot be measured directly at all, for example when small antennas or low-sensitivity receivers must be used, or when only weak sources are available. Another common application is the case of unstable gain caused by pointing errors, typically at high frequencies where an antenna's performance becomes marginal. Successful application of the template method, however, requires that the total-power spectra be free of interference.

The template method was essential in the early days of VLBI, when many of the conditions mentioned above actually prevailed. Modern VLBI arrays have largely eliminated this necessity for routine observations, but the method remains useful in extreme cases, which typically occur at the forefronts of the VLBI technique.

MITIGATION TECHNIQUES,

MITIGATION FACTORS –

What are they? What are they good for?

Klaus Ruf

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1. Introduction

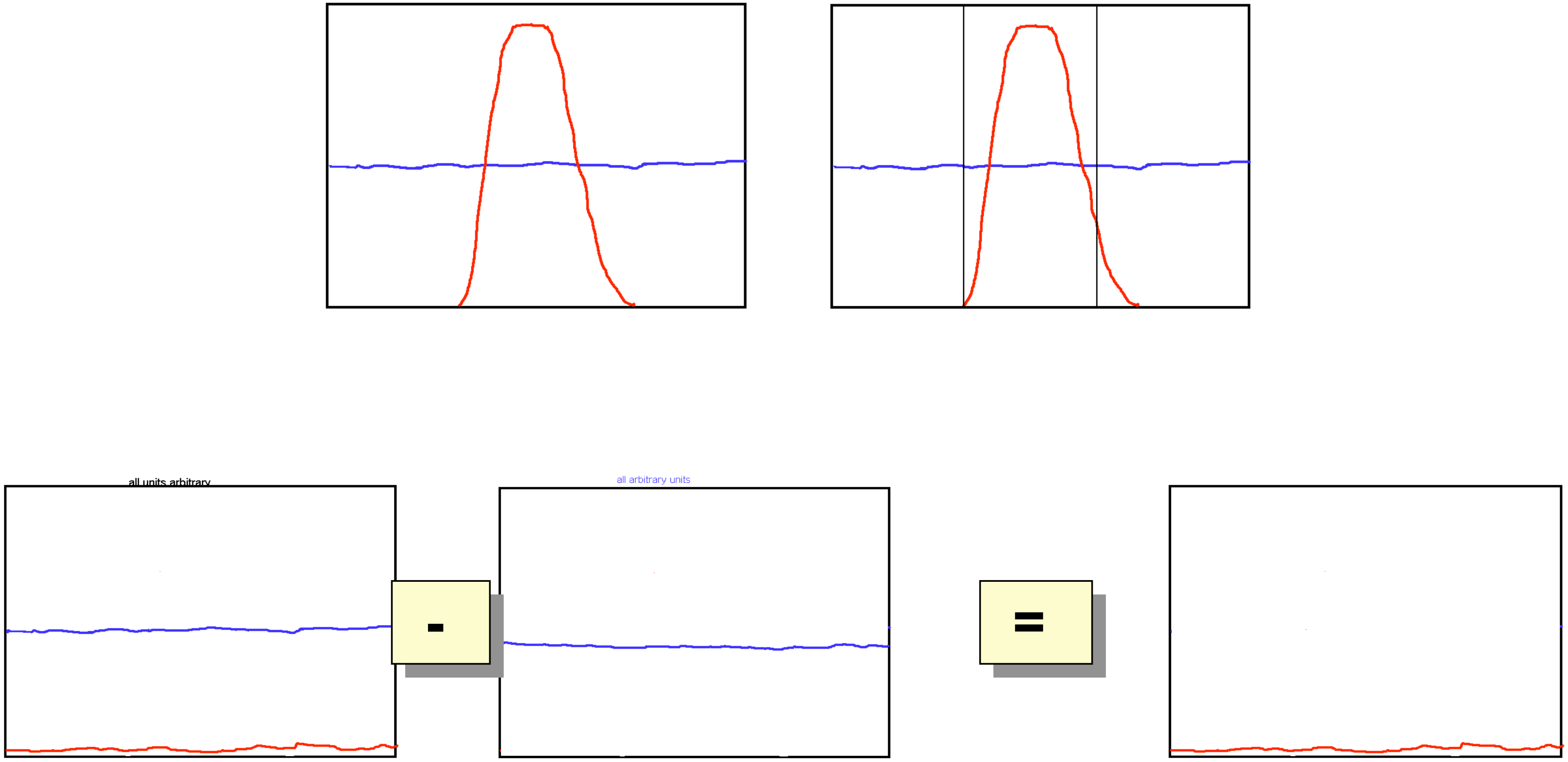
RFI can be a problem for active (i.e. transmitting) radio services, as well as for passive, receive-only services. Methods and techniques are being developed to suppress RFI or mitigate its effects on the victim service. The range of technical and operational measures that can be taken is very large.

As the spectrum is more and more crowded, and interference is becoming difficult to avoid completely, account must now be taken of mitigation factors when new radio services or applications are planned and coordinated with existing services or stations. However, the creativity of the proponents of a new service in inventing mitigation factors, which make their service invisible to others and immune against interference caused by others, sometimes seems to be unlimited. Radio astronomy, with its high sensitivity and consequent stringent protection criteria, is often asked to apply mitigation techniques in order to allow more efficient use of the spectrum. It may then be necessary to point out and demonstrate that radio astronomers have developed quite sophisticated receivers and observing methods, and that without these techniques radio astronomy would no longer be able to exist. We simply didn't in the past include these developments under the "mitigation techniques" rubric.

2. Mitigation Techniques

Radio astronomical signals are normally very weak and cannot be made louder by man. The noise power received from the atmosphere, after being augmented by the receiver noise, exceeds the power received from the cosmic source, sometimes by several orders of magnitude. In consequence it is only the development of very sensitive and stable radiometers that makes the detection and analysis of cosmic radio signals possible. In fancy speak: the mitigation techniques of switched receivers and time integration reduce the effect of interfering atmospheric and receiver noise to such an extent that radio observatories may maintain sufficient link margin when looking at faint cosmic radio sources, to have a satisfactory overall probability of service availability.

Fig. 1: (a) In the commercial world it is often appropriate to reduce the bandwidth to improve the signal-to-noise ratio;
(b) In radio astronomy it is usually necessary to increase bandwidth to improve the signal-to-noise ratio.



Cosmic radio sources emit a radio continuum, and radio astronomers try to pick up as much bandwidth of it as they can. Some active radio service engineers tell us that they reduce the bandwidth in order to increase the signal-to-noise ratio, and some of them advise us to use the same mitigation technique. It takes time and normally a piece of paper and a pencil (see the example in Fig. 1) to explain that for us observing a larger bandwidth is the mitigation technique that reduces the noise power fluctuation (not the noise power itself) to a level where the additional power introduced by the observed cosmic source becomes detectable.

Integrating over time works in the same direction and these two techniques have been in use for radio astronomical observations for a long time. In addition many other techniques have been developed by radio astronomers too without labelling them as "mitigation techniques", such, for instance, as

- observing over a large bandwidth
- integrating for a long time
- using ultra-stable receivers, e.g. switched receivers
- developing various kinds of sophisticated observing modes
- developing very high gain antennas
- going to high altitude (desert) sites
- going to very remote sites and/or radio quiet zones

Hence the preliminary conclusion: there is nothing wrong with mitigation techniques.

3. Mitigation Factors

Mitigation factors are the effect of the application of mitigation techniques, when expressed in dB, that can be added to our protection criteria, though this is not an official definition. What factors have been proposed?

For radio astronomers, mitigation factors are coupled with the machinations of Iridium (not the chemical element ^{77}Ir, but the 66 satellite constellation IRIDIUM™). This satellite system, which was proposed by Motorola in the late 80s, was allocated a band by WRC-92 in the vicinity of a secondary allocation to radio astronomy, after guaranteeing full protection of radio astronomy observations. WRC-92 was careful enough to upgrade the radio astronomy allocation to primary and to leave the satellite down link allocation as secondary. In addition a new footnote was added to the Radio Regulations, which explicitly states that harmful interference shall not be caused to radio astronomy by the mobile satellite service operating in the band in question.

After obtaining their wished for allocation, IRIDIUM replaced deploying the technical means needed to protect radio astronomy by intense lobbying and negotiation. It must have appeared cheaper to them to send a negotiating team around the world for a long time armed with a number of technical and legal studies, rather than to install a large number of filters in their active antennas. The hidden cost of a polluted spectrum would not spoil the IRIDIUM budget.

What mitigation factors have been proposed and what has happened to them?

The protection criteria for radio astronomy are defined, and flux density limits for most of the radio astronomy bands are listed in Recommendation ITU-R RA.769. These are based on an antenna gain of 0 dBi in the direction of the interfering source. The underlying antenna model reaches 0 dBi at an angular separation of 19 degrees from the pointing direction of the antenna and -10 dBi at an angular separation of 48 degrees from the main beam direction and beyond. The assumption of 0 dBi gain towards the interfering source is quite reasonable in the case of terrestrial transmitters sharing a frequency band with radio astronomy, because radio telescopes are normally pointed towards the sky rather than towards the Earth or horizon. Avoiding a source of interference, such as a distant TV transmitter, may be an operational restriction that can be done if necessary. Satellites, however, transmit down from the sky, with line-of-sight conditions to a radio telescope. It is pointed out at several places in the Radio Regulations that satellites may be particularly dangerous sources of interference to radio astronomy.

Nevertheless, IRIDIUM told us that, because their satellites move across the sky, most of the time they are seen by a radio telescope in the negative gain region. And as they pass over the sky quite rapidly, an individual satellite may not remain in the near-sidelobe/elevated gain region relative to a radio telescope long enough to cause interference. The protection criteria for radio astronomy, developed in ITU-R Recommendation RA.769, assume an integration time of 2000 seconds to be spent on a weak source. If the satellite flies through the nearby sidelobe pattern of the radio telescope in 20 seconds, for instance, the excess power it delivers to the radio telescope receiver shall be stretched out by a factor of 100 in order to assess the interference impact on a 2000 second measurement. Additionally, antennas used for radio astronomical measurements can in principle be improved in a sense when the sidelobe pattern becomes narrower and its negative gain region wider and deeper. These factors, plus a few more so called mitigation factors, make satellites in low Earth orbit less dangerous for radio astronomy than fixed transmitters on Earth. This at least is the conception of LEO satellite operators such as IRIDIUM. It must be pointed out here, that the interfering signals are not the main transmissions, but unwanted and unnecessary emissions that can be avoided to a great extent by technical means.

What happened to these factors?

They have all been adopted by ITU-R Working Party 7D (radio astronomy), together with a few others, such as the tolerable data loss to interference, and the minimum elevation angle for observations.

What other factors exist and what will be the effect of their implementation?

Within ITU-R Study Group 1 a recommendation “Protection of Passive Services from Unwanted Emissions" has been developed that lists the following factors as potentially applicable to radio astronomy:

- Site shielding and site selection
- Quiet zones and coordination zones
- Receiver architecture
- Antenna patterns
- Analogue filtering at either RF or IF stages
- Interference excision techniques
- Digital adaptive interference cancellation
- Adjustment of sensitivity levels
- Cooperative solutions
- Guard bands

All these factors would cost money and/or sensitivity to implement.

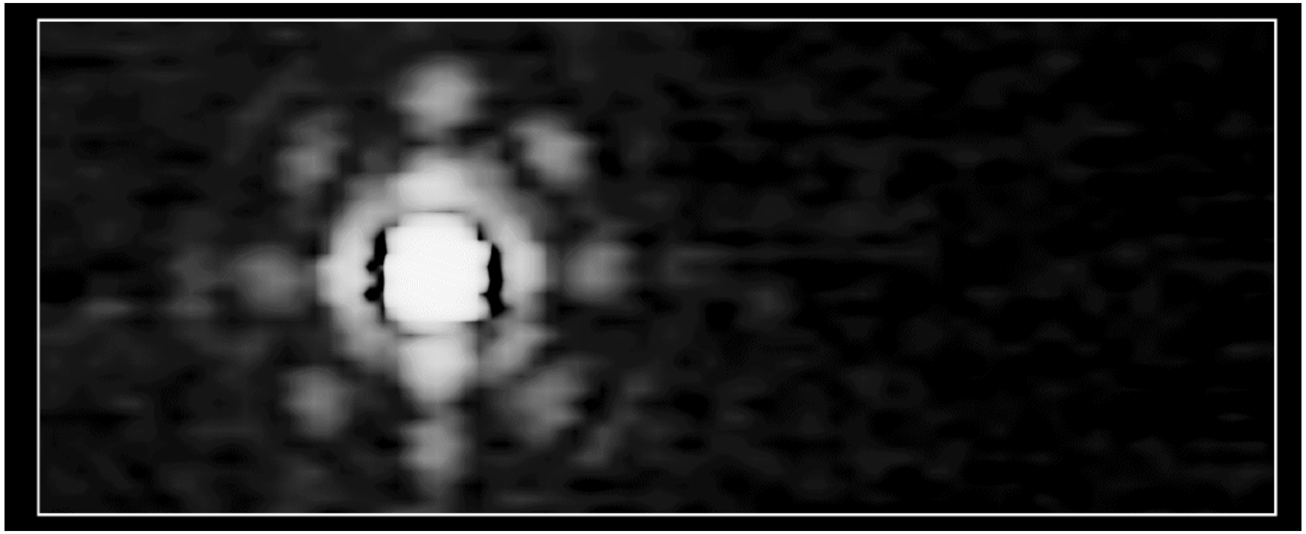


Fig. 2: The beam pattern at 10.6 GHz of the Effelsberg 100 m radio telescope, towards 3C84. field size: 30' x 12', flux 20.5 Jy (~ -247 dB(W m^{-2} Hz^{-1})).

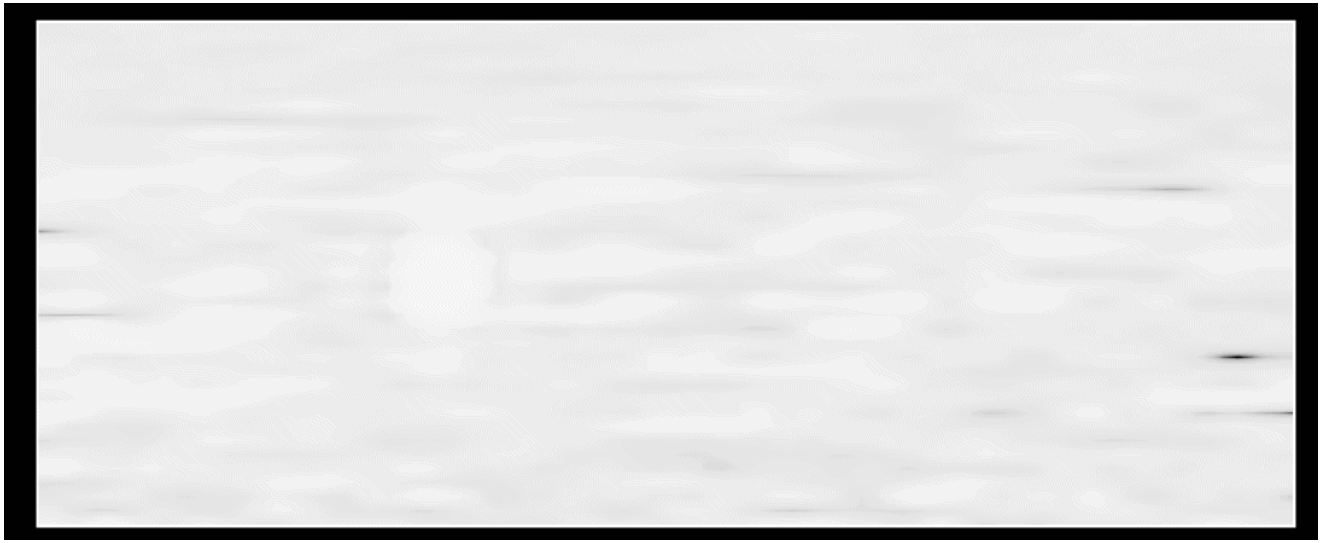


Fig. 3: The same field, with the same source, 3C84, as Fig. 2, 10 degrees away from the satellite.

Radio telescopes are known to be very large on average, and the possibility of *site shielding* is accordingly restricted given that – unlike many satellite Earth stations - radio telescopes are set up to observe the whole sky. *Site selection* can provide shielding from ground transmitters, if terrain is found with the right morphology, though mm-wave telescopes do need to be set up on high mountains in dry areas, which normally precludes factoring shielding effects into their site selection. While *quiet zones* can be very effective, only a few exist, and radio astronomy depends on a large amount of good-will to obtain such protection even if population density allows it. And neither site shielding with coordination nor quiet zones per se stop satellite transmissions. *Robust receiver architecture* is employed to make radio astronomy receivers immune to strong transmitters in frequency bands close to the observed frequency. But receiver linearity cannot be sacrificed at the expense of sensitivity. Radio astronomy antennas are large, in order to achieve high gain/discrimination, and they should be able to operate over a large frequency range. This limits the possibilities for improving their *antenna patterns*. It is only very recently that offset feed and adjustable-surface designs have been developed with the potential for reducing side lobes and scattering, though existing radio telescopes cannot profit from these developments. *Analogue* as well as *digital filtering* is widely used, but has the potential to reduce sensitivity. *Interference excision techniques*, such as *digital adaptive interference cancellation*, are under study and promise much future development; though they generally make the operation of radio telescopes more complex, and incur new dangers such as the automated suppression of the searched-for signal. *Adjustment of sensitivity levels* always goes in the wrong direction, as sensitivity is usually increased as much as possible in order to be able to detect weak sources, and should not be lowered in order to allow higher interference levels. *Cooperative solutions* have, since the days of IRIDIUM, the unpleasant smack of endless negotiation and time sharing or interference allowance being forced upon radio astronomy stations. And finally *guard bands* are considered a waste of precious spectrum, at least if commercial satellite services are affected. So while all of the proposed mitigation factors can help and are used as much as is viable, it is not true that they individually or in combination can solve all interference problems.

4. Some practical examples

4.1 Bad ones first

Figure 2 is an observation of the strong point source 3C 84, using the 100 m radio telescope at Effelsberg in Germany, in the radio astronomy frequency band 10.6 - 10.7 GHz. The structure visible in the figure is due to the beam pattern of the antenna, and is not the structure of the source. One day a TV satellite was switched on using the edge channel of the neighbouring frequency band. From that day on all of the sky visible from Effelsberg, and from all other European radio telescopes, was as bright at 10.6 - 10.7 GHz as a sunny day is at optical frequencies. Figure 3 shows the strong source, resembling the full Moon seen on a clear day.

Mitigation techniques, mitigation factors?

We are sure that a guard band would help here, because other TV satellites have been active before within the same satellite frequency band, but in higher channels. However the application of this mitigation technique was refused by the

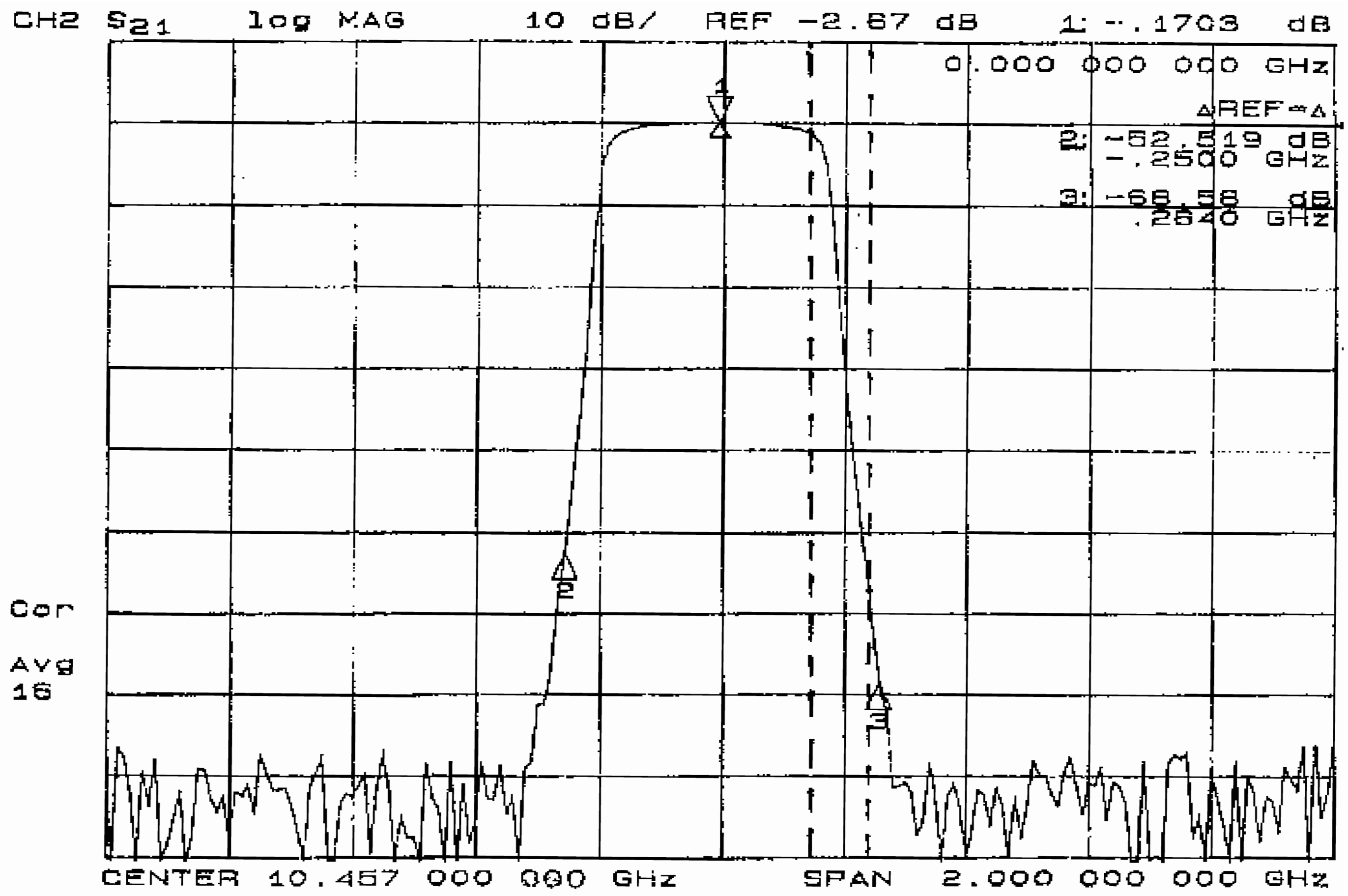


Fig. 4: A scan across one of the 10.7 GHz filters deployed to put 70 dB of attenuation between the receiver and the satellite TV channel. The radio astronomy band, shown dotted, is entirely consumed within the rolloff of the filter as guard band. Marker 1 is at -0.17 dB, marker 2 at -62.22 dB, and marker 3 at -80 dB.

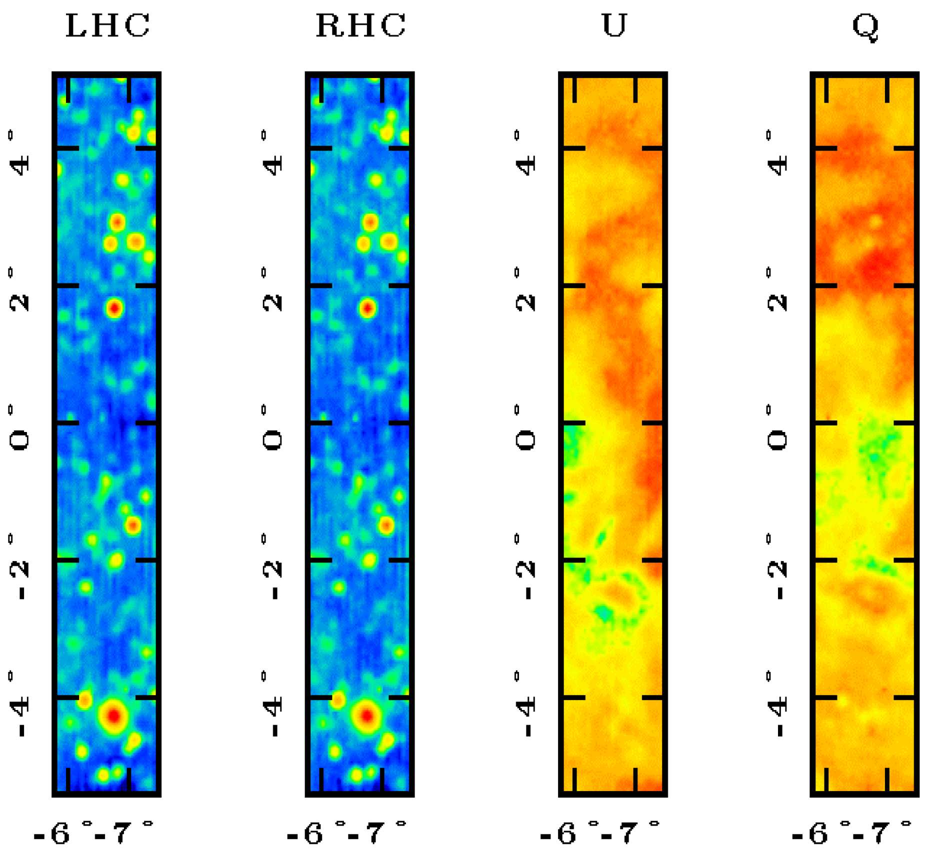


Fig. 5: An Effelsberg 1395 MHz, map of a piece of sky using a 14 MHz bandpass, simultaneously in both left and right circular polarizations, together with the resulting Stokes U & Q maps. The observation was made on 12 February2002, at UT 20.23 Ö 21.44.

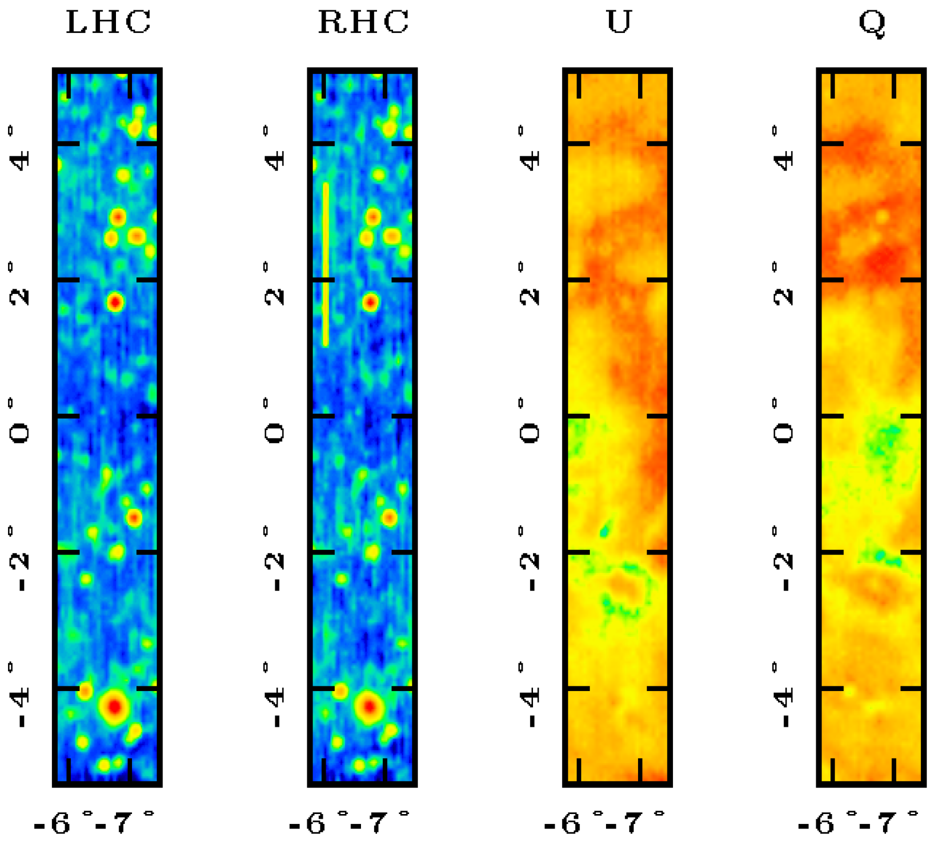


Fig. 6: An Effelsberg 1408 MHz, map of the same piece of sky and at the same time as that in Fig. 5 using a 14 MHz bandpass, simultaneously in both left and right circular polarizations, together with the resulting Stokes U & Q maps. But note here that interference occurs in just one polarization for 35 s at frequencies inside the radio astronomy band. The integration time was 1 s per pixel.

satellite operator, who used the argument that many, many more antennas are pointed at the TV satellite than at 3C84. So radio astronomers had to employ a combination of analogue filtering and a guard band. Figure 4 shows the filter pass band. It was designed to suppress the TV signal by 70dB, which results in all of the radio astronomy allocation being used (better: wasted) as a guard band, as is indicated in the figure by the dashed lines. So mitigation works in practice, but only as long as the now-observed band, which is not allocated to radio astronomy, is not used more intensively by the fixed and mobile services, which refuse to coordinate their rightful use of the band with parasitic if harmless radio astronomers.

Another important factor is the cost of implementing this mitigation technique. The 10.6 GHz receiving system at Effelsberg is a four-feed-horn, 8-channel system. To enable full use of the capabilities of the system, including precision polarisation measurements, requires not just a filter, but eight identical and matched filters for all channels.

