MITIGATION TECHNIQUES,

MITIGATION FACTORS –

What are they? What are they good for?

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1. Introduction

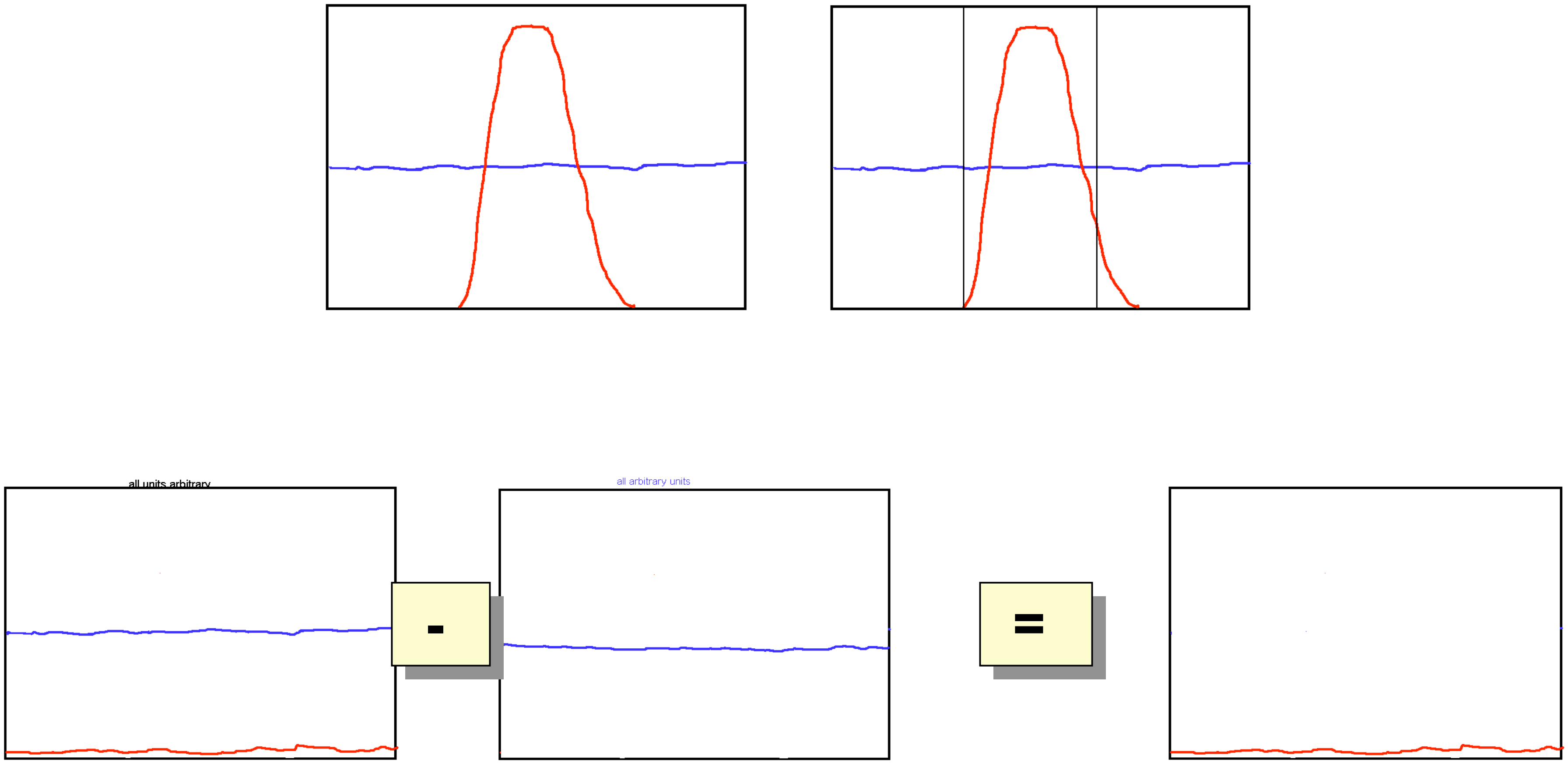
RFI can be a problem for active (