The next example is taken from the Effelsberg 1.4 GHz Medium Galactic Latitude survey (data kindly provided by Wolfgang Reich, MPIfR). Figure 5 shows part of the sky observed at a frequency band just below the radio astronomy 1400 - 1427 MHz allocation, in both left and right hand circular polarisations (Stokes parameters U and Q are derived from that). Figure 6 shows a pair of simultaneous observations within the allocated band. Here interference shows up in only one polarisation: this can be attributed to an experimental time-signal transmitter on the International Space Station, ISS. This transmitter was working outside the ITU Radio Regulations, to put it mildly. Before this interference was reported, the designers of the experiment tried to play with mitigation factors, and even invented a hitherto unknown one: the slant-range attenuation mitigation factor shown in Fig. 7. But the spectrum of the transmitter, which was surprisingly provided in the same attempted compatibility study, looks really lousy, the main transmission overlapping with the edge of the radio astronomy band (RR Footnote 5.340: all emissions are prohibited in the bands: … ,1400 - 1427 MHz,…) together with widespread unwanted emission (Fig. 8). After this interfering signal was reported, the most restrictive and costly mitigation technique of all had to be applied: the transmitter on the ISS had to be switched off!

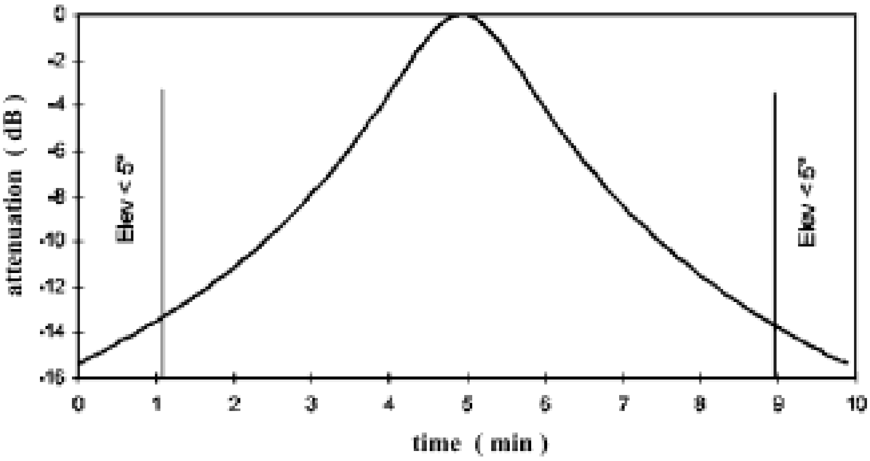


Fig. 7: GTS slant range attenuation during the overhead passage of the ISS.

4.2 But there are also good examples

On January 10th 1999 the alarm bells rang again at the Effelsberg radio observatory. Another new broadcasting satellite had been switched on and destroyed a primary

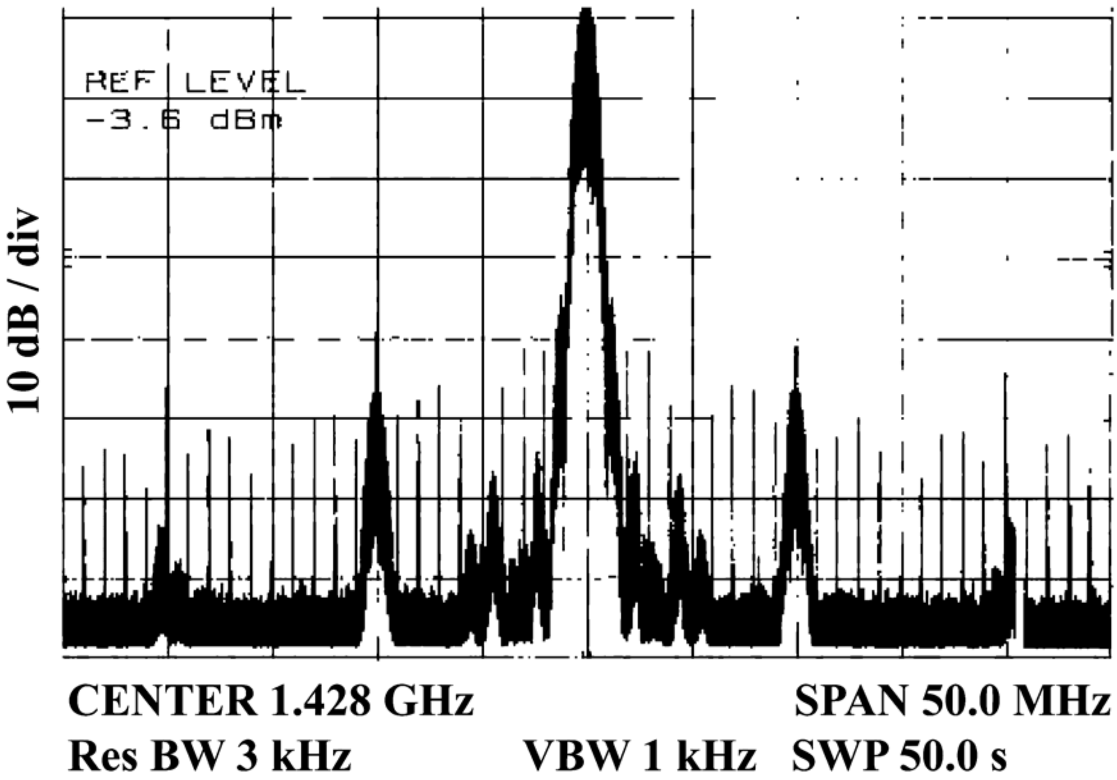


Fig. 8: A GTS transmitter 1.4 GHz Power Spectrum Plot, of 50 MHz span, without a filter.

radio astronomy band. This satellite in transmitting digital audio signals interfered with observations in the 21 cm band, 1400 - 1427 MHz. The situation was not quite as bad as in the 10 GHz case: the observations, while heavily polluted and practically worthless, could still be taken. Figure 9 again shows the left and right hand circular polarisation maps of a section of the sky, though the strong extended feature in the lower left quadrant is interference from an extremely strong cosmic source outside the field of view. This source was easily located and mapped (cf Fig. 10, to reveal even more of the antenna beam pattern than the 3C84 map). The BSS allocation starts at 1452 MHz, with 25 MHz of guard band between BSS and radio astronomy, and the satellite is known to use one of the higher channels within its allocation. A filter could therefore be built into the radio astronomy receiver, with no impact on the observation of the allocated frequency band. With the filter in place, the satellite was now impossible to find when searched for. Figure 11 shows the location in the sky, where the satellite stands, but its spurious emissions into the radio astronomy band are below the realized sensitivity level. To check the pointing accuracy of the telescope, the receiver was switched to the 18 cm (1660 - 1670 MHz) band, and here, as can be seen in Figure 12, the satellite’s unwanted emissions are again a very strong source, though roughly in line with the protection criteria for radio astronomy given in Recommendation ITU-R RA.769. Emissions at the protection level for radio astronomy do indeed correspond to very strong sources. What radio astronomers normally observe, and what makes our science so interesting and challenging, are the much much weaker sources. In this case the standard mitigation technique of filtering, employed at both the transmitter and the radio astronomy station, solved a pseudo-problem, which only appeared to be a problem when filtering was not properly applied.

Perhaps the most striking example of the artistic use of mitigation factors was given by SARA, a consortium of the car and electronics industries. SARA want to

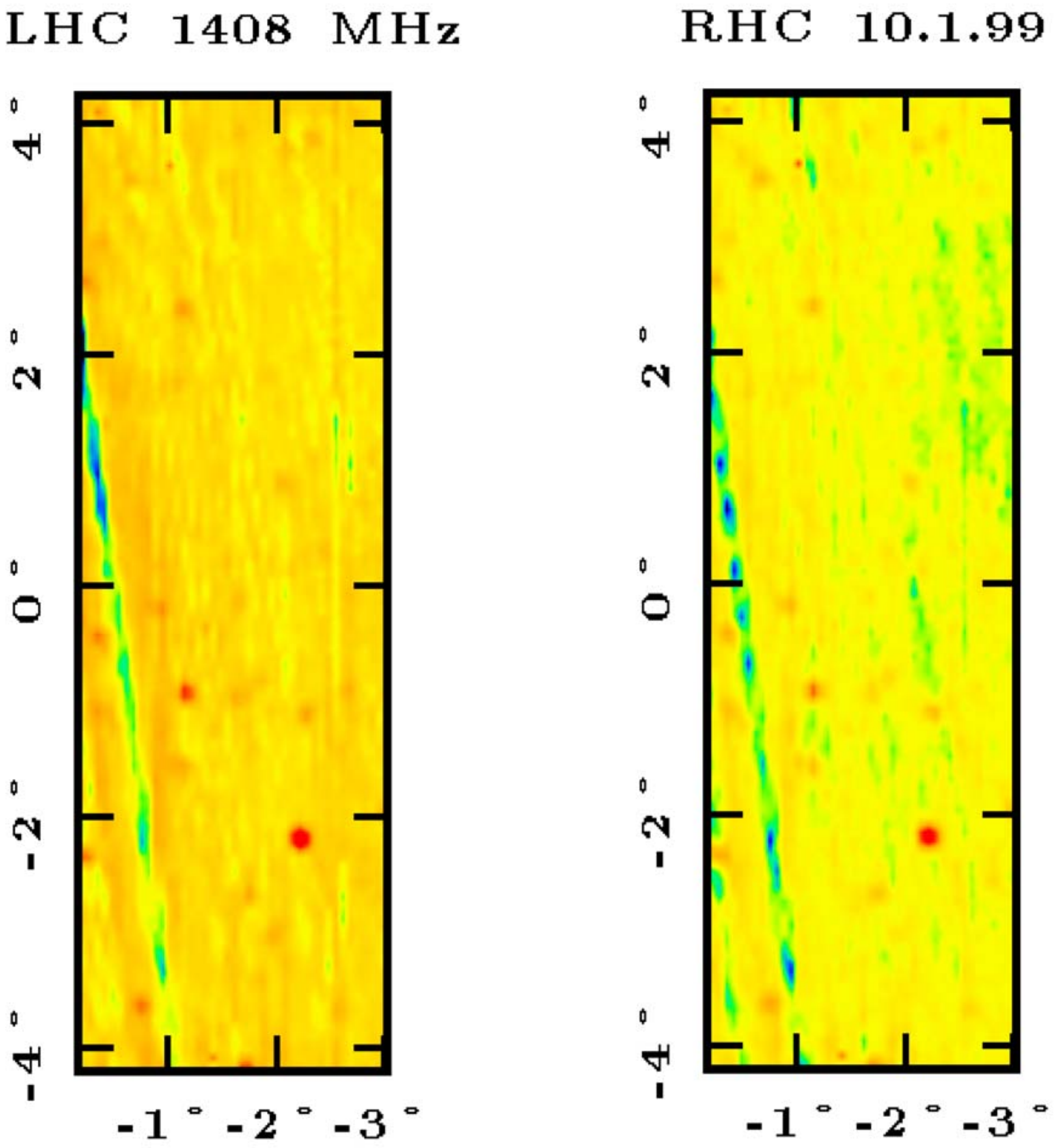


Fig. 9: 1408 MHz LHC & RHC simultaneous maps from Effelsberg.

market a radar system for cars, which is believed to be able to save many thousands of road accident victims from death by monitoring the immediate environment of a car, and actively intervene in braking or steering it when it is on a collision course, by tightening seat belts and preparing or pre-pumping air-bags, as well as by eventually calling the police and ambulance *before* an unavoidable collision takes place. It should be noted that some of the above-mentioned features are yet to be confirmed. However the system plans to use a very wide frequency band, which would cover completely the passive band from 23.6 - 24 GHz (Fig. 13). Footnote RR 5.340 –"all emissions are prohibited…"– applies to this band, but SARA keeps telling us that the transmitted power is so low that it should not be called emission at all. Though it is true that even the reflected signal can be detected with high reliability by very cheap electronic devices, for the rest of us the signal is said to be practically invisible.

Figure 14 is a viewgraph presented by SARA to provide politicians and administrators with the opportunity to pretend, firstly, that they don't understand the technical details, and, secondly, that they firmly believe it has been demonstrated that the risk of harmful interference is minimal.

A joke was circulated many years ago about a man, who talked to his boss and asked for more money. The boss explained to him that he doesn't work at all, and

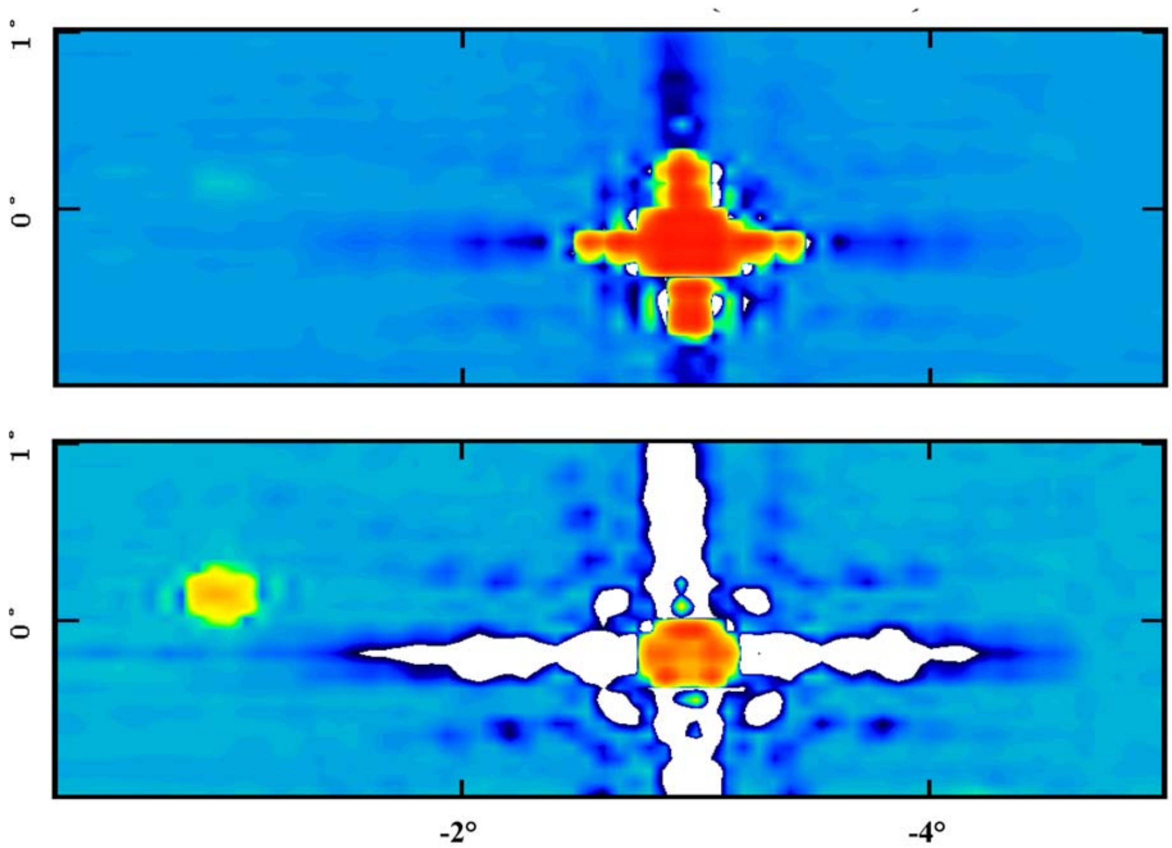


Fig. 10: The LHC (top) and RHC simultaneous maps of AFRISAT without a filter.

explained this in a way that the man couldn't argue against, even though he actually was at work, and, indeed, was at work every day. The trick of the joke was that the boss added together time intervals like sleeping time, weekends, vacations, etc., and subtracted this from the 365 days by 24 hours that a year has. Of course he double-counted much of this time so that in the end the man was working for just 2 days per year, though these days happened to be public holidays. It was a very funny and elaborate joke that seems to have inspired the calculation of mitigation factors presented by SARA.

5. Final Conclusions

- *Mitigation techniques* have been invented by radio astronomers, have always been applied, and still have great potential for future improvement.
- *Mitigation techniques* may be costly and constraining, but radio astronomers need to take the initiative to study and to define what is achievable and at what price.
- *Mitigation factors* are being used to replace the RR!

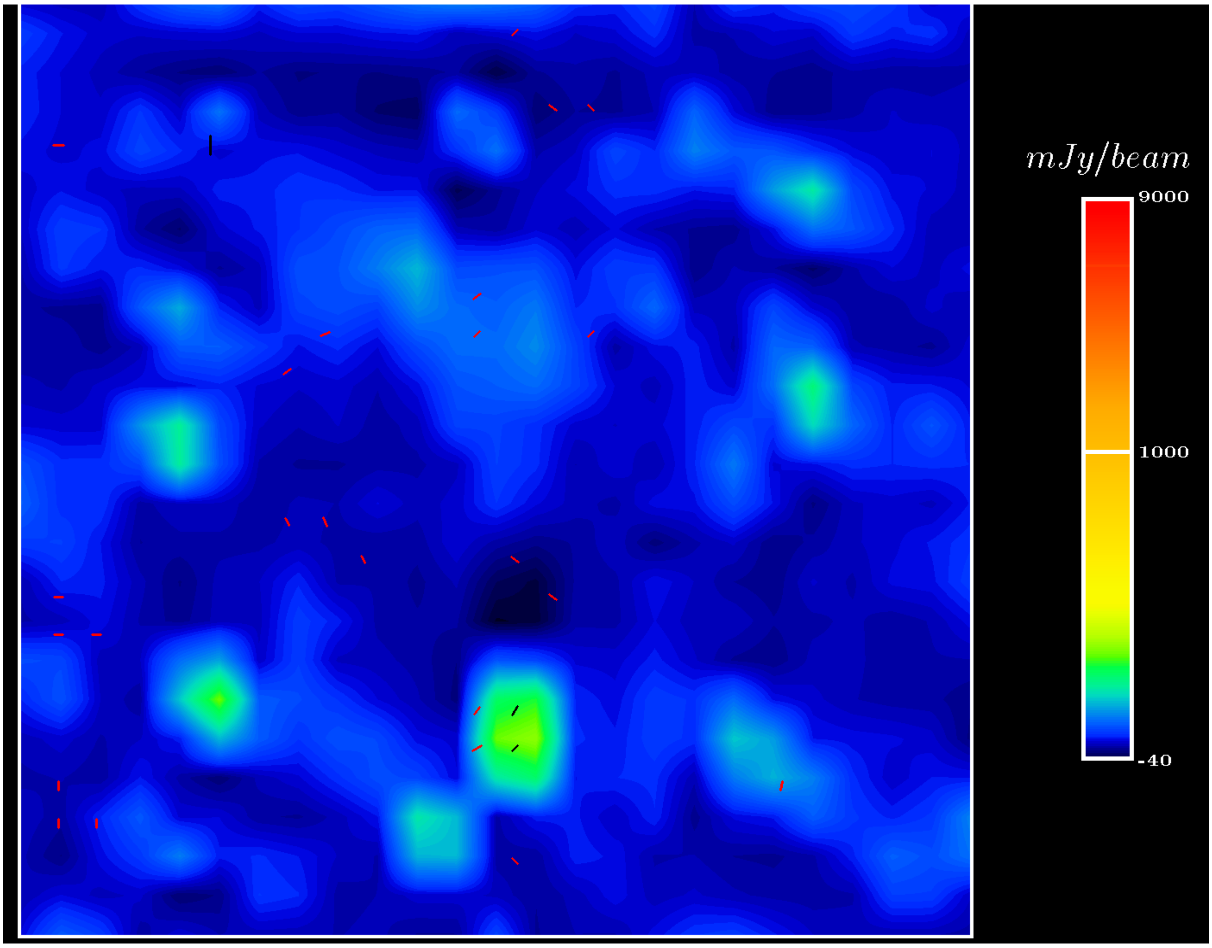


Fig. 11: An Effelsberg 1387 - 1402 MHz map of the location of AFRISAT after the filters have been installed.

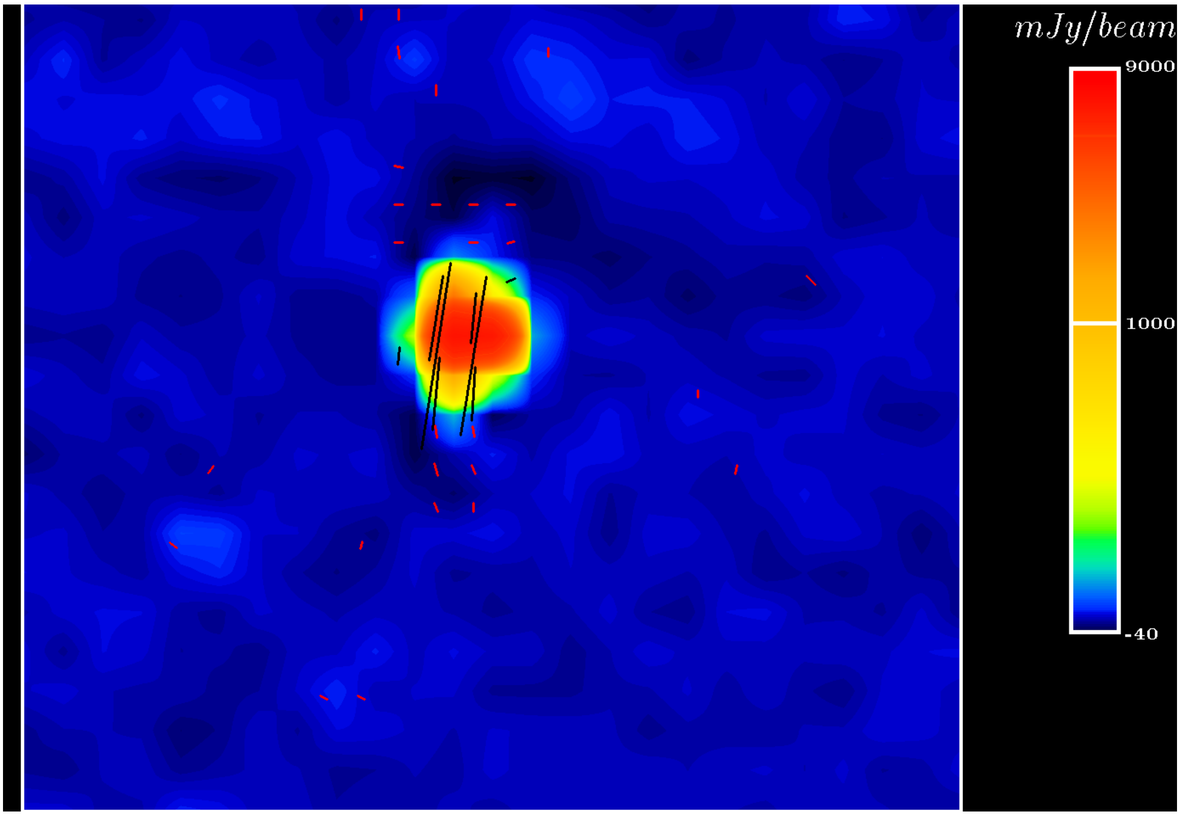
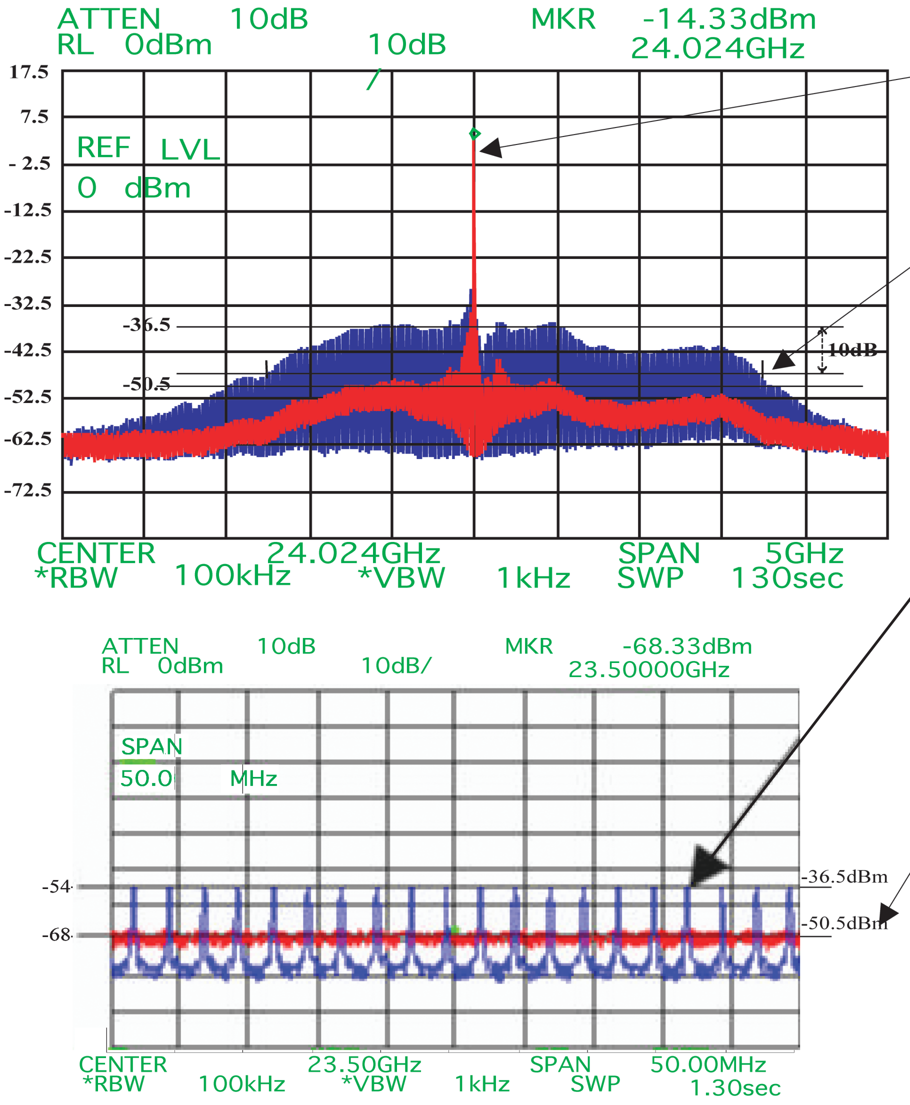


Fig. 12: An Effelsberg 1653 - 1667 MHz map of the location of AFRISAT after the filters have been installed.



Residual carrier due to limited AM index

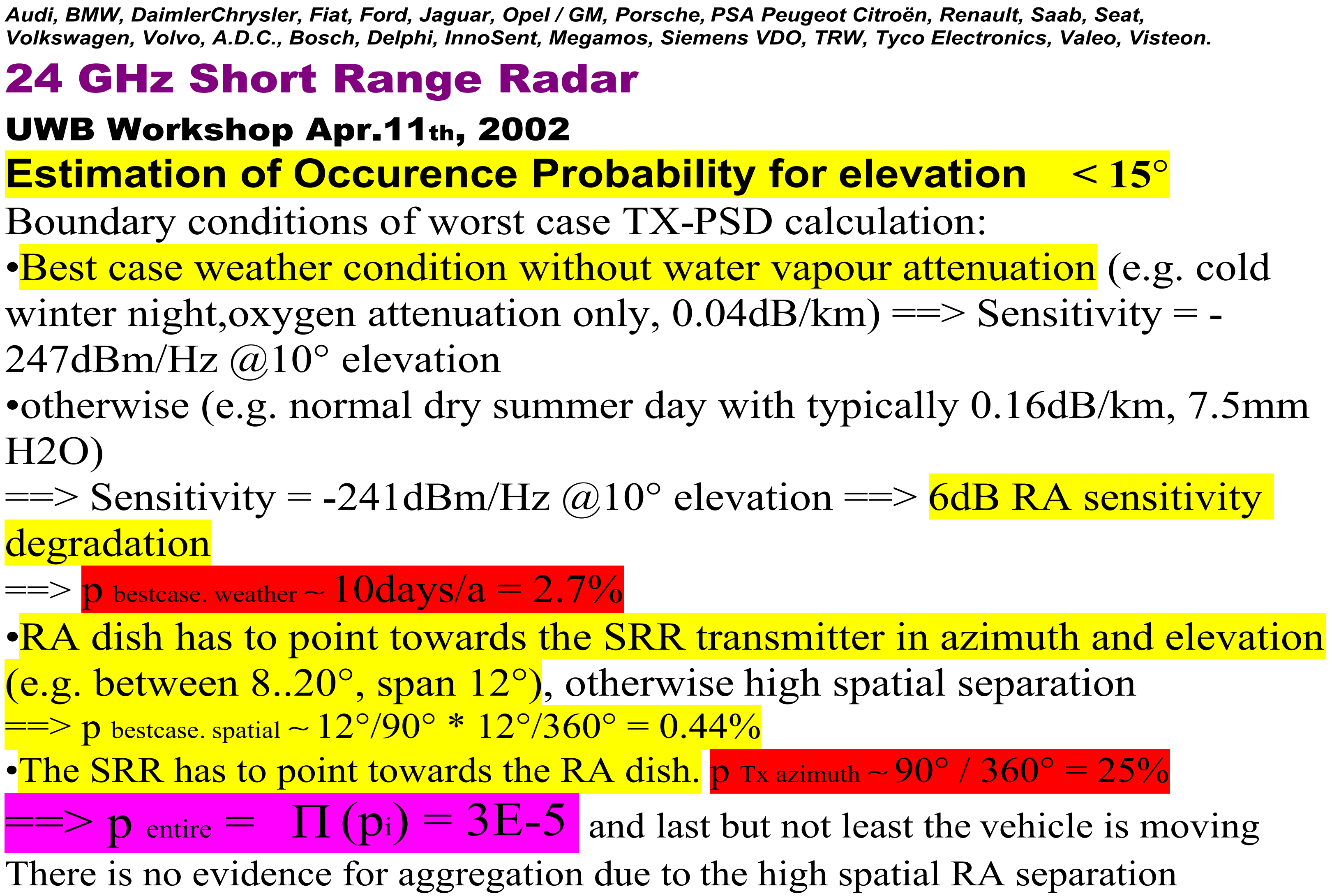
Abs. Bandwidth 3 GHz @-10 dB
fractional BW appr. 12.5%
(per definition WB or UWB ?)

Comb lines of unsmoothed spectrum placed -6 dB below power limit for spurious emissions (-30 dBm)

Power density of smoothed spectrum (appr. -100 dBm/Hz)
Emissions drop below thermal noise (kT= -174 dBm/Hz) at distance of 5m for isotropic receivers

No emissions below 20 GHz
Traditional VHF/UHF bands are not affected

Fig. 13: Proposed broadband automotive radar across a passive band at 24 GHz.



Audi, BMW, DaimlerChrysler, Fiat, Ford, Jaguar, Opel / GM, Porsche, PSA Peugeot Citroën, Renault, Saab, Seat, Volkswagen, Volvo, A.D.C., Bosch, Delphi, InnoSent, Megamos, Siemens VDO, TRW, Tyco Electronics, Valeo, Visteon.

24 GHz Short Range Radar

UWB Workshop Apr.11th, 2002

Estimation of Occurence Probability for elevation < 15°

Boundary conditions of worst case TX-PSD calculation:

•Best case weather condition without water vapour attenuation (e.g. cold winter night,oxygen attenuation only, 0.04dB/km) ==> Sensitivity = -247dBm/Hz @10° elevation

•otherwise (e.g. normal dry summer day with typically 0.16dB/km, 7.5mm H2O)

==> Sensitivity = -241dBm/Hz @10° elevation ==> 6dB RA sensitivity degradation

==> $p_{\text{bestcase. weather}} \sim$ 10days/a = 2.7%

•RA dish has to point towards the SRR transmitter in azimuth and elevation (e.g. between 8..20°, span 12°), otherwise high spatial separation

==> $p_{\text{bestcase. spatial}} \sim 12°/90° * 12°/360° = 0.44\%$

•The SRR has to point towards the RA dish. $p_{\text{Tx azimuth}} \sim 90° / 360° = 25\%$

==> $p_{\text{entire}} = \Pi(p_i) = 3E\text{-}5$ and last but not least the vehicle is moving

There is no evidence for aggregation due to the high spatial RA separation

Fig. 14: A viewgraph presented by SARA to demonstrate the unlikelihood of their system causing interference to radio astronomers.

RFI Propagation Paths

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Abstract

Protection of radio observatories from RFI from ground-based transmitters generally relies on great circle path diffraction calculations to predict signal strengths at the radio telescopes. However, signal propagation over long distances and over rough terrain is considerably more complex than two-dimensional models assume. This is a brief description of a study of radar signal propagation paths that we have been conducting at Green Bank. Signal reflections from surrounding terrain, aircraft, and rain showers have been observed with extra propagation delays of up to several hundred microseconds and a wide range of directions of arrival. Propagation losses through indirect paths can sometimes be comparable or occasionally less than the great circle path loss. The ranges of delay and directions of arrival have implications for the signal processing requirements of RFI cancellation techniques now under study.

1 Introduction

Recent interest in signal processing techniques for canceling radio frequency interference (RFI) in radio astronomy receivers [1] has prompted us to better understand the properties of signals in frequency bands used for observations with the 100-meter Green Bank Telescope (GBT). One signal of particular interest comes from an FAA air surveillance radar antenna near Bedford, Virginia, about 104 kilometers to the south-southeast of Green Bank, transmitting on the frequencies of 1256 and 1292 MHz. Because of the expansion of the universe, atomic hydrogen radiation at 1420.4 MHz from some distant galaxies is Doppler shifted to the frequencies of this radar. Hence, we would like to find ways of observing this cosmic radiation in the presence of the radar signals.

Our first look at the microsecond time structure of the radar signal received by the GBT showed that the strongest part of each pulse was not at its leading edge as one would expect if the direct great circle path had the lowest path loss. Apparently, an indirect path due to reflections from high terrain was producing a stronger signal from the radar than was the direct path so we set out to understand the propagation modes in more detail. To do this we constructed a bistatic radar map from the received pulse intensity as a function of delay from the direct pulse arrival time and the inferred direction of the sweeping radar beam as described below.

The radar signal is pulsed with a pulse length of 2 microseconds, an average repetition rate of about 340 pulses per second, and a peak transmitted power of several megawatts. The pulse transmission times are jittered by several hundred microseconds in a repeating pattern as described in [2] to resolve distance ambiguities. The radar antenna has a horizontal beam width of 1 degree and rotates about a vertical axis at 5 RPM (12 second sweep period). The forward gain of this antenna is roughly 40 dB, but pulses

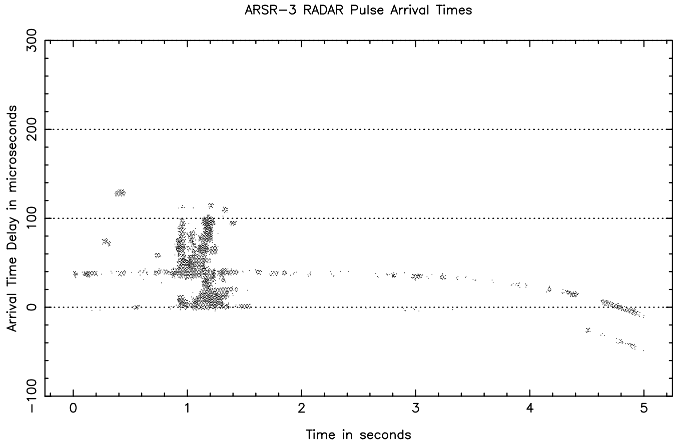

Figure 1: Distribution of measured pulse delays from the inferred direct-path arrival times in data recorded from the GBT. The curvature near the end of the graph is due to sample clock drift that was corrected in the data analysis.

can be seen with the ≈ -15 dBi far sidelobes of the GBT during most of the 12-second sweep from radar antenna sidelobes that probably have an average gain of about -10 dBi. When the radar beam is pointed in the direction of the GBT the induced pulse voltage exceeds the linear range of the GBT receiver for the duration of the pulse, but the receiver recovers immediately after the received pulse voltage falls within its linear range.

2 Terrain Reflection Maps

Figure 1 shows the distribution of measured pulse delays from the direct path arrival time as a function of time from the beginning of the 5-second data stream recorded from the GBT's 1.2-1.7 GHz receiver. Each dot in this figure is a discernible pulse power peak significantly above thermal noise from the receiver. The radar antenna beam passed over the GBT at about 1.3 seconds into this data set. Notice that the biggest cluster of pulses occurs before the radar beam is pointed directly at the telescope and at delays greater than about $40\mu s$. The width of the radar beam in this plot is about 0.033 seconds. The long horizontal stripe of points in Figure 1 is due to a strong reflection at a delay of $40\mu s$ that is visible through the radar antenna sidelobes when it is pointed well away from the radio telescope.

The pulse arrival times shown in Figure 1 may be mapped onto geographic coordinates by assuming that each pulse locus falls on the intersection of three surfaces: the delay ellipsoid with the GBT and the radar antenna at the focii, the vertical plane through the radar beam, and a horizontal plane at the elevation of the GBT. The horizontal plane assumption is not strictly correct since the reflection points are not at the same elevation, but the error is small for delays greater than about $10\mu s$.

Figure 2 shows the same data mapped onto the horizontal plane. The small cluster of points near the top of the map is very likely an aircraft reflection. All other features in this map are due to reflections from high terrain. The heavy cluster of points to

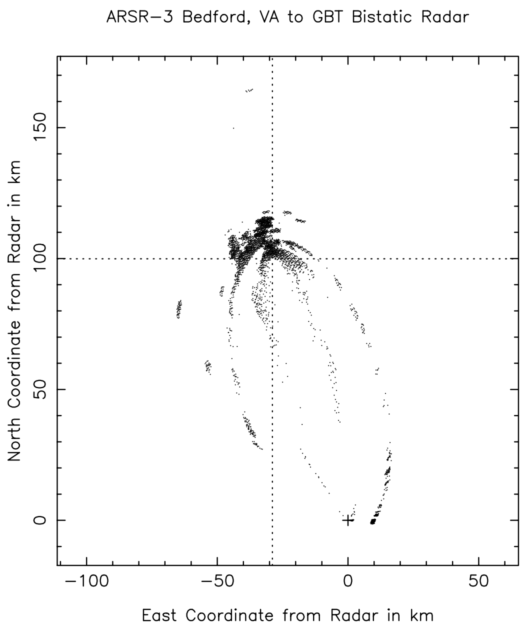

Figure 2: Reflection point locations computed from pulse arrival delays and the radar beam azimuth. The GBT is at the intersection of the two long dotted lines, and the radar is at the small cross near the bottom of the diagram.

the north-west of the GBT is from a high mountain range in this direction. The most prominent ellipse in the map is due to radar antenna sidelobes that are visible from a strong reflection at a high point in the mountains. Each small cluster of points in Figure 2 can be clearly identified with a specific terrain feature on a topographic map overlay to a resolution of a few tenths of a kilometer. In fact, the two free parameters in this data interpretation, the radar beam antenna direction at the beginning of the data set and the direct pulse arrival time offset, were fine tuned by matching many pulse clusters with their terrain counterparts.

3 Differential Delays and Azimuths of Arrival

Nearly all RFI subtraction techniques that might be employed in radio astronomy will need to account for the range of delays and directions of arrival of each signal seen by a radio telescope. Pulse blanking schemes must cover the full delay spread of the arriving pulses. Coherent cancellation techniques must use adaptive filters that can match the delay spread of the multipath propagation. The concept of placing an antenna sidelobe null in the direction of an interfering signal is often too simplistic because the same signal can arrive from many widely spaced directions. Coherent nulling must be done in a combined temporal-spatial domain.

The radar data shown in Figures 1 and 2 can be replotted to show the delay and direction-of-arrival distribution that can be expected for signals with long travel distances in mountainous terrain such as that around the GBT. These plots are shown in

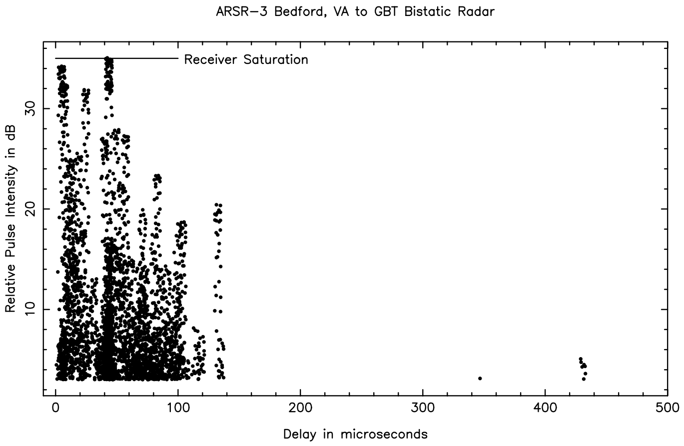

Figure 3: Pulse intensity as a function of delay for the pulses shown in Figures 1 and 2

Figures 3 and 4. Strong terrain reflection delays extend to about $140\mu s$, and the aircraft reflection is at $430\mu s$. The directions of arrival span more than 180^o. Each arc in Figure 4 corresponds to one reflection point as the radar beam sweeps over it. Narrow arcs are from distant points, and wide arcs are from points closer to the GBT. Pulses with delays less than $50\mu s$ have been suppressed in Figure 4 because their apparent azimuth spread is artificially large.

4 Aircraft and Rain Shower Reflections

The great circle path and terrain reflections are the dominant propagation paths for RFI from distant sources, but the high sensitivity requirements of radio astronomy can make even high loss paths troublesome. Two of these paths, reflections from aircraft and rain cells, were seen in some other radar data recorded with low-gain antennas at Green Bank. Both are detectable out to delays of at least $800\mu s$. Signals from these two reflection media could be quite strong for periods of time when an aircraft or storm is near the telescope, and cancellation of these reflected signals with adaptive techniques will be challenging because of the rapidly changing amplitudes and delays. We are still working on quantifying the importance of these RFI reflection paths.

Figure 5 shows two gray-scale plots in geographic coordinates relative to the location of the GBT of radar echoes recorded one minute apart. The thin arcs above and to the left of the terrain echoes are echoes from aircraft. The reflections from the aircraft just above center in the top plot is strong enough to show radar antenna sidelobes. In the bottom plot of Figure 5 you can see that all of the aircraft echoes have moved or disappeared, and one or two new ones have appeared. It is hard to follow the motion of individual echoes with just two plots, but a series of five such maps shows the tracks of about ten aircraft in the area plotted.

On one of the days that we recorded data from this radar there happened to be rain showers in the area. Figure 6 shows two radar maps recorded six minutes apart which show diffuse echoes from five or six rain cells to the north of the GBT. By comparing the two maps you can see that in the six minutes between them the northern-most cells

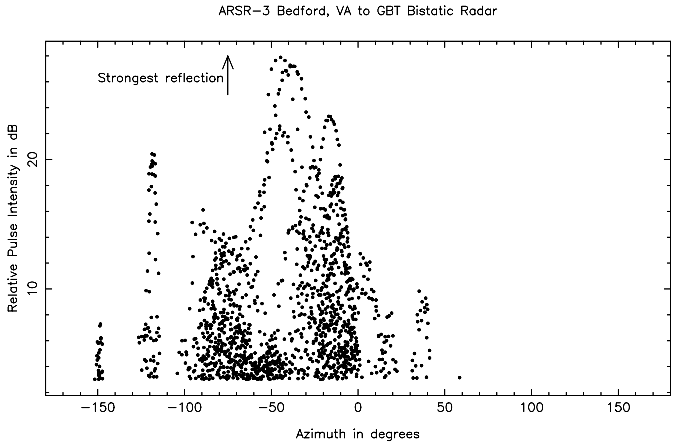

Figure 4: Pulse intensity as a function of inferred azimuth of the radar pulse reflection point for pulses with delays greater than 50 microseconds. Zero azimuth is due North and +90 degrees is due East as seen from the GBT.

have dissipated, and a strong new cell has appeared closer and to the north-west of the GBT.

Of course, a great deal is known about radar echoes from aircraft and rain showers so there is nothing terribly new in these data. However, they do point out that the business of RFI mitigation with signal processing techniques is more complex than one might think. Substantial progress in this field is going to require parallel studies of intrinsic signal characteristics, long distance propagation effects, and sophisticated signal processing techniques.

References

[1] Fridman, P. A., & Baan, W. A., 2001, “RFI Mitigation Methods in Radio Astronomy,” Astron. & Astrophys., 378, 327.

[2] Fisher, Rick, 2001, “Analysis of Radar Data from February 6, 2001,” http://www.gb.nrao.edu/∼rfisher/Radar/analysis.html

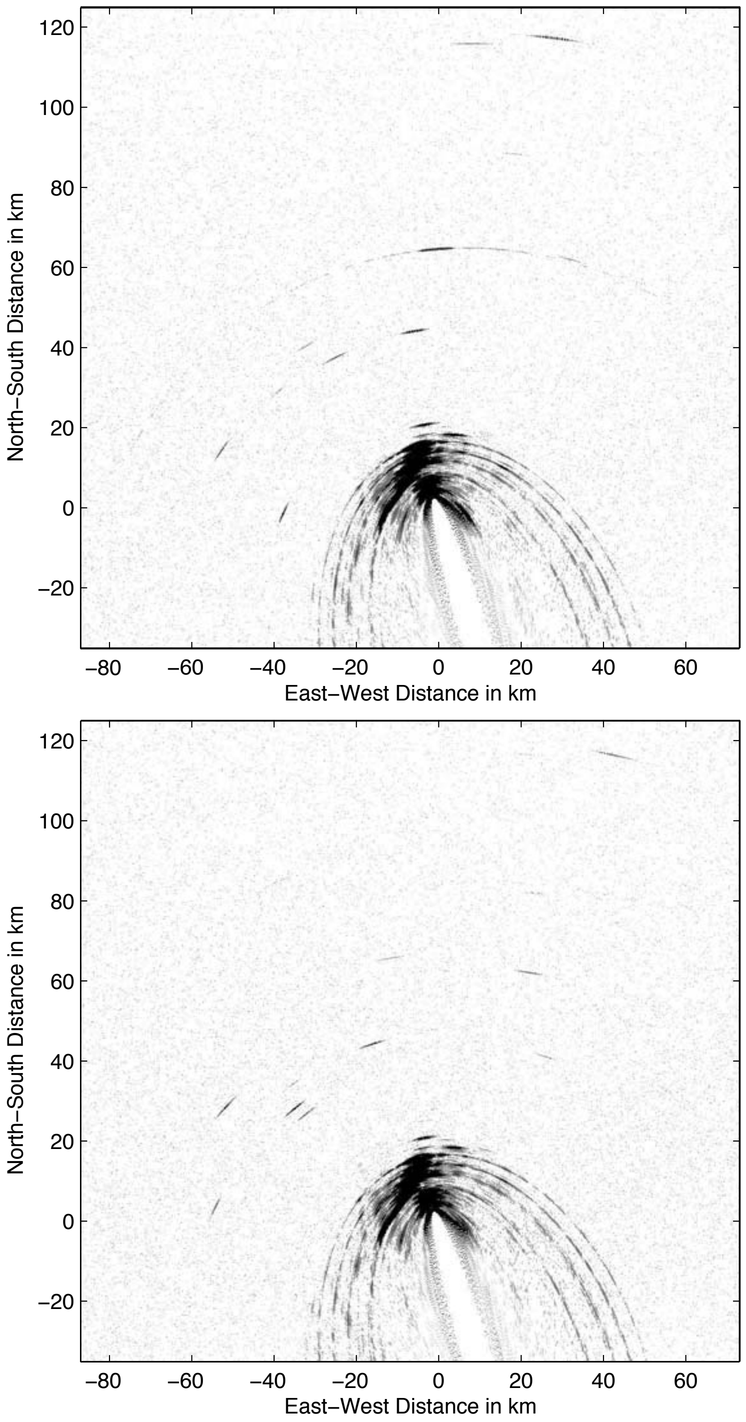

Figure 5: Radar echoes plotted in geographic coordinates relative to the GBT. The display on the top was recorded one minute earlier than the one at the bottom. Arcs that move or appear on only one display are echoes from aircraft.

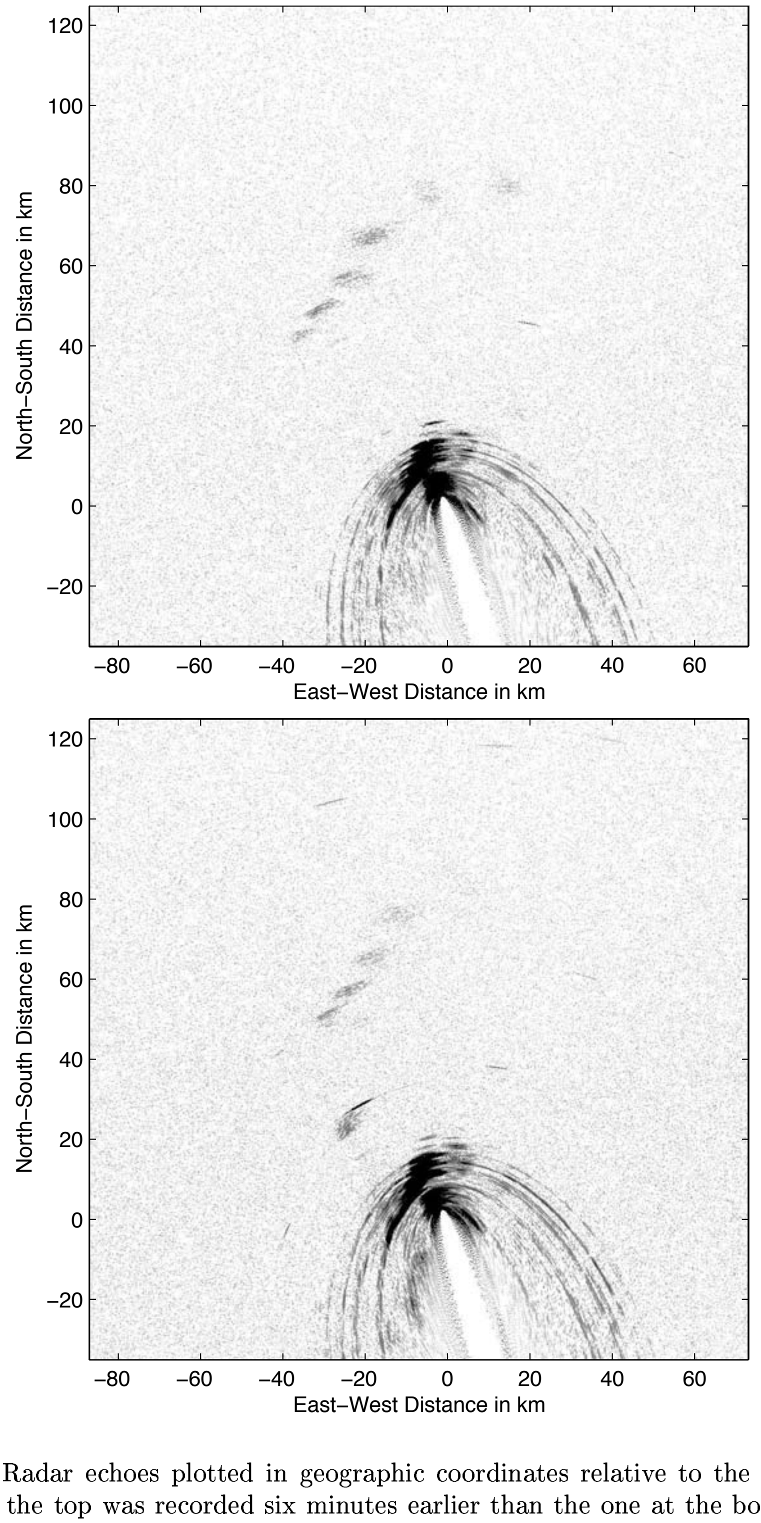

Figure 6: Radar echoes plotted in geographic coordinates relative to the GBT. The display on the top was recorded six minutes earlier than the one at the bottom. The diffuse echoes near the center of the maps are rain showers.

RFI mitigation with the time-frequency robust statistical analysis

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Abstract

The real sensitivity of radio astronomical stations is often limited by man-made radio emissions, radio frequency interference (RFI) due to activities such as broadcasting operations, radars, and a variety of communication and radiolocation systems. Time-frequency analysis with high temporal and frequency resolution allows us to detect and excise RFI better than can be done with existing standard radiotelescope backends. The statistical errors of the total power, correlation factor and spectral density may be substantially reduced when robust statisitical methods are applied to data.

1 Introduction

Radio frequency interference (RFI) substantially limits a radiotelescope's real sensitivity, [1-10]. Several methods of RFI mitigation have recently been proposed [11-33]. These methods can be applied both to existing radiotelescopes and to future projects, [34-37]. One of the main tools of **real-time** RFI mitigation is the time-frequency analysis of received signals with a high temporal (less than 1 microsecond) and frequency (less than 1 kiloHertz) resolution. This approach allows us to analyze statistics of the mixture "system noise + source noise + RFI" and to separate RFI from the Gaussian probability distribution function of the "system noise + source noise". Application of modern, robust, statistical methods to the non-Gaussian RFI mitigation problem is considered in this paper.

2 Conventional measurement schemes

There are three main types of radioastronomical statistical measurements:
a) measurement of variance or total power (making a map with a single dish, or pulsar observations);
b) measurement of correlation function (aperture synthesis, polarization observations);
c) measurement of power spectrum (spectral line observations).

2.1 Total power measurements

Figure 1 illustrates the simplified scheme of a single dish radio telescope with a total power radiometer at the output. In the absence of RFI the sum "system noise + source noise" is random noise with a Gaussian probability density function (PDF), zero mean and variance equal to the sum of the system noise's variance and the source noise's variance. For n independent "clean"(no RFI) samples $x_1, x_2, ...x_n$, (upper waveform), their joint PDF is the product $L(x \mid \sigma) = p(x_1 \mid \sigma)p(x_2 \mid \sigma)...p(x_n \mid \sigma) = \prod_{i=1}^{n} \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{x_i^2}{2\sigma^2})$, where σ is the parameter to be measured. Classical statistics gives the Maximum Likelihood (ML) estimate σ_0 which is the solution of the equation:

$$\sum_{i=1}^{n} \frac{\partial}{\partial\sigma} \log L(x_i, \sigma) \mid_{\sigma=\sigma_0} = 0. \tag{1}$$

Therefore, for the Gaussian PDF, $\widehat{\sigma_0^2} = \frac{1}{n}\sum_{i=1}^{n} x_i^2$, which is precisely the output of the total power detector (TPD). This value is proportional to the sum: system temperature + source antenna temperature, $\widehat{\sigma^2} \sim T_{sys} + T_a$. But in the presence of RFI, (lower waveform), the TPD output will be substantially different.

2.2 Correlation function

Figure 2 illustrates the simplified scheme of a two-element radio-interferometer. The bivariate Gaussian PDF for each pair of samples from the two sites in the absence of RFI is

$$p(x,y) = \frac{1}{\sqrt{2\pi\sigma_1\sigma_2(1-r^2)}} \exp[-\frac{1}{2(1-r^2)}(\frac{x^2}{\sigma_1^2} - 2r\frac{x}{\sigma_1}\frac{y}{\sigma_2} + \frac{y^2}{\sigma_2^2})]. \tag{2}$$

3 Several examples

Several examples of computer simulations of radioastronomical observations with RFI are given in this subsection. Figures 3, 4, 5, 6 all have the same structure: (a) a sample of "clean" Gaussian noise (no RFI); (b) a set of estimates derived from successive samples of "clean" noise, which correspond to an "off-source ⇒ on-source ⇒ off-source" observational set; (c) a sample with strong burst-like RFI; (d) the comparable set of estimates derived from the contaminated noise, which produces no visible "on-source" step; (e) the set of comparable estimates provided by a robust statistical algorithm (which will be specified in the following sections).

These figures obviously show that the ordinary backend processing (section 2), which is optimal for a Gaussian PDF, works extremely badly for a contaminated Gaussian PDF:

$$P_\epsilon(x, \sigma_0, \sigma_1) = (1-\epsilon)P(x, \sigma_0) + \epsilon P(x, \sigma_1), 0 < \epsilon < 1, \tag{6}$$

where $P(x, \sigma_0)$ is the "clean" PDF, σ_0 is the parameter to be measured, $P(x, \sigma_1)$ is the contaminating PDF, ϵ characterizes the fraction of $P(x, \sigma_1)$ in the total $\mathrm{P}_\epsilon(x, \sigma_0, \sigma_1)$.

There are several ways to characterize the robustness of a statistical procedure. One of the most adopted is the **influence function**.

4 Influence function

Let $T = \{T_n\}$ be a sequence of estimates of a parameter θ. $T_n(X)$ denotes the estimate made from the samples $X = (x_1, ...x_n)$ and $T_{n+1}(x, X)$ denotes the same estimate based on the sample $(x, x_1, ...x_n)$, that is one more sample x is added. The influence function (IF) is defined as

$$\varphi_n(x, X) = T_{n+1}(x, X) - T_n(X). \tag{7}$$

This function characterizes the sensitivity of the estimate T_n to the adding of one sample x. For example, the IF for the sample mean $T_n = \frac{1}{n}\sum_{i=1}^{n} x_i$ is

$$\varphi_n(x, X) = \frac{x}{n+1} - \frac{1}{n(n+1)}\sum_{i=1}^{n} x_i = \frac{x}{n+1} + O(\frac{\mu}{n}). \tag{8}$$

Therefore, the IF is not bounded, and an outlier can cause an unbounded error.

The IF for the sampled variance is

$$\varphi_n(x, X) = \frac{x^2 - \widehat{\sigma_n^2}}{n+1}, \tag{9}$$

that is for $|x| < \sigma_n$ the estimate is slightly reduced, but when $|x| \to \infty$, the error grows very rapidly following the square law.

The next section is dedicated to **robust algorithms** which are less susceptible to the outliers, and the IF for these algorithms is given.

5 Robust algorithms

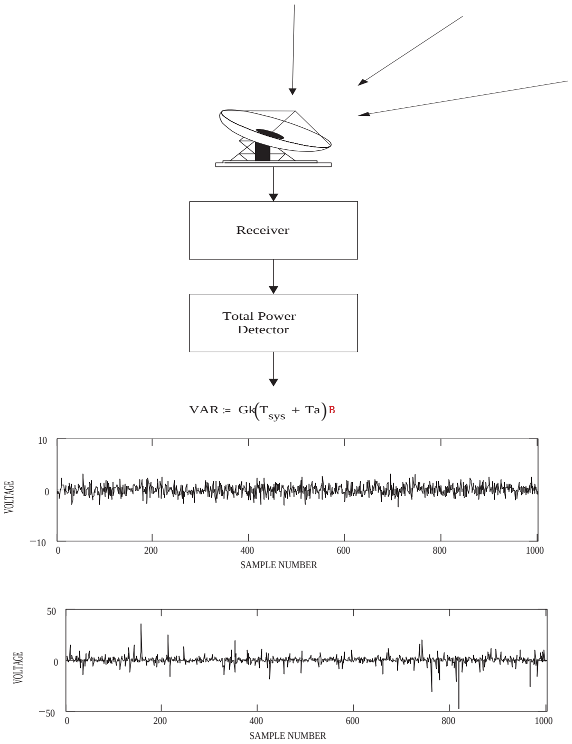
5.1 Nonparametric statistics

One of the simplest methods to overcome the lack of robustness is to analyze the "heavy tails" of the contaminated sample PDF (6). Let $(x_1, ...x_n)$ be a sample consisting of n independently observed values of a random variable x with a PDF $P(x)$. If we arrange the x in increasing order (denoting the smallest by $x^{(1)}$, the next smallest by $x^{(2)}$, etc.),

$$x^{(1)} < x^{(2)} < ... < x^{(n)},$$

then we call each of them an *order statistic.* Let $r = r_1 + r_2$ order statistics from the tails be thrown away, so that the estimate of a parameter will be based on the remained samples

$$x^{(r_1+1)} < x^{(r_1+2)} < ... < x^{(n-r_2)}.$$



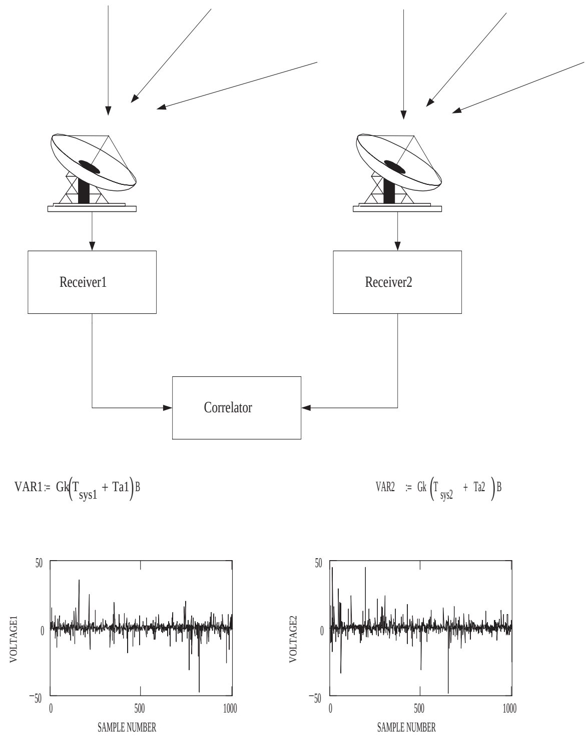


Fig. 1, (left panel). Single dish radiotelescope with the total power detector at the output, VAR is the variance of the noise at the receiver output in the absence of RFI, T_{sys} and T_a are the system and radio source antenna temperature, respectively, G is the receiver gain, B is the bandwidth. The waveforms illustrate the receiver's voltage output without and with RFI (before the total power detector and correlator).
Fig. 2, (right panel). Radio interferometer with the correlator at the output.

The ML estimates of the correlation factor r and the variances σ_1^2, σ_2^2 are

$$\widehat{r} = \frac{\frac{1}{n}\sum_{i=1}^{n} x_i y_i}{\sqrt{\widehat{\sigma_1^2}\widehat{\sigma_2^2}}}, \tag{3}$$

$$\widehat{\sigma_1^2} = \frac{1}{n}\sum_{i=1}^{n} x_i^2, \quad \widehat{\sigma_2^2} = \frac{1}{n}\sum_{i=1}^{n} y_i^2, \tag{4}$$

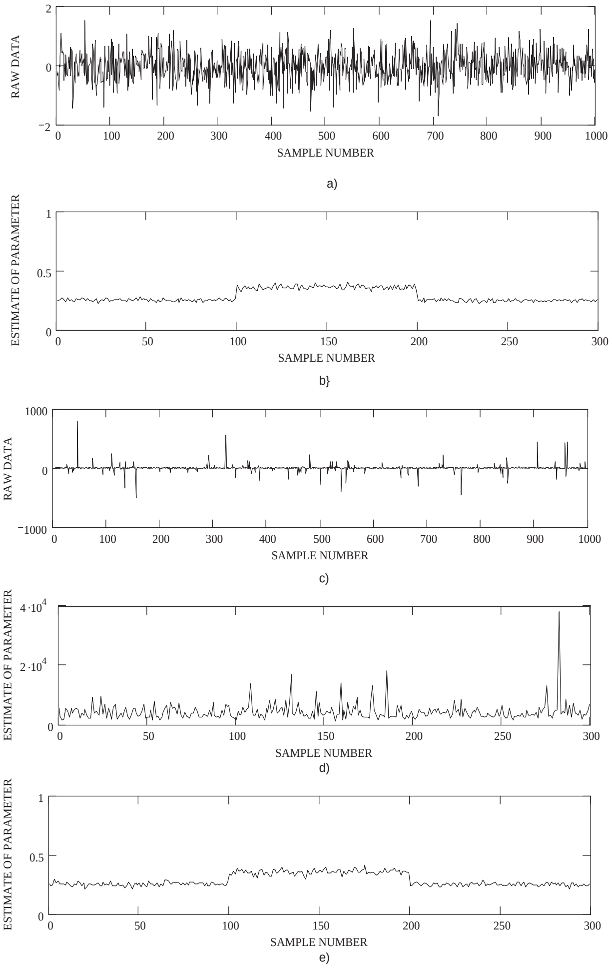
which are not statistically stable (**robust**) in the presence of outliers from RFI, as in the waveforms of Fig. 2.

2.3 Power spectrum

The power spectrum is measured during spectral-line observations using either the autocorrelation function (after a Fourier transform, with the XF spectrometer), or directly after averaging M instantaneous spectral densities at the receiver output (FX spectrometer):

$$\widehat{S(k)} = \frac{1}{M}\sum_{m=0}^{M-1}\{[\sum_{n=0}^{N-1} x_n cos(2\pi n\frac{k}{N}]^2 + [\sum_{n=0}^{N-1} x_n sin(2\pi n\frac{k}{N}]^2\} \tag{5}$$

This estimate is statistically unstable (sensitive to the outliers) as well.



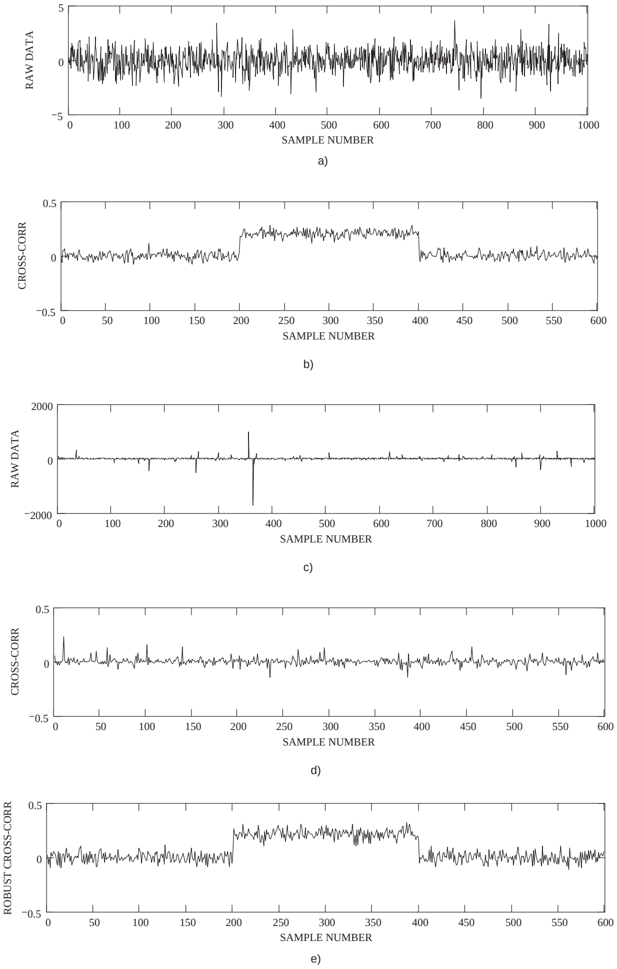


Fig. 3 (left panel). a) Noise with a the Gaussian PDF, $\mu = 0, \sigma = 0.5$, and no interference.

b) Estimate of the variance $\widehat{\sigma^2}$ of the Gaussian PDF (sample variance) at 300 points, each point being the estimate derived from n=1000 samples of the noise stream illustrated in Fig. 3a. Two steps at M1=100 and M2=200 ("on source", $\Delta\sigma = 0.1$) are visible.

c) Noise with a Gaussian PDF, $\mu = 0, \sigma = 0.5$, and interference: random impulses from a Poisson distribution ($\lambda_p = 0.05$) and lognormal distribution of amplitudes (mean=2R, standard deviation =1R, R=10) replace some variates. Note the vertical scale, which is 500 times larger than in Fig. 3a.

d) Estimate of the variance $\widehat{\sigma^2}$ of the Gaussian distribution (sample variance) at 300 points, each point is the estimate from n=1000 samples of the noise stream illustrated in Fig. 3c. No change of the mean is visible; the standard deviation = 1824 is 12680 times larger than in Fig. 3b.

e) Robust estimation of the variance $\widehat{\sigma^2}$ of a Gaussian PDF at 300 points, each point being the estimate from n=1000 samples of the noise stream illustrated in Fig. 3c. Two steps at M1=100 and M2=200 ("on source", $\Delta\sigma = 0.1$) are clearly visible. Standard deviation of the averaged data = 0.014.

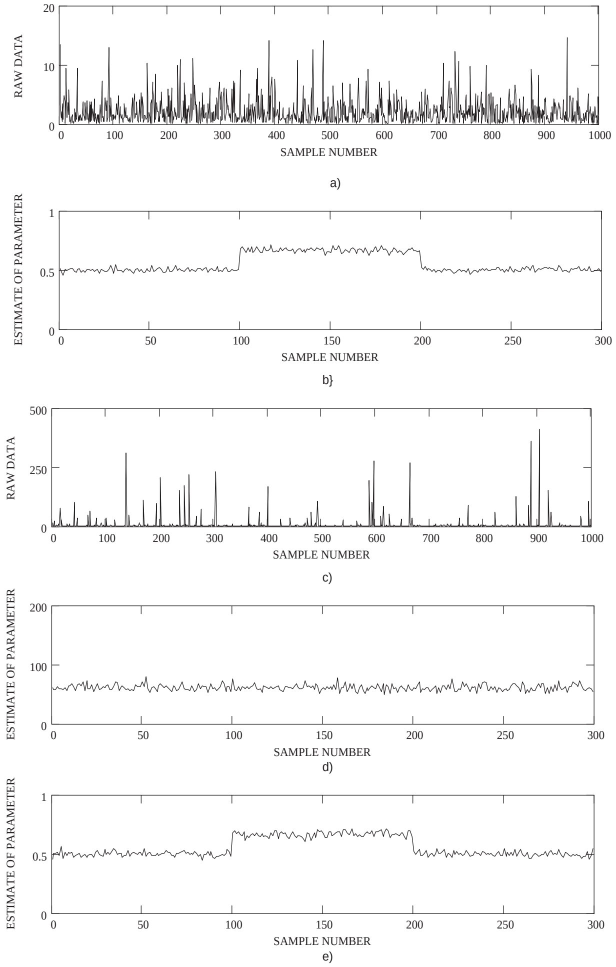
Fig. 4 (right panel). a) Noise with a Gaussian PDF, $\mu = 0, \sigma = 1$, and no interference.

b) Cross-correlation function of two signals like that in Fig. 4a with a coherent component $\Delta\sigma = 0.5$ between points M1=200 and M2=400 ("on-source"); each point corresponds to the estimated cross-corr derived from 1000 sequential variates in the data stream illustrated by Fig. 4a.

c) Noise with a Gaussian probability distribution, $\mu = 0, \sigma = 1$, and interference: random impulses from a Poisson distribution ($\lambda_p = 0.05$) and lognormal distribution of the amplitudes (mean = 2R, standard deviation = 1R, R=10) replace some variates. Note that the vertical scale is 400 times larger than in Fig. 4a.

d) Cross-correlation function of two signals like that illustrated by Fig. 4c, with a coherent component $\Delta\sigma = 0.5$ between M1=200 and M2=400 ("on-source"); each point corresponds to the estimate from 1000 variates. No change in the cross-correlation coefficient is visible.

e) Robust cross-correlation function of the two signals with RFI and a coherent component $\Delta\sigma = 0.5$ between points M1=200 and M2=400; each point corresponds to the estimate derived from 1000 variates. The steps at M1=200 and M2=400 are clearly visible, though the standard deviation is slightly larger than in the absence of interference.



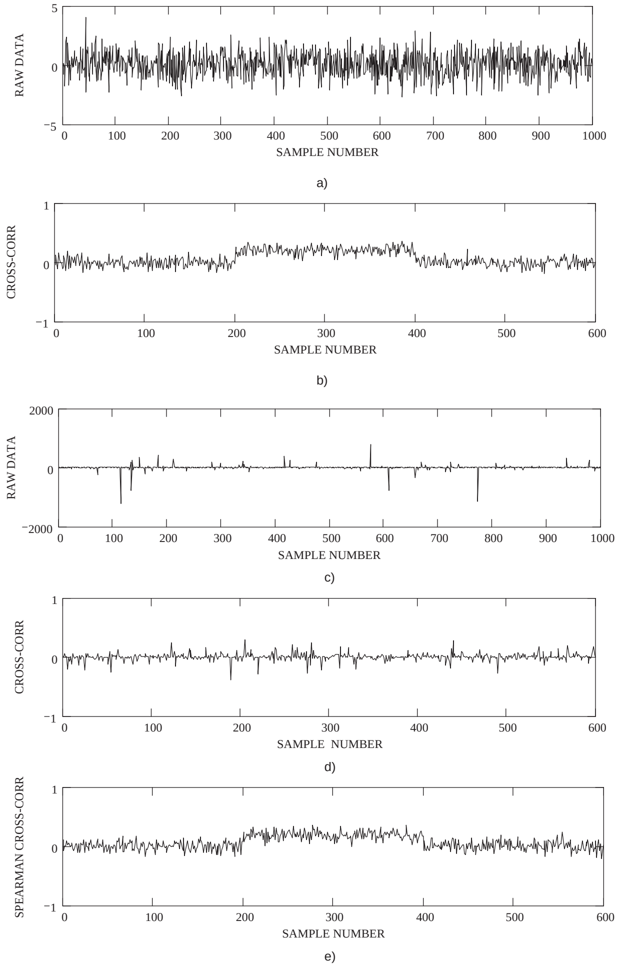


Fig. 5 (left panel). a) Noise with an exponential probability distribution, $\lambda_e = 2.0$, and no interference.
b) Estimate of the λ_e of the exponential distribution (sample mean) at 300 points, each point being the estimate from n=1000 samples of the noise illustrated in Fig. 5a.
c) Noise with an exponential probability distribution, $\lambda_e = 0.5$, and interference, together with random impulses from a Poisson distribution ($\lambda_p = 0.05$) and lognormal distribution of the amplitudes (mean=2R, standard deviation =1R, R=10). Note the vertical scale is 20 times larger than in Fig. 5a.
d) Estimate of the λ_e of the exponential distribution (sample mean) at 300 points, each point being the estimate from n=1000 samples of the noise stream illustrated in Fig. 5c. There is no visible change of the mean. The standard deviation = 4.841, which is 177 times larger than in Fig. 5b.
e) Robust estimate of the λ_e of the exponential distribution (mean) at 300 points, each point being the estimate from n=1000 samples of the noise in Fig. 5c. The two steps at M1=100 and M2=200 ("on-source", $\Delta\lambda_e = 0.5$) are clearly visible. Standard deviation of the averaged data = 0.027.

Fig. 6 (right panel). a) Noise from a Gaussian PDF, $\mu = 0, \sigma = 1$, and no interference.
b) Cross-correlation function of two signals with a coherent component $\Delta\sigma = 0.5$ between M1=200 and M2=400 ("on-source"); each point corresponds to the estimated cross-corr derived from 200 sequential variates in the data stream illustrated by Fig. 6a.
c) Noise with a Gaussian probability distribution, $\mu = 0, \sigma = 1$, and interference: random impulses from a Poisson distribution ($\lambda_p = 0.05$) and lognormal distribution of the amplitudes (mean = 2R, standard deviation = 1R, R=10) replace some variates. Note the vertical scale is 400 times larger than that in Fig. 6a.
d) Cross-correlation function of two signals like those of Fig. 6c, with a coherent component $\Delta\sigma = 0.5$ between M1=200 and M2=400 ("on-source"); each point corresponds to the estimate from 200 samples from the noise stream of Fig. 6c. There is no visible change in the cross-correlation coefficient.
e) Spearman rank cross-correlation function of two signals like that of Fig. 6c with a coherent component $\Delta\sigma = 0.5$ between M1=200 and M2=400: each point corresponds to the estimate from 200 samples dreawn from a noise stream like Fig. 6c. The steps at M1=200 and M2=400 are clearly visible, and the standard deviation is practically the same as in the absence of interference.

The samples are thus *censored.* Two options are possible [41]:
1. *Trimming*: all measurements outside the interval $[x^{(r_1+1)}, x^{(n-r_2}]$ are removed.
2. *Winzorisation*: the "left tail" is pulled to the value $x^{(r_1+1)}$, so that all $x < x^{(r_1+1)}$ are equated to $x^{(r_1+1)}$, and the "right tail" is likewise pulled to the value $x^{(n-r_2)}$. The mean, variance and other parameters are calculated with the remained samples. The estimate functions and the influence functions for the trimmed, winzorized and ordinary variance are given in Fig. 7 and 8 respectively. The *trimmed* and *winzorized* estimates are more robust, and the corresponding IFs are bounded.

If n is odd, that is $n = 2m - 1$, then the middle value $x^{(m)}$, or else, the sample *median*, is also a robust estimate of the mean for symmetrical PDF, and the median deviation around the sample median

$$s_2 = median_{1 \le i \le n}\{|x_i - median_{1 \le i \le n}\{x_i\}|\}/0.6745 \tag{10}$$

also has good robustness.

5.2 M-estimates

A more universal approach was proposed in [38]. In general, the estimate of a PDF's parameter θ is the value $\widehat{\theta}$ minimizing the sum

$$\sum_{i=1}^{n} \rho(x_i, \widehat{\theta}) \to min, \tag{11}$$

where $\rho(x_i, \widehat{\theta})$ is a continuous and differentiable function on x and $\widehat{\theta}$. For example, for the mean $\rho(x - \widehat{x}) = (x - \widehat{x})^2$, and for the median $\rho(x - med) = |x - med|$. After the differentiation of (11) with respect to $\widehat{\theta}$ we get

$$\sum_{i=1}^{n} \Psi(x_i, \widehat{\theta}) = 0, \tag{12}$$

where the anti-symmetric function Ψ is called a *score function* and the estimate is called an **M-estimator**. Again for the mean $\Psi(x - \widehat{x}) = x - \widehat{x}$, and for the median $\Psi(x - med) = sgn(x - med)$. The influence function for the M-estimator has a form:

$$\varphi(x) = \frac{\Psi(x - \hat{\theta})}{\Psi'(x - \hat{\theta})}. \tag{13}$$

The maximum likelihood (ML) estimate corresponds to $\rho(x) = -log[p(x)]$, where $p(x)$ is the PDF.

The score function Ψ for the estimate of a mean was found [38] for the worst contaminating "heavy-tailed" symmetric PDF (Laplace PDF) to be

$$\Psi_{Huber}(x - \hat{\theta}) = \begin{cases} -k, \text{ if } x - \hat{\theta} < k, \\ x - \hat{\theta}, \text{ if } -k \le x - \hat{\theta} \le k, \\ k, \text{ if } k < x - \hat{\theta} \end{cases} \tag{14}$$

where k depends on ϵ in the following way:

$$\frac{1}{1 - \epsilon} = 1 - 2\Phi(-k) + \frac{2}{k} p(k), \text{ and } \Phi(z) = \int_{-\infty}^{z} p(x)dx, \tag{15}$$

$p(x)$ is the Gaussian PDF with zero mean and a variance of 1. Several other functions $\Psi(x)$ for the robust estimates were proposed, [40, 41, 42]:

$$\Psi_{Andrews}(x) = \begin{cases} sin(x/a) \text{ if } |x| \leq a\pi, \\ 0 \qquad \text{if } |x| > a\pi \end{cases} ; \tag{16}$$

$$\Psi_{Hampel}(x) = \begin{cases} x \text{ if } |x| \leq a \\ a \times sign(x) \text{ if } a < |x| \leq b \\ \frac{a \times sign(x)(c-|x|)}{c-b} \text{ if } b < |x| \leq c \end{cases} ; \tag{17}$$

$$\Psi_{Tukey}(x) = \begin{cases} 0 \text{ if } |x| > c \\ x(1-x^2)^2 \text{ if } |x| < 1 \\ 0 \text{ if } |x| \geq 1 \end{cases} ; \tag{18}$$

$$\Psi_{Meshalkin}(x) = x \times exp(-\lambda x^2/2), \lambda > 0. \tag{19}$$

The parameters a, b, c, λ are tuned for the particular contaminated PDF (6). Fig. 7 gives the estimate functions of the variance for the three cases: Maximum Likelihood (nonrobust), Huber (14), and Meshalkin (19), while Fig. 8 illustrates the corresponding influence functions.

Now we can go to the low panels in Fig. 3, 4, 5, 6, where the simulation results are given for the robust estimates.

Figure 3e illustrates application of robust estimation to the variance $\widehat{\sigma^2}$ of the Gaussian PDF. With the assumption that the mean is equal to zero, the estimate equation (12) is

$$\sum_{i=1}^{n}(\frac{x_i^2}{\widehat{\sigma^2}} - 3/5)exp(-x_i^2/3\widehat{\sigma^2}) = 0. \tag{20}$$

The steps due to the "off-source → on-source → off-source" are clearly visible, while the input data x_i were taken from the data stream illustrated by Fig. 3c.

Figure 4e illustrates the advantage of robust processing in the case of a correlator (Fig. 2). The cross-correlation coefficient between random samples $x1_i$ and $x2_i$ is calculated with

$$\widehat{r_{12}} = \frac{1}{n\sqrt{\widehat{\sigma1^2}\widehat{\sigma2^2}}} \sum_{i=1}^{n} x1_i \exp(-\frac{x1_i^2}{3\widehat{\sigma1^2}}) x2_i \exp(-\frac{x2_i^2}{3\widehat{\sigma2^2}}), \tag{21}$$

where the robust estimates of $\widehat{\sigma1^2}$ and $\widehat{\sigma2^2}$ were found using (20), and each product $x1_i x2_i$ is exponentially weighted: the larger the variate, the lower its weight, thus eliminating the outliers.

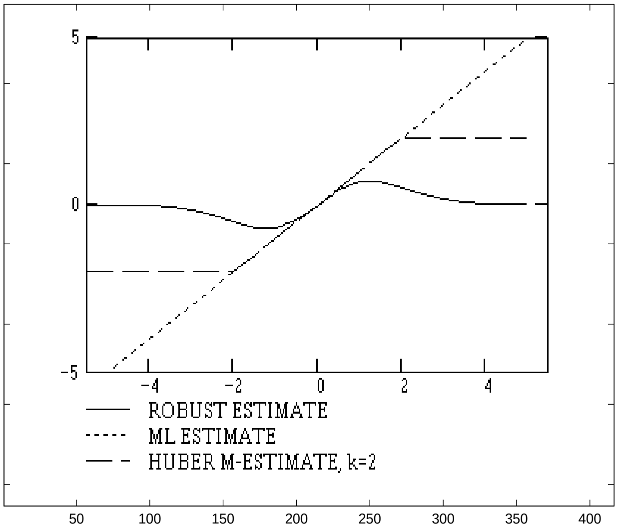
Figure 5e shows the robust estimatation of the power spectrum at the output of an FX spectrometer (instead of the straight averaging of (5)). The root of the following equation yields the estimate of the parameter λ_e of an exponential PDF [42]:

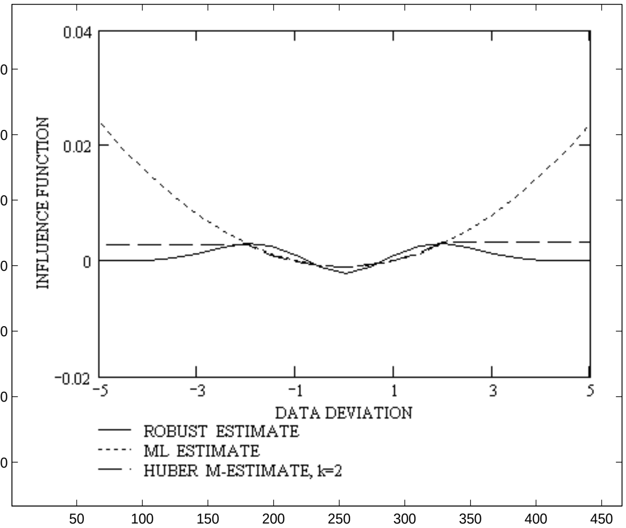
$$\sum_{i=1}^{n}(\frac{x_i}{\lambda_e} - 2/3)exp(-\frac{x_i}{2\lambda_e}) = 0. \tag{22}$$

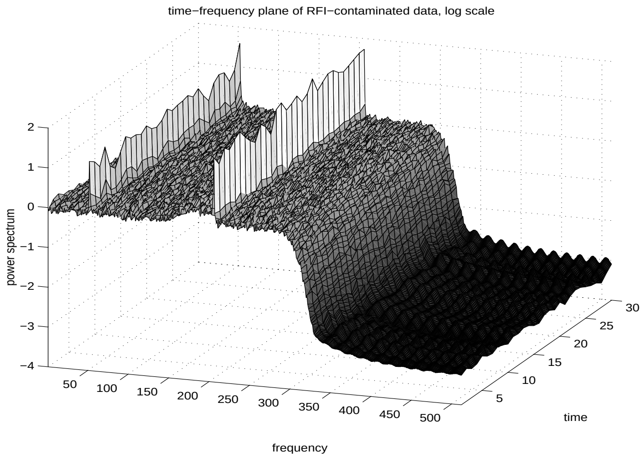
Figure 6e illustrates the application of a nonparametric procedure, Spearman's rank-order correlation coefficient [43]. The *ranks* ξ_i and η_i of the samples $x1_i$ and $x2_i$ are their numbers in the order statistics (see subsection 5.1). The Spearman's rank-order correlation coefficient is calculated from the ranks instead of the variates (as in (3)) via

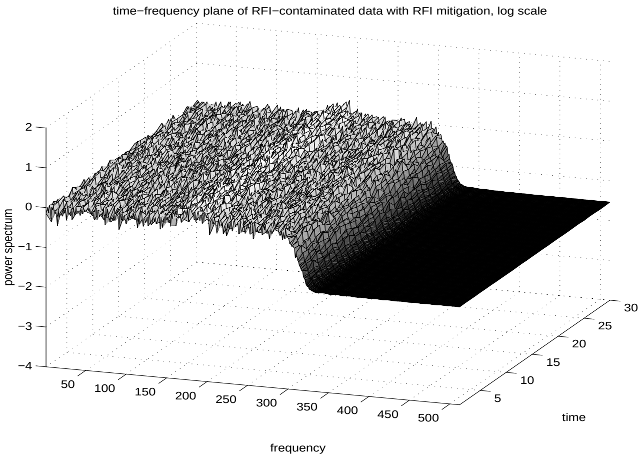
$$R = \frac{3\sum_{i=1}^{n}(2\xi_i - n - 1)(2\eta_i - n - 1)}{n(n-1)(n+1)}. \tag{23}$$

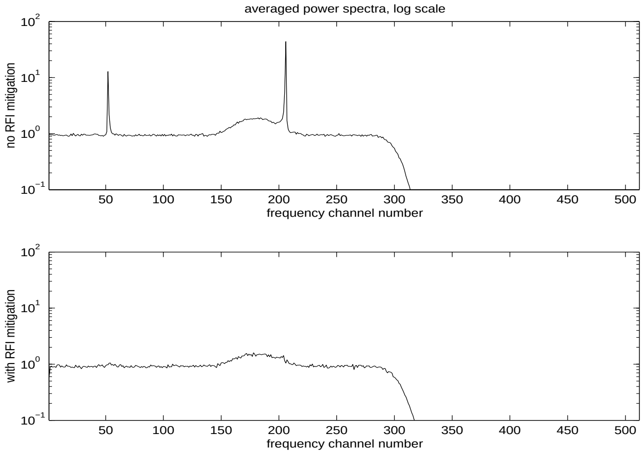
A significant improvement in the outcome is clearly visible in Fig. 6e.











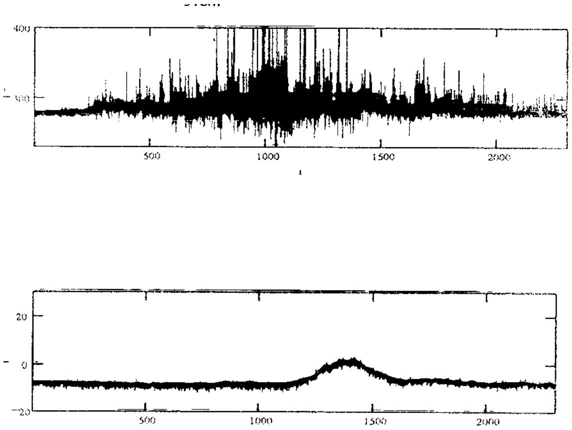


Fig. 7, (top left). Score functions for the Gaussian PDF, $\mu = 0, \sigma = 1.0$.

Fig. 8 (top right). The influence functions corresponding to Fig. 7.

Fig. 9, (middle left). Time-frequency 3D-presentation of the power spectrum with system noise, RFI and spectral lines, from a computer simulation using equation 5.

Fig. 10, (middle right). Time-frequency 3D-presentation of the robustly estimated power spectrum, which suppresses RFI: the spectral line is visible.

Fig. 11, (bottom left). The averaged power spectra corresponding to Fig. 9 (upper panel) and to Fig. 10 (lower panel).

Fig. 12, (bottom right). Real observations at RATAN-600, $\lambda = 31cm$, 20.08.1996, scan of the source 1116+28, upper panel - with RFI and without RFI excision,

lower panel - the same radio source with outliers excised before averaging, both records were made simultaneously.

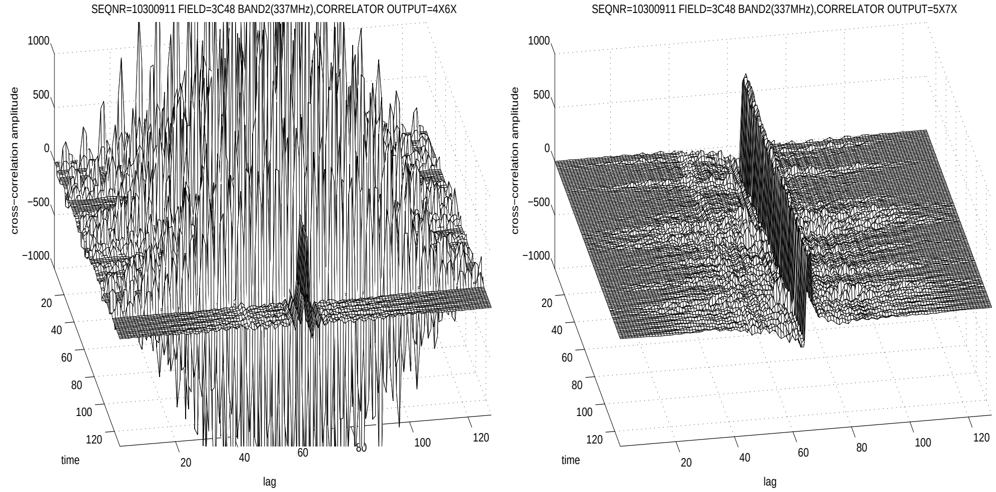


Fig. 13. Observation at WSRT n.10300911, 29 Jan 2003, source 3C48, frequency 337 MHz, bandwidth 10 MHz, DZB correlator, 60 s integration time for each of 131 records ($\approx 2h$). RFI was suppressed at channels RT5X and RT7X, but not suppressed at channels RT4X, RT6X. The time-frequency presentations of the **cross-correlation amplitudes** are given: 4X6X - left panel, 5X7X - right panel.

These algorithms work well with RFI bursts in the temporal domain, but they do not "see" narrow-band RFI, which is sometimes hidden under the system noise. On the other hand RFI of this type can be easily detected in the frequency domain as bursts above the level of the system noise spectral power density, and a robust algorithm can be applied in the frequency domain. It is worth remembering here that the power density calculated after the Fourier transform of one sequence of sample data, see (5), for $M = 1$, has an exponential PDF for each frequency bin, when the PDF of noise in the temporal domain is Gaussian. Figures 9, 10 & 11 illustrate the application of the robust Meshalkin procedure [42] to the estimation of the parameter λ_e in the exponential PDF. The solution of equation (12) has the score function

$$\Psi(x) = (\frac{x}{\lambda_e} - 2/3)e^{-x/2\lambda_e}. \tag{24}$$

RFI was simulated as sequences of a continuous wave with two different frequencies and random start times and amplitudes. The signal of interest is represented as a "spectral line": narrow-band noise is superposed with the system noise. Fig. 9 shows the 3D-presentation of the time evolution of the power spectrum with RFI that was calculated using equation 5: each section corresponds to the averaging of $M = 50$ spectra, and the number of frequency channels is 512 ($N = 1024$). Fig. 10 is the 3D-presentation of the sequence of the robustly estimated power spectra, and Fig. 11 gives the averaged spectra on a logarithmic scale, corresponding to Figs. 9 & 10: upper panel is the averaged spectrum without robust processing; the lower panel illustrates the averaged spectrum obtained after using a robust algorithm.

It should be noted that there are always certain losses after the application of robust algorithms. The variance of the robust estimate is, as a rule, higher than that for the "ideal" case (no RFI and ML algorithm), and the ratio of the estimation variances can achieve 1.5-2 in favour of the "ideal" case. But in the presence of strong RFI, these losses are more tolerable than the total loss of the observations.

Figures 12 and 13 show examples of real-time signal processing (trimming) applied during observations at RATAN-600 and WSRT, respectively. Figure 12 illustrates RFI mitigation with a total power detector: $\lambda = 31cm$, 20.08.1996, source 1116+28 is scanned by the radio telescope antenna pattern; upper panel - with RFI and without RFI excision, lower panel - the same radio source with RFI excision, both records were made simultaneously. The primary sampling interval (before averaging) was equal to 2 μs, the final averaging interval is equal to 0.1 ms.

Figure 13 illustrates RFI mitigation with a radio interferometer, where cross-correlation is measured: source 3C48, frequency 337 MHz, bandwidth 10 MHz, DZB correlator, 60 s integration time for each of the 131 records ($\approx 2h$). RFI was suppressed in the frequency domain at channels RT5X and RT7X and not suppressed at channels RT4X, RT6X. The time-frequency presentations of the **cross-correlation amplitudes** are given: 4X6X - left panel, 5X7X - right panel. The right panel illustrates the effect of RFI suppression.

Figures 12 and 13 thus show that even simple, real time algorithms can give significant benefits.

6 Conclusions

1. Existing radio telescope backends process signals following classic maximum likelihood statistical algorithms, which are optimal for a no-RFI environment. These procedures are not robust: they are statistically unstable in the presence of outliers in the time or frequency domains, or, in other words, when the PDF is contaminated.

2. Algorithms, developed to provide robust or nonparametric statistical output are more suited to our worsening RFI situation. They also provide a much more acceptable level of residual errors in the presence of strong RFI.

3. The implementation of real-time robust algorithms requires more computational power than is used in existing backends. The high performance of modern digital signal processing components (processors (DSP), field programmable gate arrays (FPGA)) permit, however, the **real-time** implementation of many efficient robust procedures. It is not always possible to combine such processing with existing radiotelescope infrastructure, but future backends should be designed to implement robust algorithms.

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An RFI Mitigation Strategy for the Allen Telescope Array

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Abstract

The Allen Telescope Array faces unprecedented challenges and opportunities with respect to radio frequency interference. Its broadband frontend gives the ATA unique observing flexibility but makes it vulnerable to interference outside of the protected radio astronomy bands. This vulnerability occurs through direct conflict at the observing frequency between radio astronomy sources and interferers and through frontend saturation in the case of strong interferers regardless of the observing frequency.

For these reasons, the ATA is the first radio telescope designed with RFI mitigation as an integral element. The large-N nature of the ATA, the reliance on programmable digital electronics and an awareness of new algorithms and techniques will make the ATA particularly effective at RFI mitigation. Mitigation is integrated into the design from the antenna to the IF processor to the correlator. Our observing strategy employs a range of techniques and new hardware elements to address specific interference problems and specific science goals. Without these tools, many of the science goals of the ATA cannot be achieved.

1. The Allen Telescope Array

The Allen Telescope Array (ATA) is a new centimeter wavelength interferometer currently being designed and prototyped by UC Berkeley and the SETI Institute. The array will be the first of the next generation of large radio telescopes including the EVLA, LOFAR, and SKA. The design exploits new technologies that allow for a large number of elements supported by flexible digital electronics.

The ATA will consist of 350 6.1-m offset-Gregorian parabolas equipped with log-periodic feeds sensitive in two linear polarizations from 500 MHz to 11.2 GHz. The entire radio frequency signal will be transported by fiber optic cables to the lab, where four individual frequency bands of 100 MHz each can be selected. Two generic types of backend will be possible: phased array processors and a correlator. Up to four phased array beams can be formed within the primary beam of the antenna for each frequency. The array is both multiple single dish antennas and an interferometer simultaneously. See the ATA website and memo series for further instrument details (`http://www.seti.org/science/ata.html`).

We discuss the unique radio frequency interference (RFI) problems and solutions available to the ATA. There are no "magic bullets" to the problem of RFI. Our philosophy emphasizes a tool box approach with different tools for different interferers and different science goals. The more we know about a particular interferer, the more we can mitigate its effects.

2. The Interference Environment

Site selection is the most important RFI mitigation technique available. The Hat Creek Radio Observatory is remote and isolated from population centers by several mountain ranges. Modeling indicates that the terrain suppresses interference from outside the Hat Creek valley by $\sim$ 100 dB. Nevertheless, interference from a variety of sources is still present at the site.

We have been able to identify, characterize and quantify many of these sources through two instruments: the Rapid Prototyping Array, a 7-element L-band interferometer dedicated to RFI studies and located in Lafayette, CA; and, the RFI Monitor, an isotropic antenna with frequency coverage from 100 MHz to 11 GHz located at HCRO. The RPA gives us detailed and high SNR knowledge of the characteristics of interfering signals. The RFIM gives us knowledge of the interferers present at HCRO.

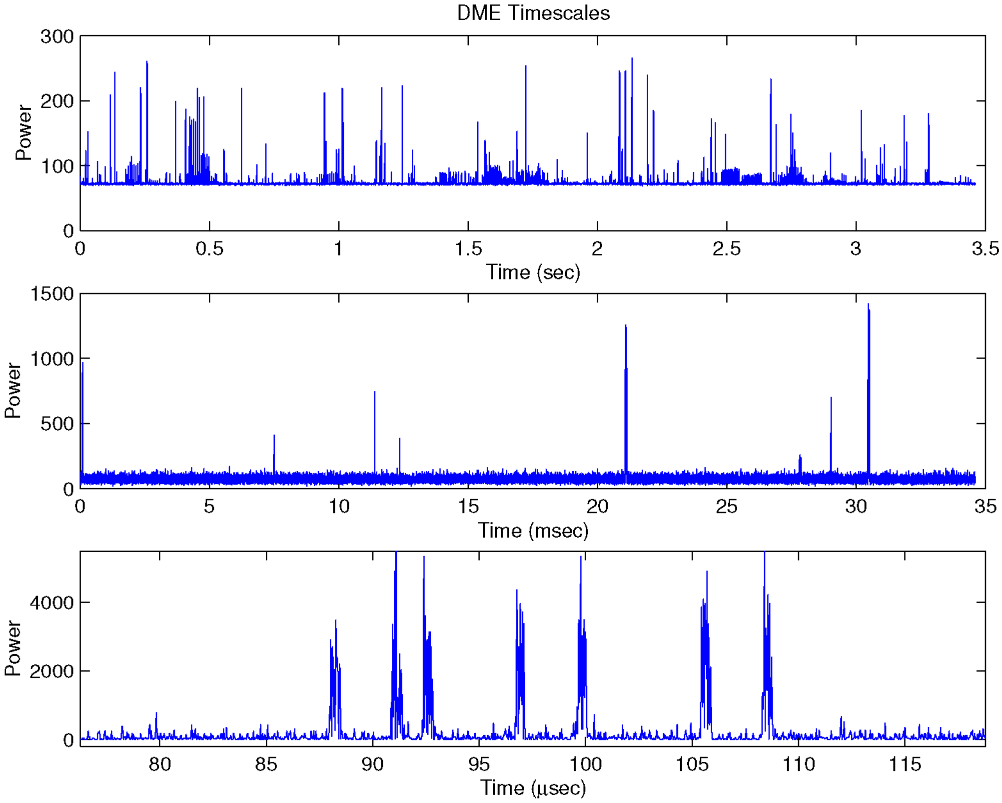
Among the interferers detected and studied are radar, aircraft distance measurement (DME), cellular phone and pager signals, microwave ovens, orbiting satellites such as GPS, Glonass, DARS and Iridium, geostationary satellites and local interference from computers, oscillators and digital electronics associated with the BIMA millimeter array. Combining the results for radar and DME from RFIM and RPA, for example, allows us to measure the spectrum and the time occupancy from microsecond to day timescales (Figure 1). This detailed knowledge allows us to tailor mitigation strategies to the specific problem.

3. Engineered RFI Mitigation

The low sidelobes of the ATA offset Gregorian antenna are an important mitigator of RFI. These provide $\sim$ 40 dB rejection of interference signals which are outside of the primary beam.

The front end simultaneously receives signals over its entire frequency range. Thus, a strong interferer such as Iridium at 1625 MHz can saturate the front end even if the observations are tuned to a different frequency.

Figure 1. Plot of the time averaged power in one channel of the DME band on second, millisecond and microsecond timescales.



To compensate for this, 20 dB of headroom above the system temperature noise is available in both the broadband front end amplifier and in the optical fiber link between the antenna and the RF/IF downconverter.

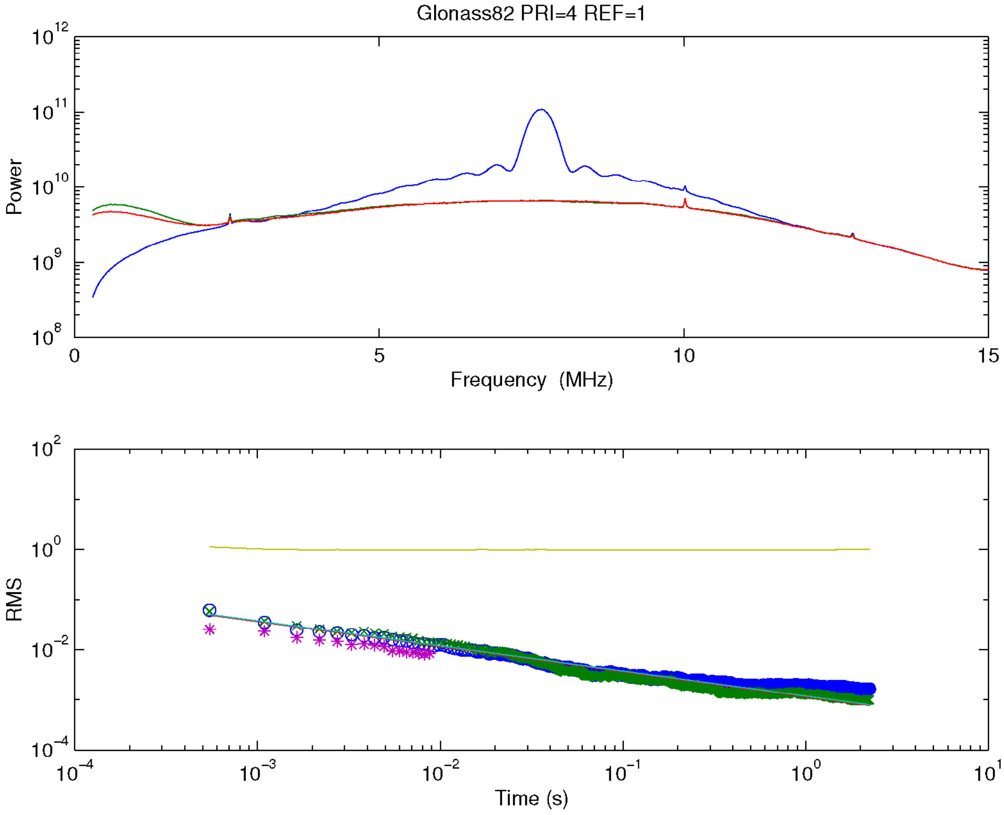
Similar techniques to prevent saturation and nonlinear effects of strong interfering signals are present throughout the system including the use of 8-bit ADCs in the IF processor. A polyphase filterbank in the correlator will prevent bleed-through of interference from one channel to the next.

4. Real Time RFI Mitigation

Scheduling is the first layer of defense against interferers in the real time system. To prevent saturation of the front end, artificial horizons will be placed around the most powerful interferers in the sky. The array will never point within 15 degrees of an Iridium satellite, for example. Additionally, the use of the RFIM will permit us to schedule experiments when particular interferers are quiet. Our monitoring has shown that aircraft DME is typically quiet in the early morning hours.

We expect to use at least four active techniques: time blanking, adaptive canceling, interferometric nulling, and post-correlation analysis. These techniques exploit the large-N nature of the ATA and are integrated into the digital design in some cases.

Figure 2. In the top panel, spectrum before (blue line) and after cancellation of a Glonass signal with a Wiener filter method. We show the residual power spectrum for single (green) and dual (red) polarization cancellation methods. In the bottom panel, blue circles and green crosses indicate the rms residual in the power spectrum from the single and dual polarization modes, respectively. These follow $t^{-1/2}$ laws (red and aqua lines). Purple stars indicate the rms residual for a measured noise spectrum. The gold line is the residual in the uncorrected power spectrum.



4.1. Time Blanking

Radar and aircraft DME occur in the frequency range from 960 - 1400 MHz. Without mitigation, it will be very difficult to observe extragalactic HI at redshifts between 0 and 0.5. While these signals overlap in frequency space with desired astronomy signals, they actually have a very small time occupancy (Figure 1). This is because they are pulsed rather than continuous. Research by Fisher (these proceedings) at the GBT has demonstrated that a predictive time blanker can achieve 90% observing efficiency. In the ATA, the time blanker will be a stand alone device that will provide blanking signals to the individual backends. Each backend can then blank or zero the signal in a way that best fits the scientific need. The time blanker will take input from the RFIM, a phased array signal, or one or more reference antennas taken from the array. Blanking can be on timescales as small as a microsecond and in individual frequency channels.

4.2. Adaptive Canceling

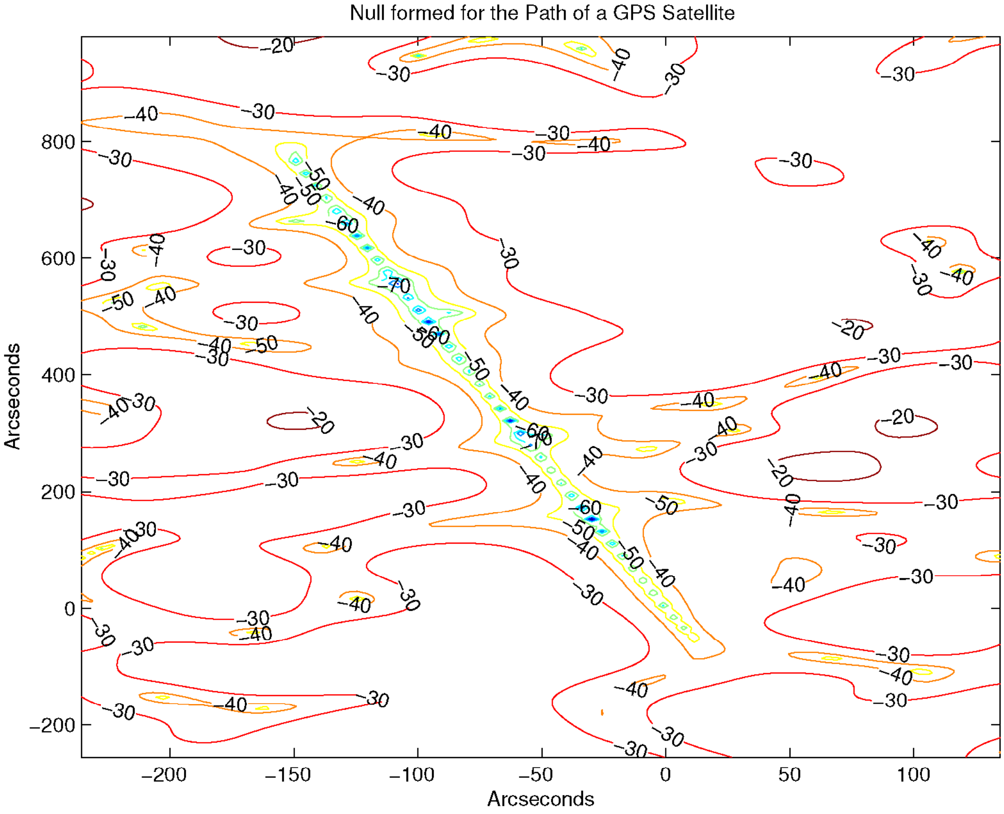
Reference antennas can also be used to implement adaptive canceling (Barnbaum & Bradley 1998, Ellingson et al. 2001). In this technique, a reference signal with a high interference-to-noise ratio is obtained and used to estimate the weaker interference present in the astronomy signal. The estimate is subtracted from the astronomy signal leaving the signal interference free. The estimate can be determined through a Wiener solution, an adaptive LMS method, or parametric estimation as in the case of GPS or Glonass where the interference signal is well-known. These techniques are inherently wideband and are insensitive to multi-path problems. They are ideal for interferers that can be tracked with an antenna: fixed transmitters and satellites with known trajectories. For the ATA, an adaptive canceler will be implemented as a stand-alone device which receives as input the signals from multiple reference antennas. The canceler will provide an interference free copy of the phased-array output of the ATA.

We have tested both the time and frequency-domain Wiener solutions and LMS methods with data obtained at the RPA (Bower 2001a, Mitchell & Bower 2001). We can achieve > 30 dB suppression of GPS and Glonass signals (Figure 2), where the limiting factor in these result is the amount of data that we have obtained, not the algorithm.

4.3. Interferometric Nulling

We can exploit the full power of the array through the use of interferometric nulling. For interfering sources in known positions, we can manipulate the complex gains of the array to place a null in the location of the interferer while maintaining most of the gain of the array in the direction of the astronomical source (Bower 2001b, Harp 2002). Since these gains must be updated rapidly for fast moving interferers, we have designed into the IF processor the capability to update the gains every 10 msec. In cases of multiple interferers or in cases of interferers with poorly determined positions, it will be desirable to place a large number of nulls on the sky (Figure 3). The ATA is well-adapted for this technique since the number of nulls which can be placed on the sky is limited by the number of antennas in the array (Figure 4). Finally, while this technique is intrinsically narrowband, we have shown that just as one can place multiple nulls in the spatial domain, one can place multiple nulls in frequence space. So, 100 nulls can be placed

Figure 3. Null formed for the path of a GPS satellite. Fifty individual nulls were placed along the 1.5 second path of the GPS satellite.

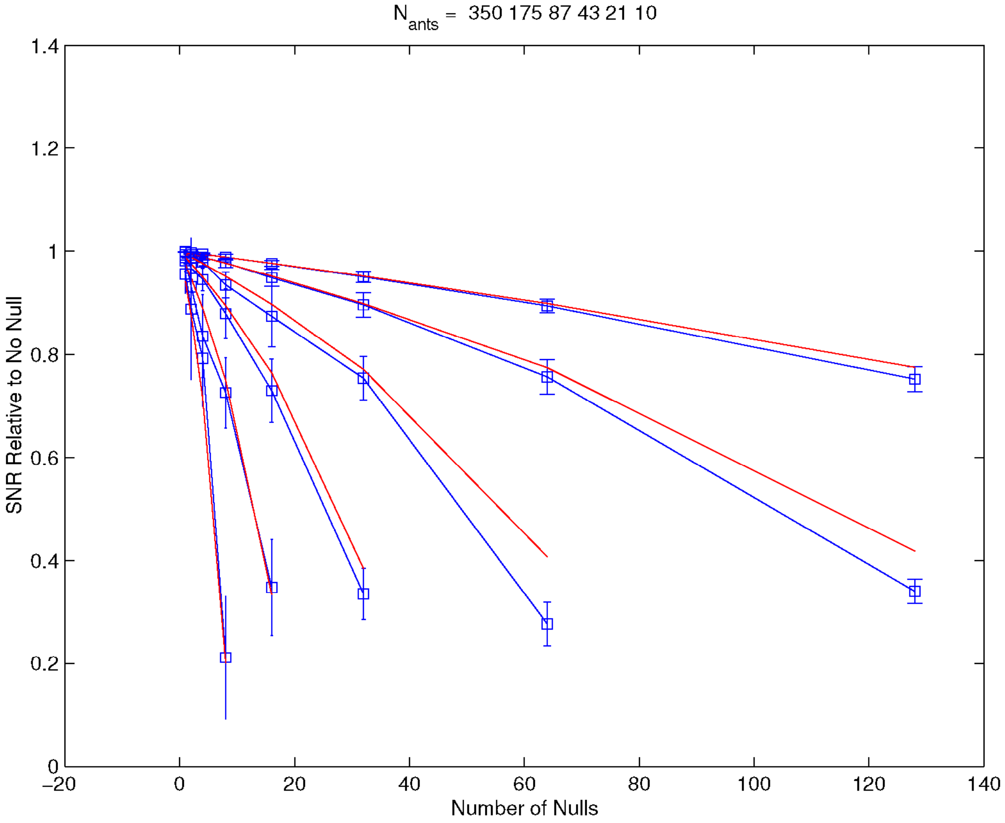


to null out a region that is 45 arcmin^2 in solid angle or 10 MHz in frequency space, while maintaining greater than 80% efficiency.

4.4. Post-Correlation Analysis

A number of mitigation techniques exist which require a measured correlation matrix (Leshem et al. 2000, Briggs et al. 2000). Some of these are essentially adaptive counterparts to the a priori technique of interferometric nulling described above. We are designing the correlator and its backend so that it is capable to implement these techniques. The correlator will be able to dump the correlation data at a maximum rate of 100 Hz, which is necessary for fast moving interferers. A multi-processor backend such as a Beowulf cluster will handle both general calibration and imaging tasks as well as implement post-correlation techniques. These techniques are very general in their application. The software implementation allows for a variety of techniques as algorithm development.

Figure 4. SNR at the phase center as a function of number of nulls and number of antennas. The blue curves indicate the results of simulations for arrays of 350, 175, 87, 43, 21 and 10 antennas. The red curves are the theoretical values expected. As an example, the ATA with 350 antennas can place more than 100 nulls while maintaining > 80% sensitivity.



5. Summary

We have described a variety of techniques for RFI mitigation with the ATA. These techniques exploit the unique capabilities of the ATA, especially the large number of antennas and the flexible digital electronics. The ATA will be the first array built with active mitigation strategies designed into the system.

We emphasize that these are experimental techniques. The flexibility of the system will allow us to develop and test these and other new techniques. Future generations of hardware will include substantially more sophisticated implementations.

6. References

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The National Radio Quiet Zone

Wes Sizemore & Jeff Acree

NRAO, Green Bank

Abstract
NRAO operates theNational Radio Quiet Zone at Green Bank. We briefly outline its salient characteristics, and our experience with its day to day operation.

1. Introduction

A very special, important, and as yet unique tool for spectrum management at the Green Bank site of the National Radio Astronomy Observatory is our National Radio Quiet Zone (NRQZ). This was set up in 1958 in the earliest days of Green Bank's use as a site for radio astronomy, while there was an imperative for the USA to match the Russian space exploits first heralded by their launching of the Sputnik satellites. The Green Bank site was carefully chosen in the first instance for its relative proximity to Washington, its radio-quiet properties that are in part due to terrain shielding, and for the natural features of its surroundings, which suggested there was little danger of its ever being densely settled or industrialized in the future. The Federal Government therefore determined at that time to augment these natural advantages by creating a radio-quiet zone around Green Bank, which is our NRQZ. The formal document detailing the coordination requirements and operational paradigm for the NRQZ is included here as an Appendix.

2. The Green Bank Radio Quiet Zone

Green Bank is not a totally radio-quiet site. The satellite services are sources of rfi for Green Bank, just as they are for everyone else. Moreover, in accordance with long established procedures of spectrum management, active services with existing valid transmitter licenses continue to have priority over new users. So the airport surveillance radar near Bedford, Virginia, about 104 km from Green Bank, continues to operate at 1256 & 1292 MHz: it thus remains a severe source of rfi for observers of red-shifted 21 cm radiation from galaxies (cf Rick Fisher's contribution to this volume). However, the grandfathered transmitters are not a big problem in the NRQZ, as it was established so long ago that there were VERY few pre-existing services. We in practice have more problems from transmitters on big mountains, just outside the NRQZ, which we could wish to be just a little bit bigger. Still, the problematic transmitters from outside the NRQZ are so few that we know them all. The key feature to the success of the NRQZ in remaining a radio-quiet zone is its terrain shielding.

Under the rules governing the NRQZ, which are administered by the FCC and/or the NTIA as appropriate, any potential licensee for the operation of new fixed transmitter(s) in the vicinity of the Observatory must engage in a close coordination with the NRQZ Administrator. This in practice means that the precise siting, and often the exact form of the installed equipment, can be adjusted so as to maintain Green Bank as a radio-quiet site after the new service is operational. For example from 538 transmitter sites evaluated in 2002, ERPd restrictions were required for only 24. In 2003 592 transmitter sites were evaluated with ERPd restrictions required for just 30. Nevertheless, by working diligently with the applicants, mutually acceptable solutions were found for most of the sites that were issued with power restrictions. Our experience thus shows that it is rare indeed for a technical solution to both the Observatory's needs and those of new licensees **NOT** to be found. Note, however, that it is not known how many applications were not filed as a result of the existence of the NRQZ.

Mobile transmitters are harder to control and necessitate eternal vigilance, both in identifying their licensing requests before their potential eruption on the scene, and in monitoring the real-time environment of the site. But they also offer some of our greatest satisfactions. An observer may experience unexpected rfi, on the basis of which he/she alerts the NRQZ administrator. The advantages of local know-how and long acquaintance with our local environment can then sometimes kick in. Thus on one such occasion we considered the time of day (Friday near 16:00), the time of the year (summer), and so deduced that X was quite probably mowing his field. We accordingly made a site visit, confirmed our deduction, and then successfully mediated an end to the rfi. On another occasion we got a call that broadband rfi was being detected by the observers. After loading our truck with a receiver, amplifier, spectrum analyzer, and a directional antenna, we set out to locate the source by triangulating our way to the spot, only to find that an old couple had a penned dog. The dog lay on a heating pad, which had become so worn that cracks in its wiring were arcing across. We preserved our radio-quiet environment in this case by replacing the pad. Our bottom line is that communal sources of rfi, both intentional and unintentional, that are not covered by the NRQZ rules, are handled with great success in a spirit of mutual cooperation.

Due to the ever-increasing demand for spectrum, the level of effort required to administer the NRQZ has grown steadily. We have a stream of licensee and potential licensee applications to evaluate in a timely and earnest fashion, some of which take a great deal of effort to reach mutually satisfactory coordination agreements. It is always best if potential licensees contact us at as early a stage as possible in their planning, since this is by far the most cost-effective way of initiating a new service. However a few of our reviews do result in bad feelings, and even threats of litigation. But the payoff for Astronomy from operating the NRQZ is large and very worthwhile.

The payoff for Green Bank as an operational site is probably even larger, as the existence of the NRQZ comes under attack from time to time. Until now these attacks have been fended off by concerned friends at NTIA, the part of government that looks after federal science interests with regard to their use of the spectrum, and by concerned members of Congress. However, the existence of the NRQZ was a prime motivation for the location of the new 100 m Robert C. Byrd Green Bank Telescope (GBT), and we trust that the significant investment in the GBT will, in turn, help to preserve the NRQZ.

3. Controlling Self-Generated RFI

The boon of having the benefit of a NRQZ makes it all the more incumbent and important for the Green Bank site to pay exceedingly close attention to controlling and suppressing all sources of self-generated rfi. Indeed this need has influenced many facets of the detailed design of the complement of equipment for the GBT, including particularly the sequestration of much of its digital equipment and control computers at a distance from the telescope in carefully shielded rooms. Using rfi conscious designs for the racks, housings, control & power lines, as well as shielded rooms our engineers have endeavored to make our in-house electronic systems "invisible" to radio astronomy instruments. These efforts naturally extend to limiting traffic movement around the site to transportation within the Observatory's own fleet of rfi-quiet diesel vehicles.

With time receiver systems become ever more sensitive. Green Bank has a history of making incremental improvements to its equipment, and is always pushing the bounds by lowering the system temperature: with the GBT we have also achieved greater sensitivity by using an off-axis feed arm to reduce both the blockage this would otherwise cause, and baseline ripple. But these improvements lead to a concomitant need to improve the levels to which rfi from on-site equipment is suppressed, which in turn leads to a need for ever better rfi-detection equipment. Our Interference Protection Group (IPG) has recently installed a remotely controlled field measurement station, and developed a 0.5 - 18 GHz portable rfi measurement system, as well as commissioned an anechoic chamber, the better to characterize rfi from individual pieces of equipment. Finally our staff continues to work diligently to mitigate power line rfi and other sources of interference originating in the local community.

4. Community relations

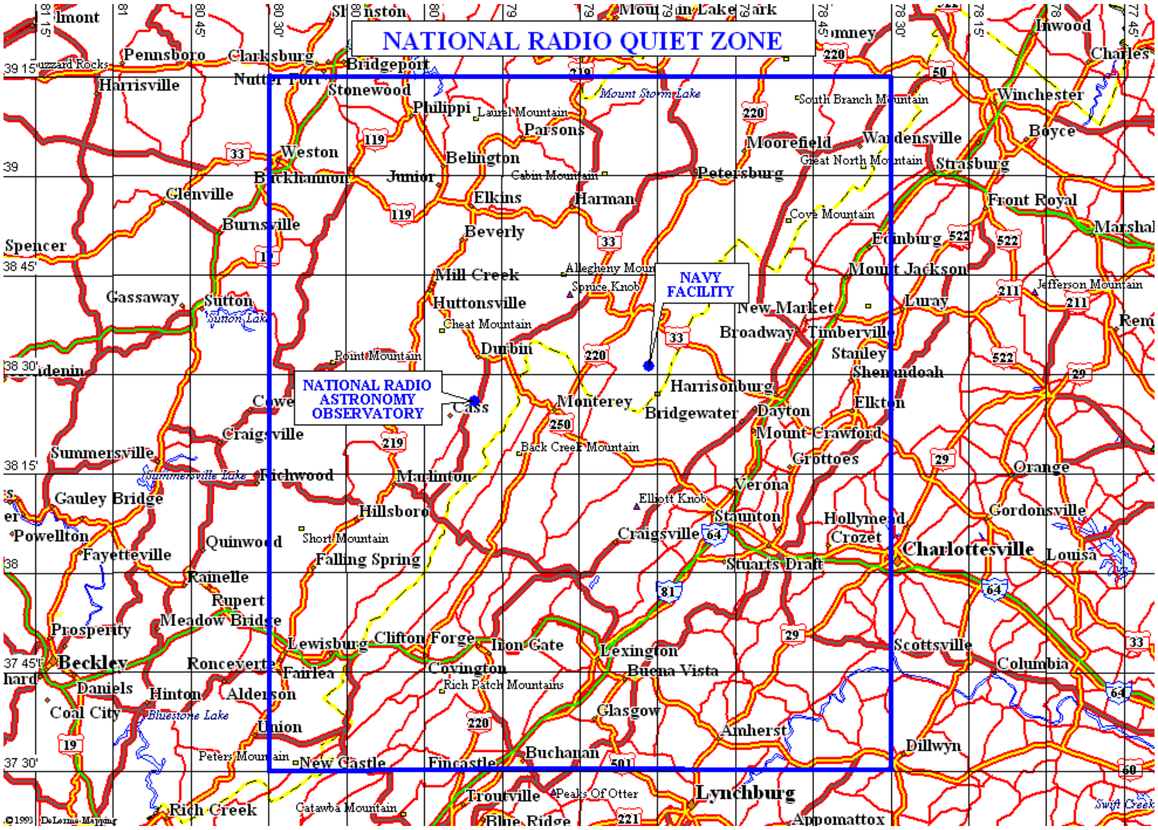
The Green Bank telescope attracts tourists, which in its own right presents challenges. Many of the needs of tourists are accommodated in our new Science Center, which is of course well shielded and located near the edge of our site. Moreover visitors enter the Center via a curving corridor lined with very evident radio-wave absorbing material, to ensure that its exhibits do not produce any radiation that can escape to the outside. We thus kill two birds with one stone, by using the occasion of visitors seeing the Observatory to impress on them the detrimental effect rfi has on our observations, as well as the need for having a NRQZ to further our science. Acceptance of the constraints of an operational NRQZ is naturally dependent on the continuance of good public outreach, as well as an ongoing demonstration of the positive aspects of hosting an Observatory for the surrounding community.

Appendix

National Radio Quiet Zone

Description

The National Radio Quiet Zone (NRQZ) was established by the Federal Communications Commission (FCC) in Docket No. 11745 (November 19, 1958) and by the Interdepartmental Radio Advisory Committee (IRAC) in Document 3867/2 (March 26, 1958) to minimize possible harmful interference to the National Radio Astronomy Observatory (NRAO) in Green Bank, WV and the radio receiving facilities for the United States Navy in Sugar Grove, WV. The NRQZ is bounded by NAD-83 meridians of longitude at 78d 29m 58.0s W and 80d 29m 58.5s W and latitudes of 37d 30m 0.9s N and 39d 15m 0.8s N, and encloses a land area of approximately 13,000 square miles near the state border between Virginia and West Virginia.



Coordination Requirement

In order to minimize harmful interference to operations in Green Bank and Sugar Grove, all requests for frequency assignments within the NRQZ shall be coordinated by the applicant, prior to authorization, with:

Director (Attn: Interference Office)
National Radio Astronomy Observatory
P. O. Box 2
Green Bank, WV 24944

This procedure applies to all stations except mobile and transportable stations.

Federal Government Transmitters:

All frequency assignments for Federal Government transmitters which are to be located within the NRQZ are required by the National Telecommunications and Information Administration (NTIA) to be successfully coordinated with the NRAO Interference Office prior to the approval of the assignment.

Non-Federal Government Transmitters:

All applicants for non-Federal Government transmitters for certain radio services within the NRQZ are required by the FCC to notify the NRAO Interference Office prior to or simultaneously with the filing of the FCC application. Both a copy of the completed FCC application form and the antenna technical data should be sent to the Interference Office.

Applicants for some radio services are required to file their applications through independent frequency coordinators (e.g. APCO, PCIA, and IMSA). The coordinators assume the responsibility of notifying the Interference Office that an FCC application has been filed and hold the application until the Interference Office responds with its evaluation.

Transmitter Evaluation

The NRAO Interference Office reviews all assignments or applications for new or modified fixed transmitters within the NRQZ to insure that the computed power flux density at the reference point does not exceed frequency-dependent thresholds. In order for the Interference Office to accurately and promptly review the transmitter application, the applicant should forward the following technical data to the Interference Office:

Name and address of applicant.
Radio service.
Frequency of each transmitter.
Transmitter power.
Transmission line losses in dB.
Antenna location(s) in latitude and longitude to nearest second.
Antenna site ground elevation(s) above mean sea level (AMSL).
Antenna height(s) above ground level (AGL).
Antenna gain or horizontal pattern and orientation in azimuth.

These data are required to compute the transmitter's effective radiated power relative to a dipole (ERPd) towards Green Bank, WV and Sugar Grove, WV.

In some instances, the ERPd requested by an applicant exceeds the level that is harmful to observations in Green Bank or Sugar Grove. When this occurs, applicants should discuss possible modifications to their transmitters (e.g. using a directional antenna, relocating the antenna to an area that provides additional terrain shielding, or selecting a different frequency where the power density limits are different) with the Interference Office. In our experience, a technical solution can almost always be found to provide the area coverage desired by the applicant while simultaneously minimizing the impact of the interference upon Green Bank or Sugar Grove. In the extremely rare case when differences between the applicant's desires and the Interference Office's evaluation cannot be resolved, both the applicant and the Interference Office should forward comments on the transmitter installation to the FCC or IRAC for a final resolution.

We emphasize that the Interference Office has no authority in the granting of an FCC license or a Federal Government frequency assignment. The Interference Office only has the privilege of submitting its comments on a particular transmitter installation to the FCC or IRAC.

Applicants who feel that their applications have been evaluated unfairly or inadequately can contact the office of the Green Bank Site Director for a review of their circumstances.

Preliminary Evaluations

As a service to applicants who are planning to install transmitters within the NRQZ, the Interference Office can evaluate proposed transmitter installations long before an applicant decides upon a final transmitter location or equipment configuration. These preliminary evaluations can help the applicant determine the best location for a transmitter while keeping NRQZ interests in mind and can ultimately expedite the application process. The result produced by the preliminary evaluation is the maximum ERPd that can be radiated by the proposed transmitter towards Green Bank. Requests for preliminary evaluations should be submitted to the Interference Office at the above address and should contain the following information:

Name and address of proposer or future applicant.
Radio service.
Frequency of each transmitter.
Antenna location(s) in latitude and longitude to nearest second.
Antenna site ground elevation(s) above mean sea level (AMSL).
Antenna height(s) above ground level (AGL).

Reference Point

The reference point for calculations of transmitter power density is the prime focus of the Green Bank Telescope (GBT). The location of the GBT prime focus is

Latitude: 38d 25m 59.2s N (NAD83)
Longitude : 79d 50m 23.4s W (NAD83)
Ground Elevation : 776 Meters or 2546 Feet AMSL (NAVD88)
Height : 139.6 Meters or 458 Feet AGL

Power Density Thresholds

The calculated power density of the transmitter at the reference point should be less than

1 x 10^{-8} W/m^2 for frequencies below 54 MHz
1 x 10^{-12} W/m^2 for frequencies from 54 MHz to 108 MHz
1 x 10^{-14} W/m^2 for frequencies from 108 MHz to 470 MHz
1 x 10^{-17} W/m^2 for frequencies from 470 MHz to 1000 MHz
f 2 (in GHz) x 10^{-17} W/m^2 for frequencies above 1000 MHz

except for frequencies that reside in the radio astronomy observing bands, in which case the power densities listed in Recommendation ITU-R RA.769-1 shall apply.

Applicable Radio Services

The radio services that are affected by the NRQZ and the FCC rules that discuss them are:

FCC Rule	Radio Service
1.924	Public Mobile, Wireless Communications, Maritime, Aviation, Private Land Mobile, Personal Radio, Fixed Microwave
21.113(a)	Domestic Public Fixed
23.20(b)	International Fixed Public
25.203(f)	Satellite Communications
73.1030(a)	Radio Broadcast
74.12, 74.24(i)	Exp., Aux., & Special Broadcast
78.19(c)	Cable Television Relay
97.203(e), 97.205(f)	Amateur Radio (repeaters, beacons)

NRQZ coordination is also required for the Personal Communications Service (FCC Part 24) and the General Wireless Communications Service (FCC Part 26). These services are not exempt from NRQZ coordination under geographic area licensing.

For more information about the NRQZ please contact:

Denise Wirt
(304-456-2107)

or

Jeff Acree
(304-456-2157).

Radio-Quiet Zones

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Abstract

In order to protect a radio observatory from radio frequency interference we need a package of measures to deal with the many different aspects of the problem. We need regulatory protection at the highest level, we need strong local protection, and finally we need self-protection through interference mitigation techniques. The International Telecommunication Union provides regulatory protection from licensed radio transmitters, through the allocation of passive frequency bands, through limits to unwanted emissions, and so on. The ITU process of coordination can be used to safeguard radio astronomy in shared frequency bands, by keeping radio transmitters at calculated distances from an observatory. At mm-waves it is feasible to coordinate transmitters at all frequencies, not just those allocated to radio astronomy. Such a coordination zone is being negotiated for ALMA. The ITU-R Recommendations on radio astronomy also draw attention to two naturally quiet zones in space: the shielded zone of the Moon, and the Sun-Earth Lagrangian point L_2. Terrestrial radio observatories also need local protection against electrical devices not commonly recognized as radio transmitters ranging from heavy machinery to consumer electronics, which are ouside the remit of the ITU. A radio-quiet zone (RQZ) can be set up locally using state or national law to restrict housing and industrial developments in the vicinity of a radio observatory and to restrict the use of electrical equipment. The largest and best known such radio-quiet zone is that about Green Bank (described elsewhere in this volume). It is noteworthy that this RQZ was set up before the large radio telescopes were built at the site, and indeed before there were any frequency bands allocated to radio astronomy. Future large facilities, such as the Square Kilometer Array, will require a new type of international RQZ to gain access to much more of the spectrum than the officially allocated bands, and to receive protection from transmitters on satellites. The OECD Task Force on Radio Astronomy and the Radio Spectrum has considered this issue. The report of this task force is expected to recommend among other things the early identification of a small number of sites for International RQZs, with a view to getting protection for these sites onto the agenda for WRC-07.

A fuller version of this contribution has been published as:

"*Radio-Quiet Zones: protection of radio astronomy sites"* by R. J. Cohen, G. Delgado, E. Hardy, T. Hasegawa, and L.-A. Nyman, 2003, *In "Light Pollution: The Global View*", ed. Hugo E. Schwartz, pp 225-257 (Kluwer Academic Publishers, Dordrecht, The Netherlands).

Monitoring EMI and the radio spectrum in Europe

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Abstract
This paper provides some comments on monitoring electromagnetic interference and spectrum occupancy. It also gives details on the monitoring facilities available in Europe and on the functions of the CRAF monitoring database tools.

1. Introduction

A quiet and interference-free “radio”-climate and “radio”-weather are necessary prerequisites for high quality radio astronomy observations. Daily practice, however, shows that radio astronomy observations often suffer from harmful interference, even in frequency bands allocated to radio astronomy.

Understanding and quantifying the impact of man-made transmissions on radio astronomy observations enables radio astronomers to take adequate action to alleviate this problem, either by quantifying the interference and bringing such data to the attention of the Administrative Authority that is mandated to take action to cure the problem, or by developing operational measures at the victim radio astronomy station.

One of the means to develop knowledge about the “radio”-climate within which observations are done is to perform dedicated monitoring. In some instances, monitoring is seen as *the* key to obtaining knowledge about the probability of being able to make high-quality interference-free observations.

2. Before you start

Before speaking of “*the* key to obtaining” and starting on monitoring, an initial question must be answered: "*What is the question you want to answer with this activity*”? The answer to this specific question must determine which data are monitored, with what time frequency, with what accuracy, etc. The collection of large amounts of data should be avoided by all means, since at some moment in time (usually much sooner than one expects) it will be noted that the complexity of the issue at stake implies that the database is no longer manageable.

Furthermore, it is strongly recommended that one store and exchange the monitoring data in a harmonized data format to ease the exchange of information between interested parties.

3. Instrumentation

Several radio astronomy stations operate monitoring facilities in parallel with their regular observations. Usually one observes as a function of frequency where the spectrum is occupied or clean. Although this monitoring is very useful, it should be noted in such a project that one does not monitor radio frequency interference, RFI, or electromagnetic interference, EMI, but rather spectrum occupancy: *monitoring spectrum occupancy is not EMI/RFI monitoring.* Spectrum occupancy does not give information about the interference one suffers in an observation.

Interference is "*the effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunication system, or loss of information which could be extracted in the absence of such unwanted energy*", as the ITU Radio Regulations define in their Article 1.166. This implies that a radio astronomer can only obtain information about EMI by inspection of the observations themselves. EMI is then understood as the 'quantification' of the degradation of the quality of an observation due to unwanted emissions, radiations, or inductions upon reception in a radiocommunication system. Thus monitoring EMI is exclusively done by inspection of radio astronomical observations.

Spectrum occupancy information identifies the probability of becoming a victim of interference. This information can be useful both for the management of a radio astronomy station and to its operators when they make decisions about scheduling, frequency selection, and project planning.

While the monitoring of spectrum occupancy is done by dedicated instruments, the monitoring of EMI can only be done with the radio telescope itself during an observation. This implies that the telescope is really the best monitoring station for its EMI troubles.

4. Purpose of monitoring

Monitoring EMI provides quantified evidence and details about interference that can be used in discussions with the responsible Administrations in the case of interference trouble. It should be noted that when interference is not adequately reported to the Administrations, the interference does not exist and the Administration concerned cannot take action!

Monitoring of the development of the EMI "climatology" or "weather" provides useful additional information which is also relevant for the Administrations.

Quantified knowledge about the "radio"-climate and "radio"-weather sets the stage for improving the observing conditions at the radio astronomy station concerned. It may also serve to inform special projects, such as the development of interference-robust receivers, and interference-suppression techniques.

5. Europe

At present, about a dozen European radio astronomy stations have their own facilities (fixed or mobile) for monitoring spectrum occupancy; and about half a dozen of them are also stations in the European VLBI Network. This information is usually kept in house: but “all data are stored”.

5.1 CRAF facilities

CRAF has developed and currently manages a facility to manipulate monitoring data for all European radio astronomy stations. This facility is accessible via the CRAF website. Data are fed to the CRAF clearing house in the so-called ‘CRAF data-format’, which is a slight variant on the data-format used by NASA for similar work. This means that with a little transformation software the CRAF database and the NASA databases can be combined in principle.

CRAF has developed a range of analysis tools for both the EMI and spectrum occupancy database. Both databases have the same data format. The EMI database can be queried through the following options:

- Interference intensity as a function of time of the day
- Interference intensity as a function of days of the week
- Interference intensity as a function of frequency
- Development of interference intensity as a function of time
- Observational degradation as a function of time of the day
- Observational degradation as a function of days of the week
- Observational degradation as a function of frequency
- Development of observational degradation as a function of time
- Interference occurrence as a function of time of the day
- Interference occurrence as a function of days of the week
- Interference occurrence as a function of frequency
- Development of interference occurrence as a function of time

The spectrum occupancy database can be queried through the following options:

- Signal intensity as a function of time of the day
- Signal intensity as a function of days of the week
- Signal intensity as a function of frequency
- Development of signal intensity as a function of time
- Signal occurrence as a function of time of the day

- Signal occurrence as a function of days of the week
- Signal occurrence as a function of frequency
- Development of signal occurrence as a function of time

It is obvious that the latter facility has fewer options to query than the EMI database since the number of different questions that can be answered properly is less. Ausername and a password because in many countries it is strictly forbidden to monitor spectrum occupancy or to 'publish' monitoring data. One of the reasons behind this is obviously commercial sensitivity.

5.2 Administrations

Administrations usually operate some kind of monitoring facilities, though this effort generally addresses ground-based interferers. The German Administration's facility is at Leeheim, near Darmstadt, which specializes in monitoring space systems.

In some countries there is an increased interest in monitoring by the Administration (e.g. in The Netherlands, where there is close cooperation between the Administration and the radio astronomers on the exchange of information). At the pan-European scale, the Administrations forming the "Conférence Européene des Postes et des Télécommunications", CEPT, agreed in a Memorandum of Understanding on satellite monitoring. This MoU arranges coordination between Administrations on satellite monitoring and adequate funding of this activity. The German Leeheim monitoring station is the key node in this activity and is therefore developing into *the* European station for satellite monitoring.

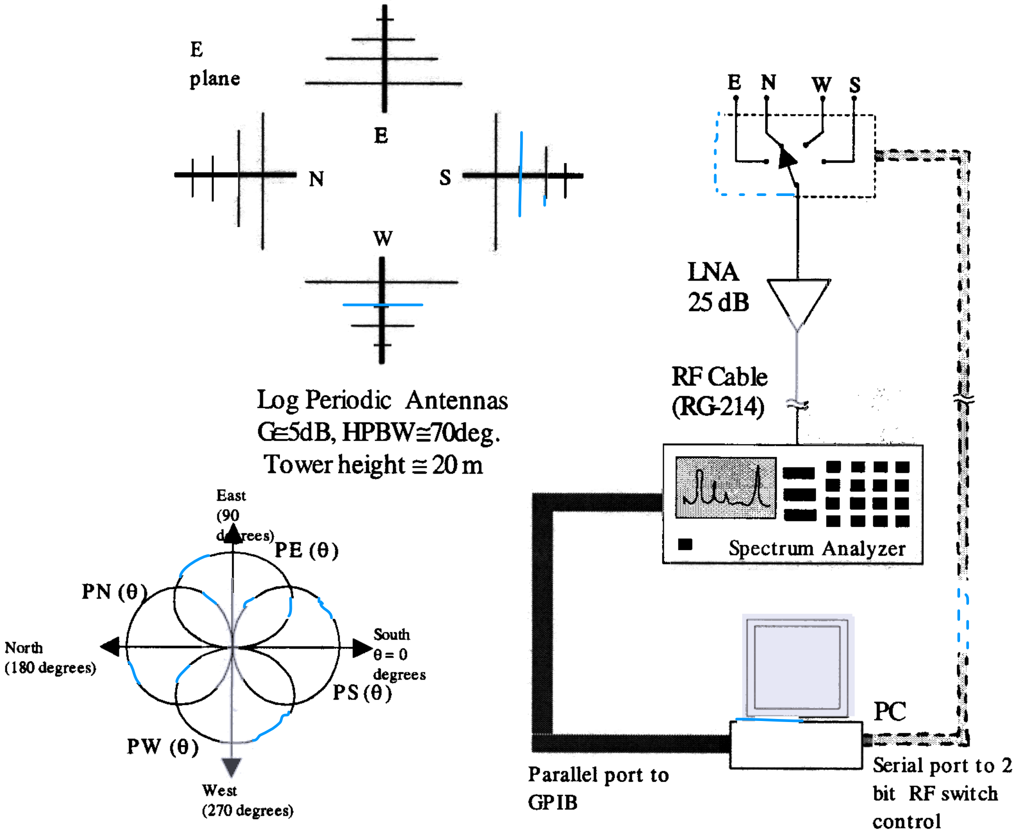
The Omnidirectional RFI Monitoring System of GMRT

Shubhendu Joardar

Abstract: RFI is a major concern at GMRT and there are number of tools for studying interference. We describe here an omnidirectional RFI monitoring system (ORMS) that has been recently developed. It consists of 4 log periodic antennas (LPA) pointing to the east, west, north and south directions mounted on a tower at a height of 20m. The RF spectrum in the four directions is recorded sequentially. Software tools have been developed to display the data and estimate the direction of the incoming RFI.

Introduction: The radio astronomy community is facing a serious problem of frequency protection for scientific observation. Although a lot of the progress has been made in radio observation technology, the radio environment is deteriorating and we stand virtually at the same place facing new RFI problems and trying to find some solution. The GMRT (Giant Meter-wave Radio Telescope) though located in a remote location is still facing these difficulties. Radio interference recorded over the year 2001-2002 in the 150, 233 and 327 MHz bands clearly indicate the problems from artificial RFI is worsening.

Hardware details: Fig.1 shows basic hardware of ORMS. A radiation pattern in the E-plane at 150 MHz is shown in Fig. 2.



Overall radiation pattern in the E-plane

Fig. 1: The Omnidirectional RFI monitoring system of GMRT

Hardware details: Fig.1 shows basic hardware of ORMS. A radiation pattern in the E-plane at 150 MHz is shown in Fig. 2.

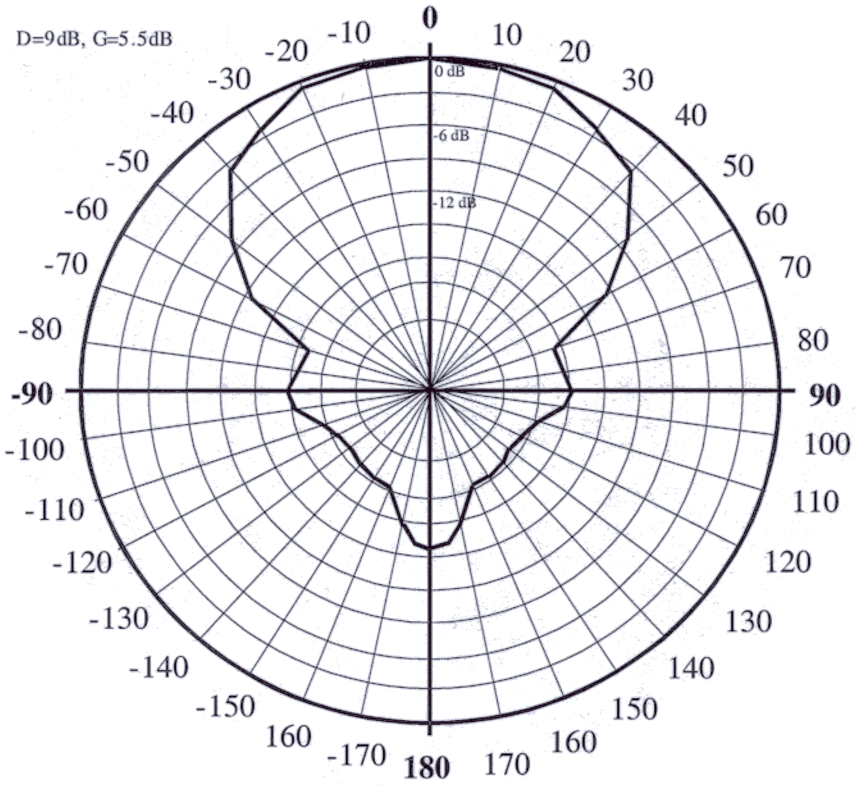


Fig.2: E-Plane radiation pattern at 150 MHz of the LPAs used in ORMS

The rest of the RF characteristics are listed below:-

Antenna characteristics:

Frequency (MHz)	***Gain (dB)***
150	5.67
233	4.7
327	4.2
610	4.4

RF switch:

RF Switch type	***Manufacturer***	***Model no.***	***Insertion loss (dB)***
SP4T	Mini Circuits	ZSDR-425	1.1

LNA:

Model No.	***Manufacturer***	***Avg. Gain (dB) measured***	***Noise Fig. (dB)***
ZFL-1000LN	Mini Circuits	25	2.9

Spectrum Analyzer: HP 8590 L

RF Cable: An RF cable (RG-214) of 100 m length is connected after the LNA to the spectrum analyzer. The cable loss is listed below:

Frequency(MHz)	***150***	***233***	***327***	***610***
Cable loss (dB)	1.4	2.2	2.9	6.1

System: The LNA receiver temperature is calculated as 754 K. 75% of the antenna beam faces the sky and the rest faces the ground.

Frequency (MHz)	***150***	***233***	***327***	***610***
Sky temperature (K)	308	99	40	10
Antenna temperature (K)	306	149.25	105	82.5
System temperature (K)	1062	903	859	836.5

Sensitivity: Minimum resolution bandwidth = 3 KHz.

Minimum receptable signal by the spectrum analyzer = -125 dB

S = (4 π Pin)/(G λ^2) ....(1)

Pspec = (Pin Gamp)/(Lswitch Lcable) ....(2)

where,

S = Power flux density per unit area appearing at the antenna.
Pin = Power appearing at the antenna terminals.
G = gain of the antenna (frequency dependent).
Pspec = Power reaching the spectrum analyzer
Gamp = Gain of the LNA (almost constant over 30 – 1000 MHz).
Lswith = Insertion loss of the RF switch (nearly constant over 30 - 1000 MHz).
Lcable = Loss of the RF cable (frequency dependent).

Frequency (MHz)	***150***	***233***	***327***	***610***
S (mW/m^2)	2.68 10^-15	1.14 10^-14	3.6 10^-14	1.9 10^-13

Software: There are two types of software; one for operating the system and the other for analysing the data.

System operating software: The output from the antennas are multiplexed using a computer controlled RF switch followed by an LNA and the signal is fed to the spectrum analyzer through an RF cable of 100m length. The spectrum analyzer is also controlled by the same PC using a printer-port to GPIB conversion software. The PC also participates in data dumping by the spectrum analyzer and its storage.

Spectrum analyzer control through GPIB (Printer port GPIB communication software):

Most of the computers available today have a bidirectional printer port. The GPIB has 3 control bits which are connected to 3 control lines of the printer port. The 8 data lines of the GPIB is mapped 1:1 by the printer port data lines. The end or identify (EOI) line of the GPIB is connected to one of the five status lines of the printer port. The actual operation is software based which functions in the following manner:

Initialization: The PC identifies and initializes the connected device (Spectrum Analyzer).

Writing string into the device: The PC writes the command strings into the Spectrum Analyzer's buffer.

Get data string from the device: When the Spectrum analyzer indicates that the data is ready the PC reads this data from the buffer in the form of a strings.

The first step is executed once at the start. Later the second and the third steps follow each other till the data acquisition is complete.

SP4T RF Switch controller:

The SP4T switch requires two TTL inputs for port selection, viz.00-East, 01-West, 10-North, 11-South. The DTR (Data Terminal Ready) and RTS (Request to Send) bits in the modem control register of the UART of a serial communication port of a PC can be held in 0 or 1 positions. Since the output of a serial port is RS-232, the voltage levels are converted to TTL first before sending it to the switch.

After one set of data collection through GPIB

The overall system operation through software is shown in figure 3.

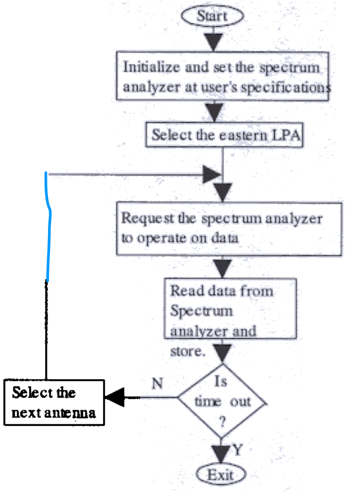


Fig 3. flow chart for system operation

Data analysis software: Fig.4 shows the basic flow chart of the data analysing software.

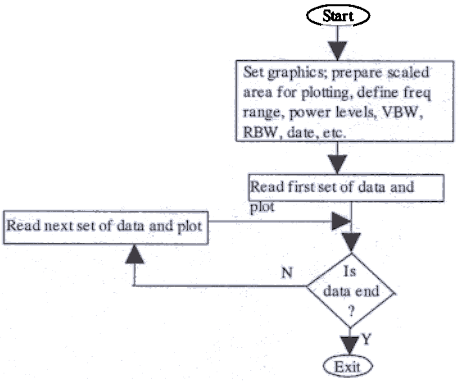


Fig 4. flow chart for data analysis

RFI Direction finding: The actual direction of the incoming signal is obtained from some algorithms based on the radiation patterns. The entire azimuth angle can be divided into four quadrants, viz. E-N, N-W, W-S and S-E. Let the normalized radiation patterns of the east, west north and south antennas be expressed as a function of azimuth angle θ , viz. $P_E(\theta)$, $P_W(\theta)$, $P_N(\theta)$, $P_S(\theta)$. The ratio of the radiation pattern of adjacent antennas falling in a quadrant for the 150 MHz is shown in fig.5.

To detect the direction of an RFI line, the power levels are various antennas are compared first. The antenna pair delivering largest and the second largest power signifies the azimuth quadrant of the incoming RFI. The direction angle θ corresponding to the ratio of largest power to second largest power is found from a graph shown in fig.5.

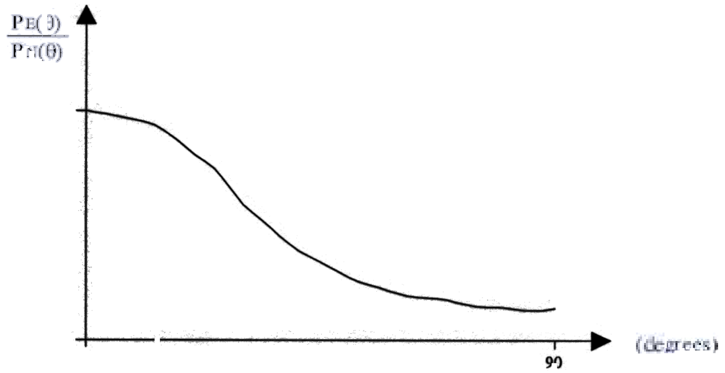
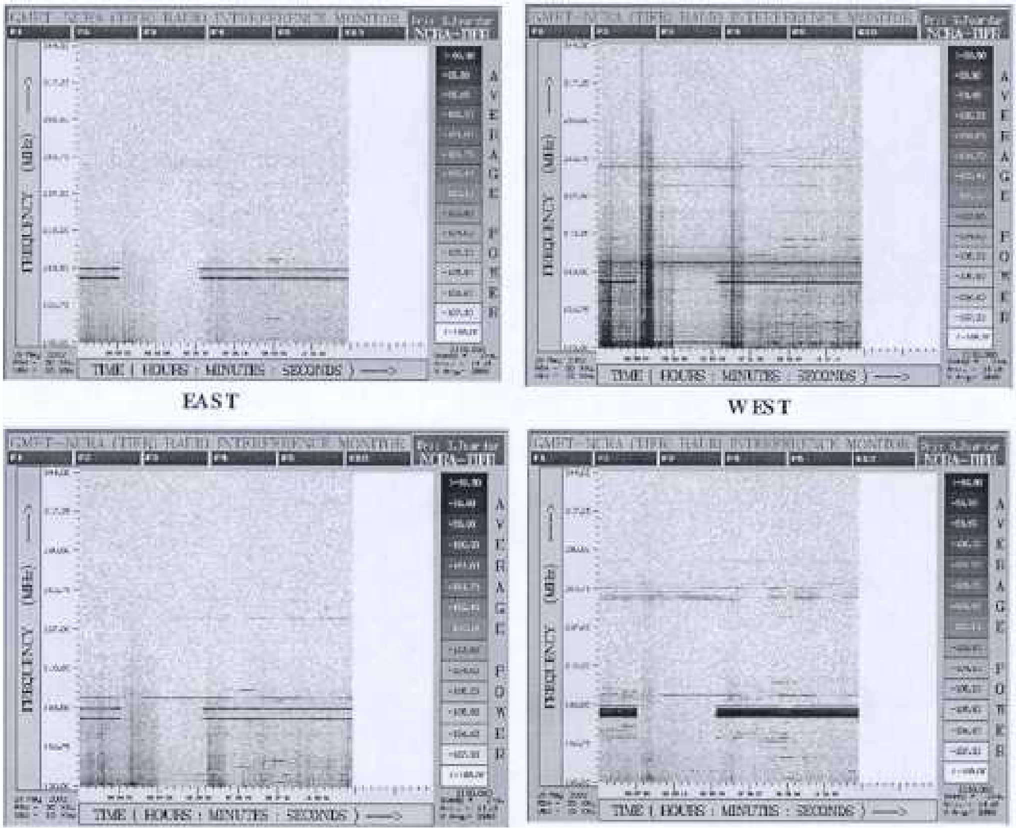


Fig.5 Adjacent antenna's radiation pattern ratio
Reference Antenna: East, 150 MHz



EAST

WEST

NORTH

OUTH

Fig 6: Power line and TV Interference; data taken in GMRT

Fig. 6 shows a set of gray plot data observed using the GMRT RFI monitoring system.

The vertical dark patches spread over wide frequency shows the power line interference from high tension ac lines in the N-W quadrant. There was a power failure between 2:35 to 5:30 hrs where we find the patches absent.

The two dark lines and some of their sister lines sitting near 175 MHz are from a TV transmitter located towards south.

To conclude, the GMRT is facing the problems from RFI. Instrumentation like ORMS are being added to assist the GMRT. .

Acknowledgment: I am thankful to the students and trainees of GMRT: Vikram Kharat, Bandhumoni Roy Rahul Bhosale and Syed Minhaj, who also worked on this project. I am also thankful to Prof. S.Ananthakrishnan and Prof A.Pramesh Rao for their guidance and help.

RFI Mitigation / Excision Techniques

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Abstract

Radio frequency interference (RFI) is increasingly affecting radio astronomy research. A few years ago, active research to investigate the possibility of observing in the presence of interference using RFI mitigation techniques was initiated. In this paper, I briefly discuss four RFI mitigation/excision projects. These projects are: (1) A technique to suppress double sideband amplitude modulated interference using which I show that an astronomical signal in the presence of a DSB interference can be observed with a signal-to-noise ratio a factor of 2 less compared to observations if the RFI were not present. (2) Techniques to suppress interference due to synchronization signals in composite video signals are presented. A combination of noise-free modeling of the synchronization signals and adaptive filtering is used for suppressing the interference. (3) Design techniques to minimize spurious pick-up at the analog input of an Analog-to-digital converter are discussed. (4) Spectral RFI excision using a spectral channel weighting scheme and its application to Green Bank Telescope observations are also presented.

1 Introduction

The need to find ways to deal with radio frequency interference (RFI) is becoming more urgent because: (1) increase in research interests outside the allocated frequency bands for radio astronomy and (2) growing technological resources which are potential sources of radio frequency interference. Spectrum regulations alone cannot help future astronomy research. Active research was started a few years ago to investigate the possibility of doing radio astronomy observations in the presence of interference using RFI mitigation techniques. Several new mitigation techniques have been developed and applied on radio astronomy data in the past few years [1 and references therein].

In this paper I briefly discuss four RFI mitigation/excision projects. These projects are (1) technique to suppress double sideband (DSB) interference; (2) technique to cancel composite video signal interference; (3) design of a "clean" Analog-to-Digital converter (ADC) and (4)spectral RFI excision.

2 'DSB suppressor'

Consider an astronomically interesting spectral feature (for example, a red-shifted HI feature; see Fig. 1) at the upper sideband side of a DSB modulated interference. The output of the radio telescope can be written as

$$y(t) = I_c\cos(\omega_c t)\,[1 + I_m\cos(\omega_m t)] + n(t) \tag{1}$$

where, I_c & ω_c are the amplitude and angular frequency of the carrier signal, I_m & ω_m are the amplitude and angular frequency of the modulating signal and $n(t)$ is the astronomical signal. For simplicity, we consider only one Fourier component of the modulating signal. Multiplying $y(t)$ with $\sin(\omega_c t)$ gives

$$y'(t) = \frac{I_c}{2}\sin(2\omega_c t)\,[1 + I_m\cos(\omega_m t)] + n(t)\sin(\omega_c t) \tag{2}$$

Equation (2) shows that after multiplication the interfering signal will be present only at $2\omega_c$ and not at the baseband. The astronomical signal $n(t)$ is essentially a Gaussian random noise. Multiplying $n(t)$ with $\sin(\omega_c t)$ therefore produces noise signals at $(\omega+\omega_c)$ and $(\omega-\omega_c)$ frequencies. The noise at $(\omega+\omega_c)$ is contaminated by interference. The noise at $(\omega-\omega_c)$ frequency is at the baseband free of any interference (see Fig. 1). However, at the baseband, the noise below ω_c folds back resulting in a degradation of the signal-to-noise ratio by 2 compared to the detection of the astronomical signal in single sideband mode in the absence of the interfering signal.

In reality, the phase of the carrier frequency changes with time due to a variety of reasons, like for instance propagation effects. This change has to be taken into account by the suppressor for effective RFI rejection. This is done by filtering the

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[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

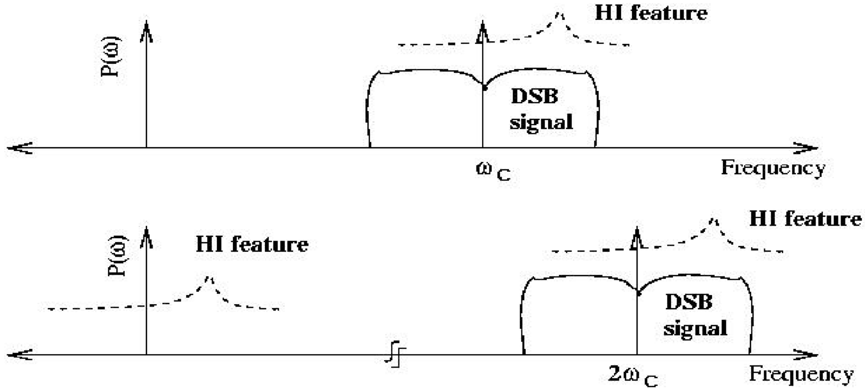

Figure 1: Schematic of the power spectrum of a double sideband (DSB) modulated interference along with an HI feature (top). The carrier frequency of the DSB interference is ω_c. The bottom figure shows a schematic of the spectrum after multiplying the RFI contaminated signal with the quadrature of the carrier of the DSB interference. The DSB interference is translated to $2\omega_c$ due to the multiplication. The astronomical signal will be present at the baseband as well as near $2\omega_c$ after multiplication. Thus low-pass filtering the multiplied output will give the astronomical signal without any RFI contamination. The spectral components of the astronomical signal and any noise below the carrier frequency, however, folds back in frequency at the baseband. This results in the degradation of signal-to-noise ratio by a factor of 2 compared to the case when the astronomical signal is observed in the absence of DSB interference.

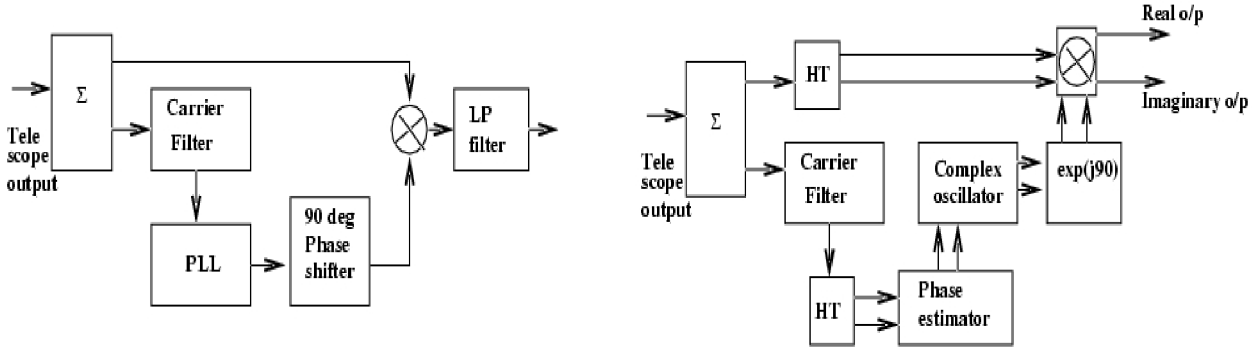

Figure 2: Simplified block diagrams of a 'DSB suppressor' (left) and its MATLAB implementation (right).

carrier signal from the output of the telescope and phase locking with an oscillator (see Fig. 2). The oscillator is then phase shifted by 90^o and mixed with the telescope output. The mixer output is low-pass filtered to get the desired astronomy signal. We implemented a variation of this technique in MATLAB, where a Hilbert transform of the telescope output is taken first to convert it into an analytic signal. This signal is then multiplied with a complex oscillator, which is phase locked to the carrier. The output of the multiplier is now a complex signal. The real part of the complex output ('real' output) is equivalent to that described above. The imaginary part of the complex output ('imaginary' output) is equivalent to the telescope output being multiplied by the oscillator signal with 0^o phase shift with respect to the carrier – essentially a coherent detector.

The performance of the 'DSB suppressor' is measured using a data set consisting of DSB modulated video signal in NTSC format (see Section. 3.1 for details on the data). Fig. 3 shows the result of the performance test. The measured *lower limit* on the interference rejection is $\sim$ 12 dB. The limitations of the 'DSB suppressor' are: (1) good suppression can be achieved only if both sidebands are of equal amplitude and their relative phase is as expected theoretically and (2) any non-DSB noise from the interfering source will degrade the system temperature of the radio telescope. From an observational point of view, the DSB suppressor is good for continuum observations. For spectroscopic observations, the spectral feature should be positioned either on the upper or lower side of the carrier frequency. Otherwise the spectral feature gets folded in frequency.

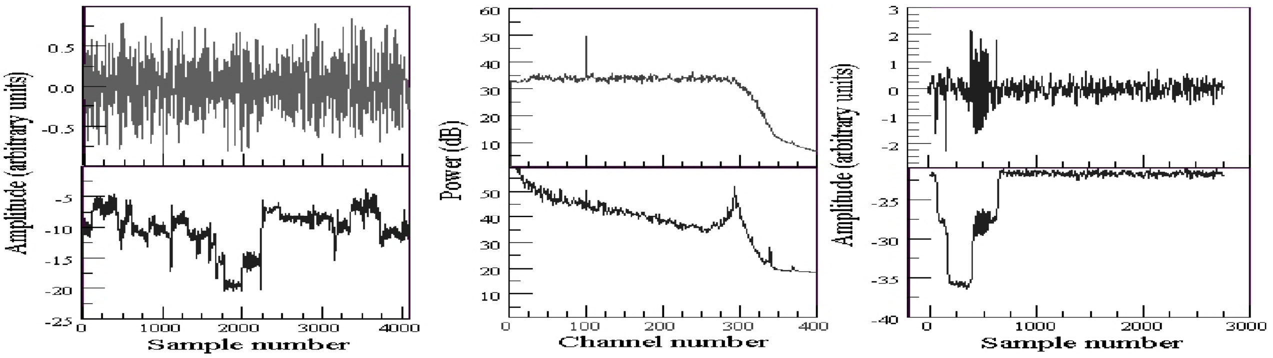

Figure 3: Time series of the 'real' (top-left) and 'imaginary' (bottom-left) outputs when the TV signal is passed through the 'DSB suppressor'. The average spectra (average over 1.6 x 10^5 samples; spectral resolution 12 KHz) of the two outputs are shown in the top-middle and bottom-middle panels respectively. A narrow band signal near channel 100 (top-middle plot), which is a spurious pickup in the ADC and not related with the TV signal, is clearly detected. This pickup is also present in the bottom-middle plot but barely detectable due to interference. The 'real' (top-right) and 'imaginary' (bottom-right) output when a VSB modulated signal is passed through the DSB suppressor is shown on the right. No picture signal is added to the input signal for this plot.

3 Cancellation of Interference due to Composite Video Signal

A considerable fraction of the radio frequency spectrum in the VHF (54 – 88 and 174 – 216 MHz) and the UHF (470 – 890 MHz) bands are allocated for television (TV) transmission. These frequency ranges can be of potential importance for a variety of astronomical observations. For example, the signature of reionization of the Universe is expected as a sharp step in the spectrum of the sky due to red-shifted HI 21-cm line emission anywhere in the frequency range $\sim$ 70 to 240 MHz[2]. Developing techniques to suppress TV signals are thus important. As described below, for TV transmission, a composite video signal is modulated on a carrier. In this section I present techniques to suppress synchronization signals in composite video signal. The suppression of the picture components of composite video signal will be discussed elsewhere.

3.1 Characteristics of TV signal and the data used for the work

TV signals consist of picture and frame synchronization signals and is referred to as composite video signals (see Fig. 4). Synchronization signals consist of horizontal and vertical synchronization and blanking pulses and 8 to 10 cycles of the 3.58 MHz color sub-carrier ('color burst'). The picture part of the composite video signal consists of luminance and chrominance components. The chrominance components are quadrature modulated on a sub-carrier of frequency 3.58 MHz. The total bandwidth of the composite signal is 4.5 MHz. The composite video signal is then vestigial sideband (VSB) modulated on a carrier for transmission. The picture frame rate and other details of the composite video signal depend on the standard used for TV transmission. Here we use data with NTSC standard.

The data for the present work were obtained from the output of a video player. The RF output of the video player was digitized and acquired using a commercial data acquisition system. The carrier frequency of the video player output was near 61.2 MHz and the data were sampled at 50 MHz rate with an 8 bit analog-to-digital converter. A contiguous set of 50 Mbytes of samples was stored in the computer hard disk. Interestingly, the video player output was double sideband (DSB) amplitude modulated. A VSB modulated signal was obtained by appropriately bandpass filtering the recorded data.

3.2 Synchronization signal suppressor

The NTSC TV transmission retains about 1.25 MHz of the lower sideband. Since the spectral power of the synch and blanking pulses increase by more than 10 dB in the frequency range 0 to 1 MHz, the lower sideband in TV transmissions can be used to suppress this power using a 'DSB suppressor'. Thus, after passing the VSB modulated TV signal through the 'DSB suppressor' the 'real' output consists of frequency components all above 1 MHz (see Fig. 3). These components include the color burst and the higher frequency components of the synch and blanking pulses in addition to the picture signal.

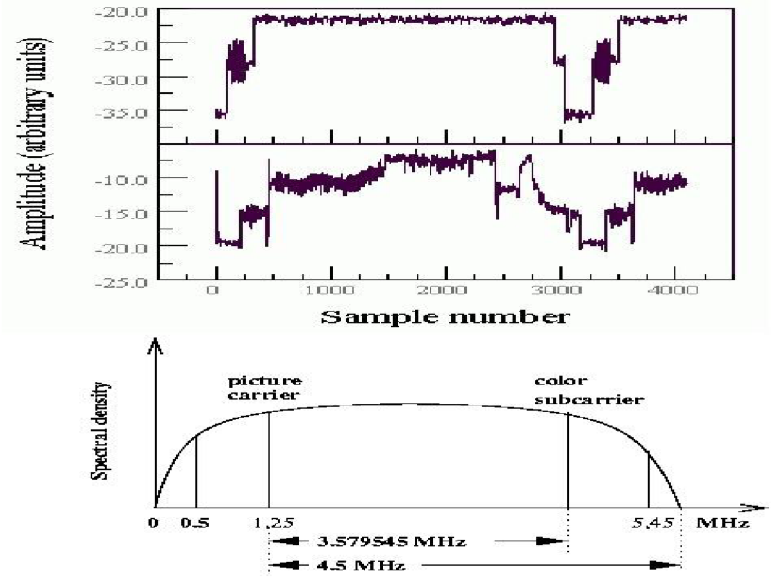

Figure 4: The top panel shows the synchronization signal with no picture information. The largest amplitude pulses are the horizontal synchronization pulses and the intermediate amplitude, wider pulses are the horizontal blanking pulses. The 3.58 MHz color burst is seen just after the synch pulses. The middle panel shows an example of the composite video signal; both picture and synchronization signals are present. A schematic of the spectral details of NTSC TV transmission is shown in the bottom panel. The composite video signal is VSB amplitude modulated on a carrier for transmission.

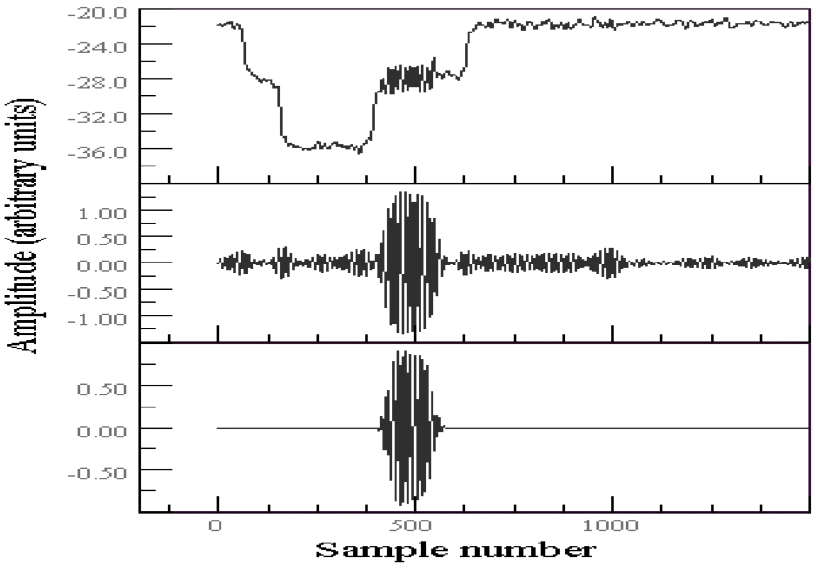

Figure 5: The top panel shows the 'Imaginary' output and the middle panel shows the high pass filtered output of the signal shown in the top panel. The synthesized noise-free model of the color burst is shown in the bottom panel.

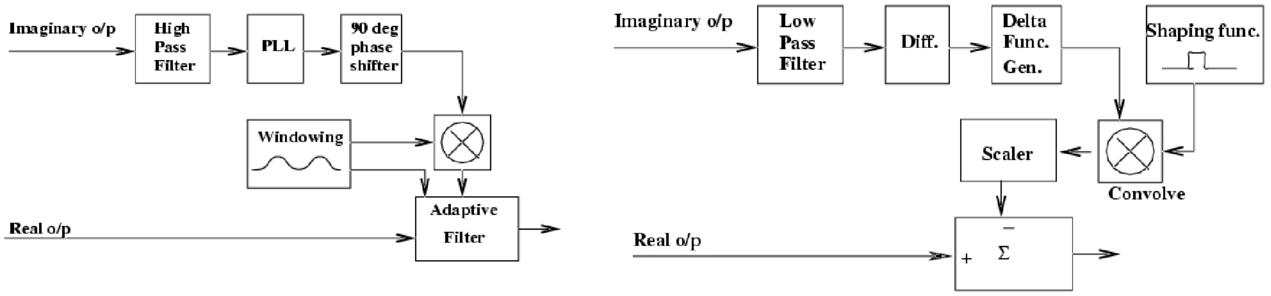

Figure 6: Block diagram of the color burst (left) and synch signal (right) suppressors.

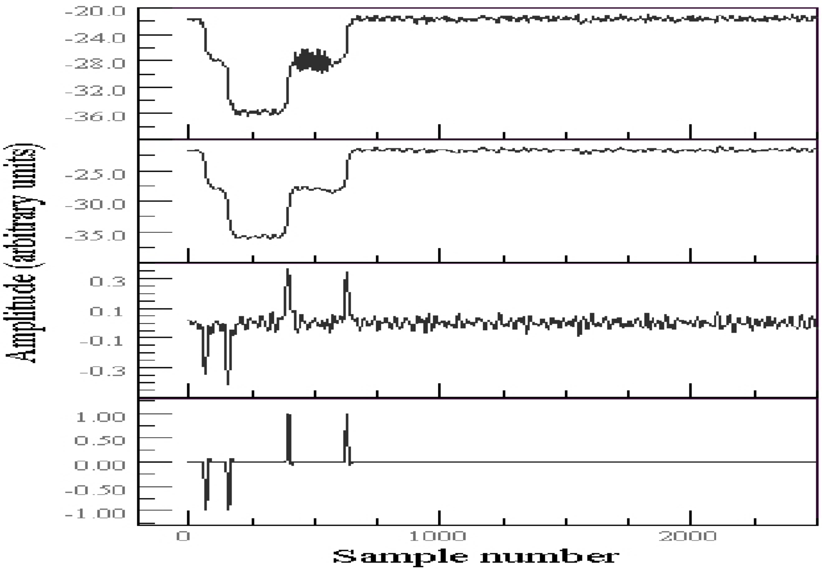

Figure 7: (a)Time series of the 'Imaginary' output. (b) Time series after passing the signal shown in (a) through a low-pass filter. The filter cutoff frequency is adjusted to reject the 3.58 MHz color burst. (c) The derivative of the signal shown in (b). (d) The noise free model of the synch and blanking pulse in the 'Real' output.

We first try to suppress the color burst in the 'real' output by subtracting a noise-free model of this signal. The color burst signal in the 'imaginary' output, which is now considered as a reference signal, is used to make the noise free model. The color burst is filtered out from the 'imaginary' output and used to synchronize the phase of an oscillator (see Figs. 5 & 6). This is done every horizontal synch period where a color burst is present. The oscillator output is then multiplied by a 'window' function to generate the model. The position of the window function in time relative to the horizontal synch signal is estimated in sample numbers and used for synchronizing. The shape of the window function is initially estimated from the reference signal itself and held constant. Subtracting a scaled version of the noise-free model, however, did not give good RFI rejection. Therefore the noise-free model is used as the reference signal for a three tap adaptive filter and the 'real' output is used as the second (main) signal for the filter. New filter weights are computed only during the time interval when the color burst amplitude is not changing rapidly. The need for the adaptive filter is because the shape of the weighting function is changing with time.

After passing the 'real' output through the 'color burst suppressor', what remains are the residuals of synch and blanking pulses. To get a noise-free model for the residual, the synch and blanking pulses from the 'imaginary' output are filtered out first for each horizontal synch period (see Figs. 6 & Fig. 7). Passing the derivatives of these pulses through a threshold detector gives the time of occurrence of these pulses. A 'delta' function model of the residuals is generated using this information. This model is then convolved with a shaping function, which is determined initially from the 'imaginary' output. The noise-free model is then scaled and subtracted from the 'real' output. The scaling factor is adjusted manually to get the best suppression. A typical output after passing the signal through the color burst and synch and blanking pulse

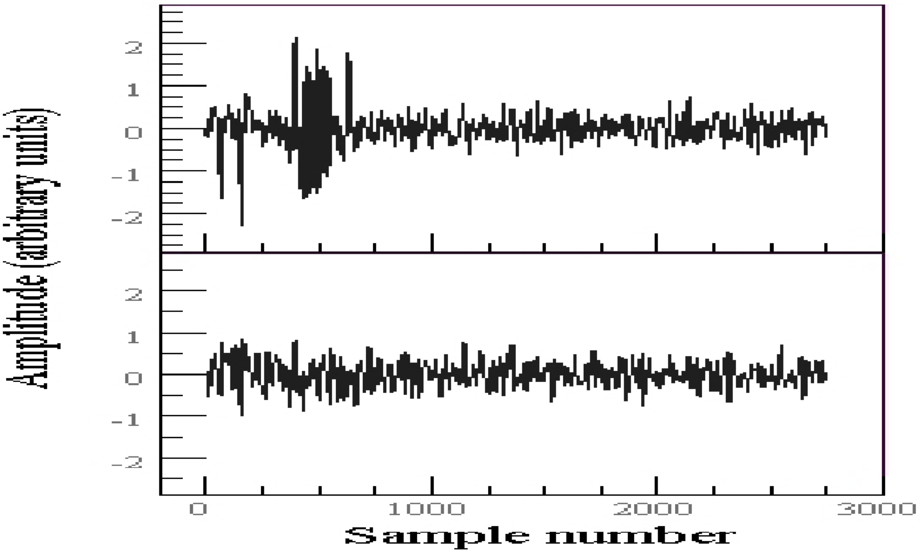

Figure 8: Top panel shows the time series of the ‘Real’ output. Bottom panel shows the signal after passing the ‘Real’ output through color burst and synch and blanking pulse suppressors.

suppressors is shown in Fig. 8.

The performance of the synchronization signal suppressors is tested using a data set with no picture information. An average spectrum of the interference is obtained from the samples where the synchronization signals are present in the ‘real’ output. To measure the achieved RFI rejection, an average spectrum after suppressing the interference is obtained from the same set of samples. These spectra are shown in Fig. 9. The averaging is done over 8.6 x 10^6 samples, which corresponds to about 160 msec. No residual of the color burst is present in the second average spectrum, which gives a lower limit on the interference rejection of 12 dB. The average spectrum of the output of the suppressors is compared with a reference spectrum, which is obtained from the samples with no picture and synchronization signals. The comparison shows good agreement between the reference and average spectrum. The total power in the average spectrum of the output of the suppressors is, however, about 0.6 dB more than that of the reference spectrum. The excess power is mostly due to the inadequate suppression of the synch and blanking pulse residuals.

4 Design of a ‘Clean’ ADC

The outputs of most commercially available ADCs have spurious components in addition to the digitized form of the desired signal. These spurious components usually appear as narrow band features in the spectrum of the digitized waveform. The spurious components at the output of the ADC limit the performance of the converter for many applications – for example RFI mitigation. The spurious components are due to noise, generated in the associated digital circuits (“digital noise”), coupling to the analog input. The most common reasons for such noise coupling are (a) poor isolation of analog and digital grounds (b) insufficient power supply filtering and (c) poor design of associated digital circuit, which results in excessive ground bounces. In this section I briefly discuss some design techniques to minimize noise coupling to the analog input of an ADC.

4.1 Circuit Design

An analog-to-digital converter circuit is carefully designed to minimize any noise coupling at its analog input using the integrated circuit ADS831 (Burr-Brown product). The ADS831 is an 8 bit ADC. A schematic of the circuit diagram is shown in Fig. 10. The design techniques used to minimize noise coupling are:

1. The ADC is designed to take a balanced analog input. The balanced input is immune to any common mode noise pickup.

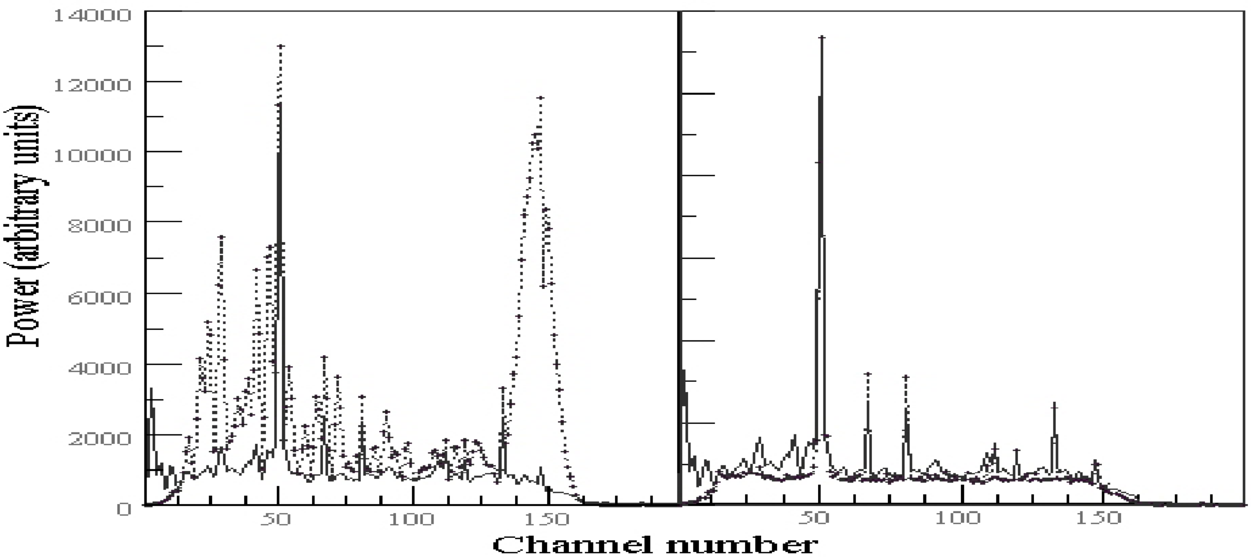

Figure 9: The average spectrum of the samples where interference is present at the 'Real' output is shown on the left panel in dotted line. The average spectrum obtained from the same set of samples after passing the data through the color burst and synch and blanking pulse suppressors is also shown on the left panel in solid line. The spectrum shown in dotted line on the right panel is a reference spectrum, which is obtained from the samples of the 'Real' output that do not have picture or synchronization signals. The average spectrum shown in solid line on the right panel is the same as that shown on the left panel in solid line. The spectra are integrated over 6 x 10^6 samples ($\sim$ 120 msec). The spectral resolution is about 24 KHz.

2. All digital circuitry associated with the ADC is designed to operate at 3.3 V. The low-power supply voltage reduces the digital noise power.

3. Ferrite cores based filters are used for the power supply, which minimizes noise coupling through power connections.

4. Ferrite core based filters are used at the digital power pin of ADS831 for better decoupling.

5. Low-voltage buffers (74LVTH162244) with internal series termination resistors of 25 Ω were used for the design. Also external series resistors are provided (but not used during the tests) at all digital interconnections for better matching of the gate output impedance to the transmission lines (PCB layout). The impedance matching reduces the reflections in the transmission lines thus minimizing ground bounces.

6. The PCB (printed circuit board) is designed such that the analog and digital power/ground planes are separated. The ground planes are interconnected near ADS831 to provide the signal return paths.

7. In the PCB design, the separation between the power planes is 10 and 20 times the separation between the ground and power planes ("20-H rule"[3]).

8. Along with the ADC card, a data acquisition system (DAS) was designed to acquire data from the ADC. Care is taken to isolate DAS ground from the ADC ground and also from the PC ground. The ADC ground and DAS ground are "isolated" using differential line drives (MC100LVELT22) and receivers (MC100LVELT23). The PC ground is optically isolated from the DAS ground. These ground isolations are provided to minimize the digital noise coupling to the ADC circuit.

4.2 Test Results

To test the performance of the ADC, a noise source is connected to its input and the digitized data is acquired using the DAS. The bandwidth of the noise is limited to about 12 MHz and the power level is adjusted such that the ADC output range of 0 to 255 represents roughly 5 times the RMS fluctuations. The data is sampled at 30 MHz. Fig. 11 shows a

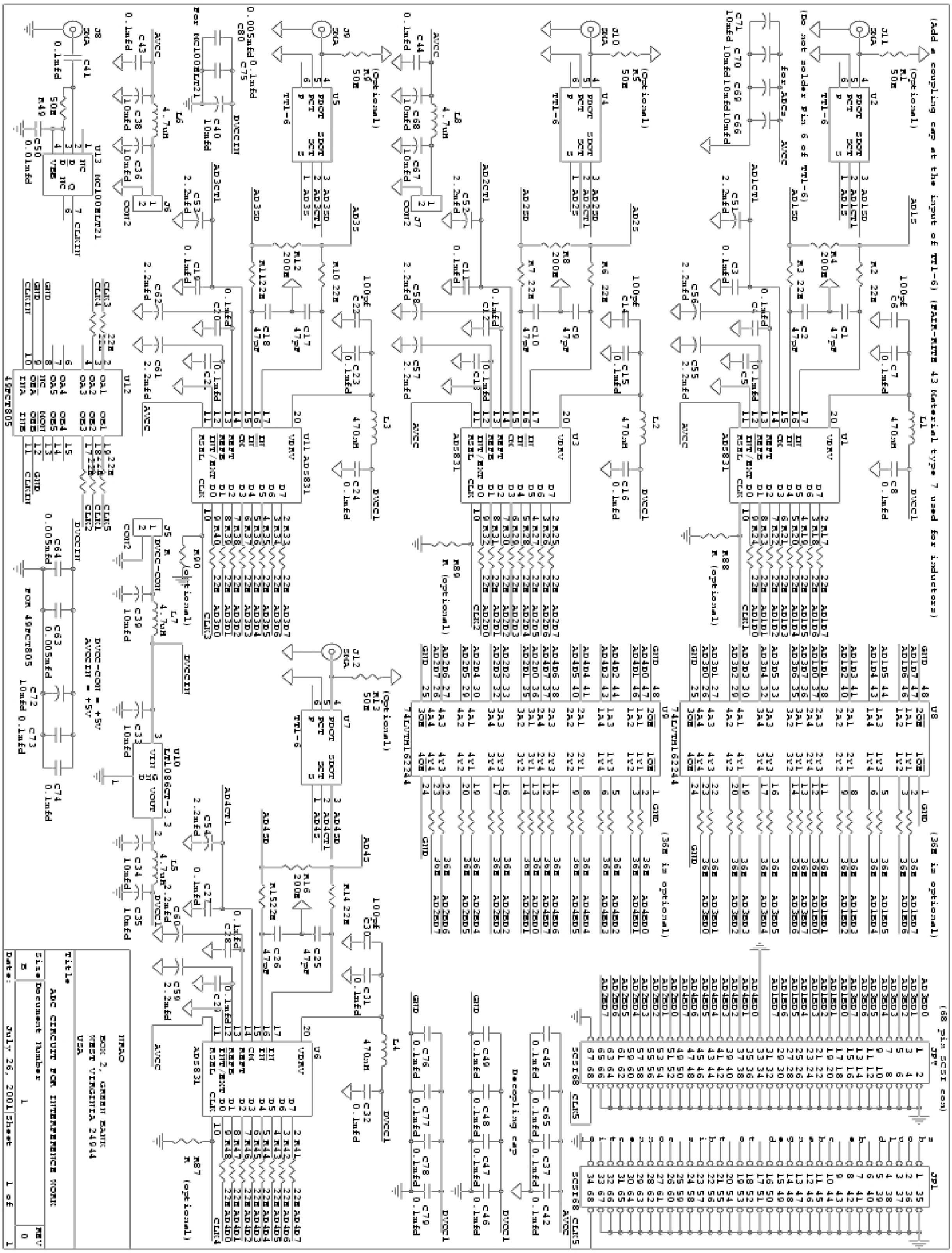

Figure 10: Schematic of the Analog-to-digital converter circuit. The circuit is designed with four ADS831 so that 4 analog inputs can be simultaneously digitized.

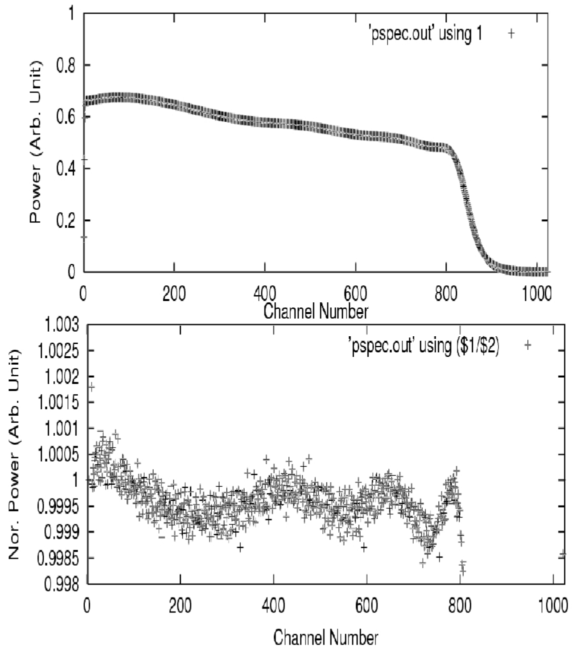

Figure 11: 34 minutes integrated spectrum of the ADC output. To obtain this spectrum, a noise source is connected at the input of the ADC. The integrated bandshape of the noise source is shown on the top and the spectrum after correcting the bandshape is shown on the bottom. No spurious narrow band signals are present at the 3 sigma value of the channel to channel power fluctuations, which corresponds to a spurious level of < -32 dB relative to the noise power.

34 minutes averaged spectrum of the ADC output. To correct the bandshape, the integrated output spectrum is divided by a smoothed (9 point boxcar) version of the same spectrum, which is also shown in Fig. 11. The bandshape corrected spectrum shows that no narrow band spurious signal is present at the output data. The 3 sigma value of the channel to channel power fluctuation in the spectrum corresponds to a spurious suppression better than -32 dB relative to the input noise power. The channel to channel power fluctuation in the averaged spectrum is close to that expected theoretically.

5 Spectral RFI Excision

Spectroscopic observations at low-frequencies ($<$ 1 GHz) are often limited by RFI. Fig. 12 shows an example spectrum over the frequency range 380-420 MHz obtained using the low-frequency receiver of the Green Bank Telescope (GBT). The narrow band features seen in this spectra are RFI. At sufficiently high spectral resolution ($\sim$ 1 KHz), the RFI are usually confined to a few spectral channels and the spectral region between narrow band RFI is often free of any contamination. In addition, some of the RFI are time variable, thus there are time ranges where parts of the spectrum are free of RFI. For certain types of observations only a fraction of the total frequency range of the receiver is needed. An example is the observations of galactic recombination lines (RLs) at low-frequencies. The bandwidth needed for such observations is $\sim$ 1 MHz centered at the expected line frequency (see Fig. 12). This means that RL transitions located at frequencies relatively free of RFI can be observed. Fig. 13 shows four spectra centered at the hydrogen RL transitions H243α (455.4863 MHz), H246α (439.0575 MHz), H249α (423.4093 MHz) and H250α (418.3587 MHz). The spectral resolution and integration time of these spectra are 4.9 KHz and 60 sec respectively. The narrow band features in these spectra are again RFI. In this section, I present a technique to excise the narrow band, time variable RFI using a spectral channel weighting scheme.

5.1 Spectral Channel weighting scheme

To excise RFI a channel weighting scheme is used. In this scheme, at the basic integration level (say 60 sec or less), a weight of unity is assigned to all spectral channels which are “free” of RFI. Fig. 14a&b show respectively an example spectrum and the weights assigned to each channel. The contaminated spectral channels are identified through inspection

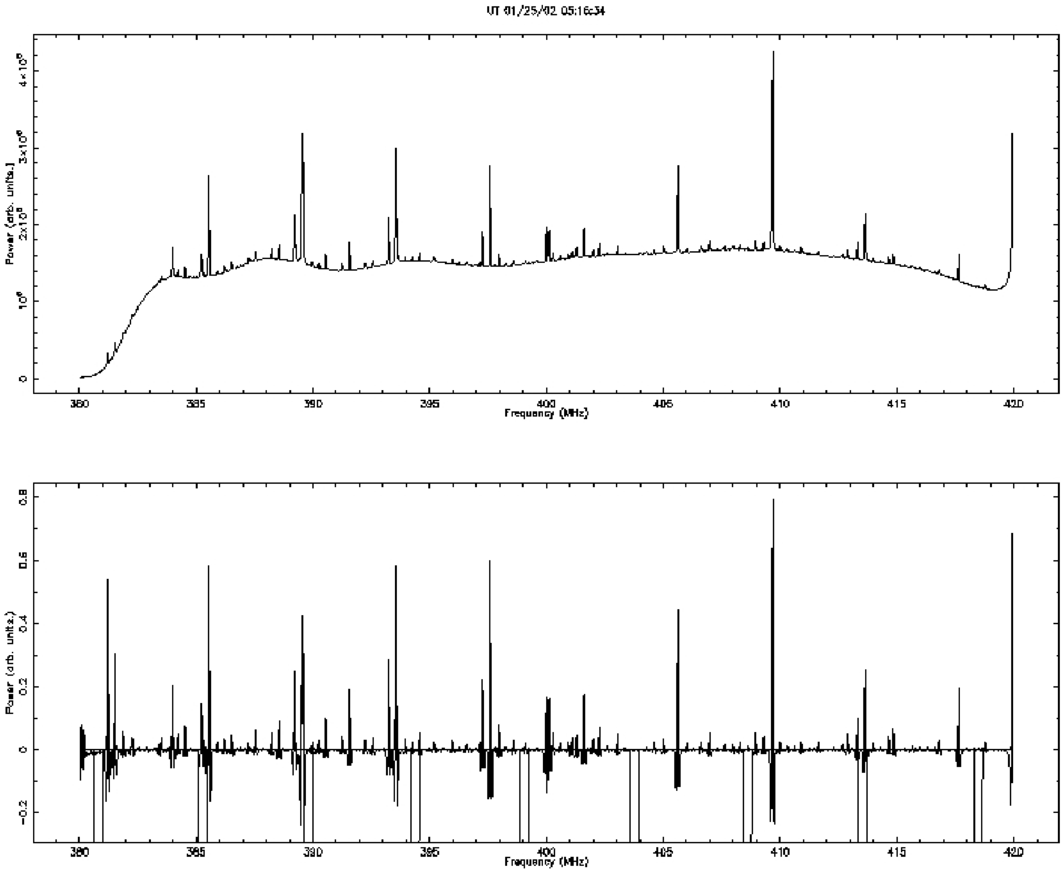

Figure 12: Power spectrum over the frequency range 380-420 MHz obtained from the output of the low-frequency receiver of the GBT (top). The band-shape corrected spectrum is shown on the bottom. The band-shape is obtained by 5 point median filtering the power spectrum shown on top. The spectrum is integrated for about 120 sec. The vertical lines in the bottom spectrum show a 300 KHz spectral window near hydrogen recombination lines.

by eye and their weights are assigned zero. The excision will be made automatic by determining the spectral RMS of the RFI free spectral channel through an iterative process and assigning zero weights to those channels whose spectral amplitudes exceeds a threshold (say 5σ). The final integrated spectrum is obtained by weighted averaging the edited spectra.

5.2 Result of the observations toward G28.4+0.1

With the intention to test the RFI excision scheme, we observed recombination lines toward G28.4+0.1 near 420 MHz with the GBT. Fig 14 shows the RFI excised spectrum obtained toward this source and the corresponding channel weights. For comparison, a spectrum with out any RFI excision is also shown. The effectiveness of the RFI excision scheme is clear from Fig 14.

In the excision scheme, the weights essentially represent the number of points averaged on each channel. Thus non-uniform weights imply that the RMS of the spectral values differ from channel to channel. This has to be taken into account for the estimation of the parameters of the astronomical spectral feature. This will be discussed in detail elsewhere.

Acknowledgment

I thank Rick Fisher and Rich Bradley for the many fruitful discussions I had with them while I worked on this project.

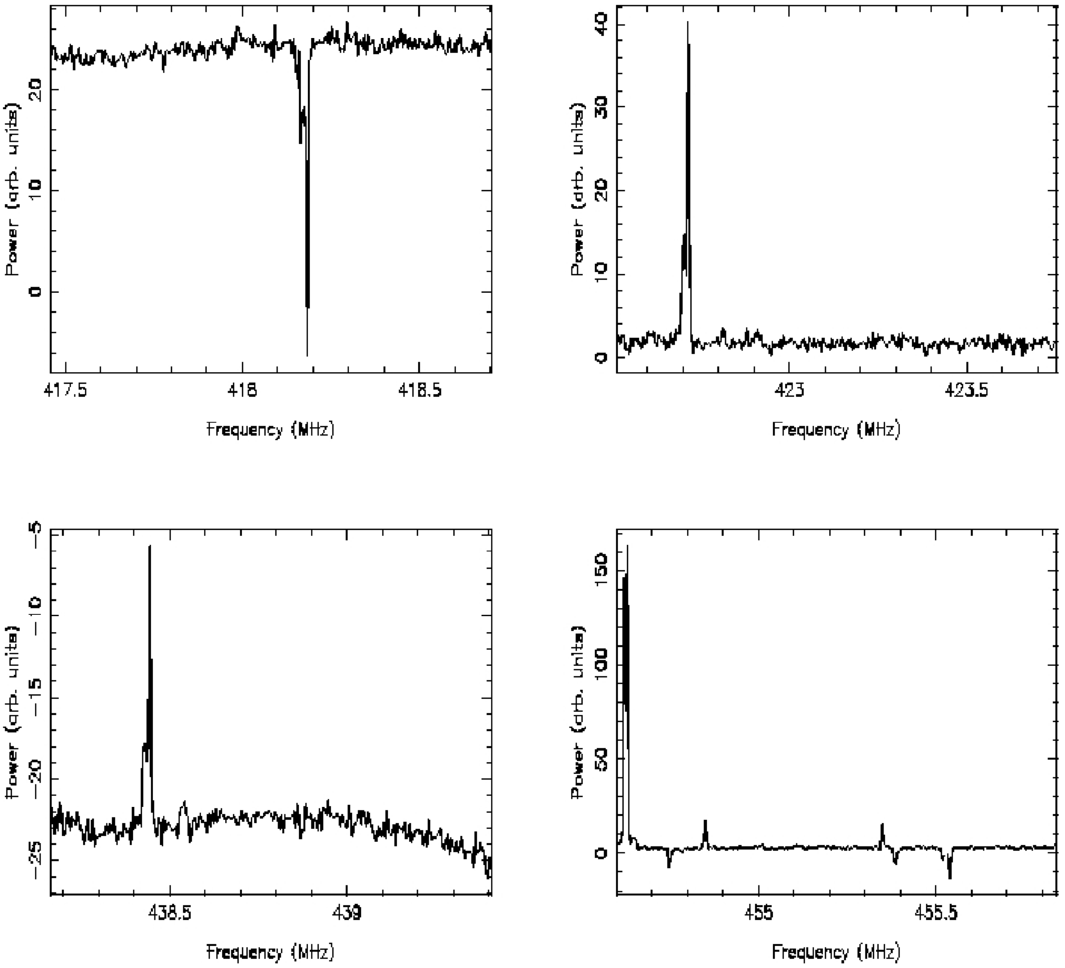

Figure 13: Four 1.25 MHz wide bandshape corrected spectra selected for recombination line observations with the 420 MHz band of the GBT. These bands are centered at hydrogen recombination lines H243α (455.4863 MHz), H246α (439.0575 MHz), H249α (423.4093 MHz) and H250α (418.3587 MHz). The integration time of these spectra are 60 sec. The bandshape is corrected using a reference spectrum, which is obtained by frequency switching.

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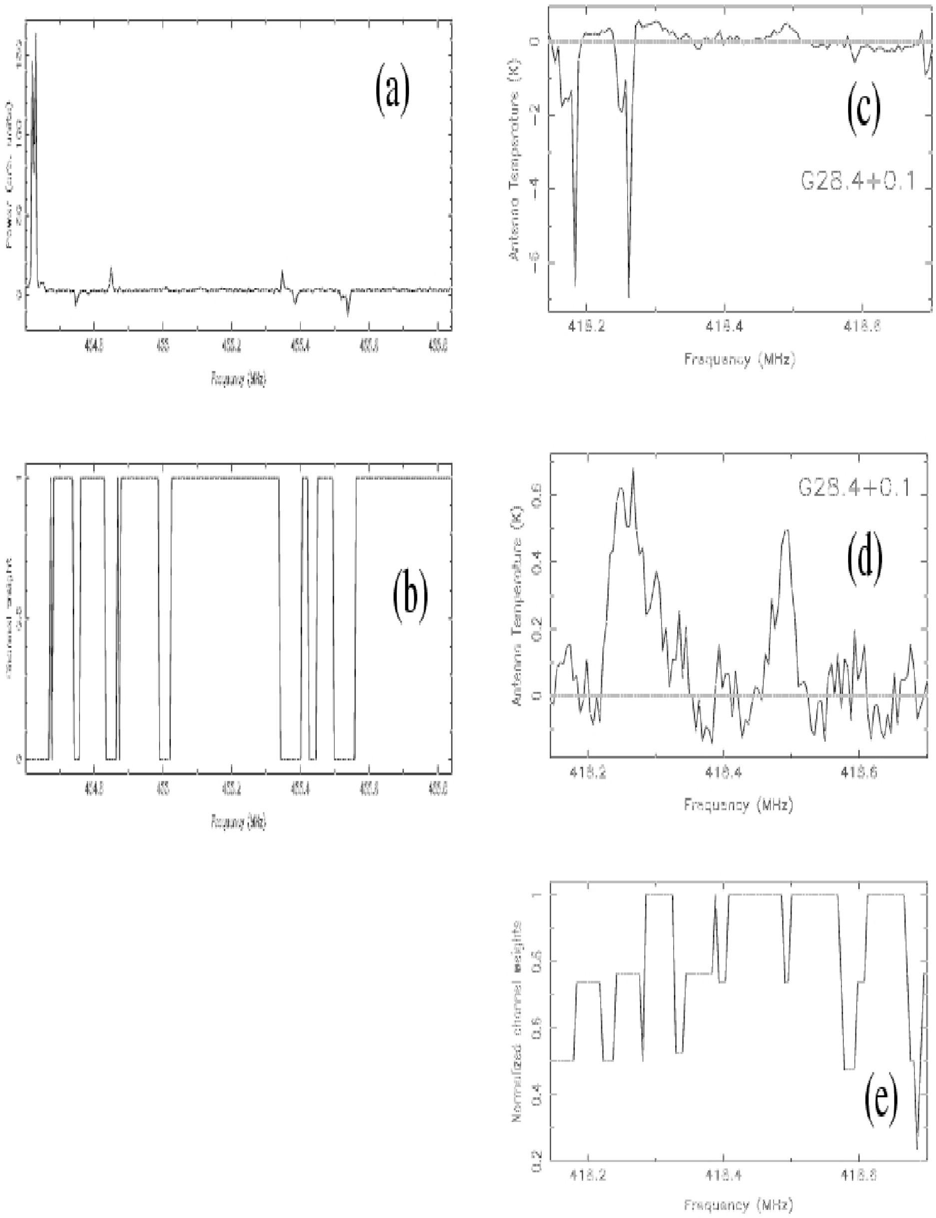

Figure 14: (a)60 sec integrated bandshape corrected spectrum toward G28.4+0.1. The bandshape is corrected using a reference spectrum, which is obtained by frequency switching. (b) The channel weights assigned to each channel at the first stage of editing is plotted as a function of frequency. (c) Average spectrum without any RFI excision. The averaging is done over all integration time and the two transitions H249α (423.4093 MHz) and H250α (418.3587 MHz). The reference spectrum is measured in dual-Dicke frequency switching mode and the plot shows the bandshape corrected ‘folded’ spectrum. Note that the frequency axis corresponds to the observing band centered at 418.3587 MHz. The bandwidth of the spectrum is only half that of the spectrum shown in (a) because of spectral ’folding’. (d) Average spectrum with RFI excision. The feature near 418.3 MHz is the hydrogen line and that near 418.5 MHz is the carbon line. (e) The normalized channel weights corresponding to the spectrum in (d).

Concluding Remarks

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It is now nearly two years since the first Summer School on Spectrum Management for astronomers ended, and its failures and successes can be evaluated with some perspective.

Possibly the most visible proof of success is this volume itself. For the first time those in the astronomy community who, voluntarily and sometimes less so, engage in spectrum management will have at their disposal a comprehensive volume where they can find guidance on some of the technical and regulatory issues they need to tackle. And this is perhaps a good time to note that this volume didn't just spring into existence. It represents an enormous amount of work by Darrel Emerson, who first took it upon himself to edit the Proceedings, and by Murray Lewis, who took over when Darrel had to move on to other responsibilities. The radio-astronomy community owes a very big thank you and well done to Darrel and Murray for bringing this volume to a good conclusion.

The school also seems to have succeeded in fulfilling the participants' expectations. Many of them told the organizers that they had a very fruitful and enjoyable week. Many of them also asked about follow ups, and it was agreed that the summer school should be offered on an approximately three-yearly basis, rotating among the various ITU Regions. Arrangements are already under way in Europe to host the next one in the series. Repeating the school periodically seems to be a good idea, as spectrum use evolves rapidly and a number of problems that radio astronomers (and other spectrum users) face today were just beginning to surface two years ago. I am thinking for instance of the explosion of wireless applications all over the spectrum, ultra wide bandwidth (UWB) devices, broadband over power lines (BPL) transmissions, and the new regulatory approaches that are being proposed to accommodate them. These are either not mentioned in this volume, or barely get a footnote anywhere.

Where have we failed? I believe that, in spite of the enthusiasm expressed by many who attended the school, we failed to attract new people to spectrum management activities. While many attendees indicated interest in such activities, I don't find any of our "graduates" in the spectrum-protection activities that I attend. So our biggest challenge remains -- attracting new people interested in protecting astronomical uses of the spectrum into active participation. I am still hopeful that this goal will be achieved, perhaps at the next summer school.

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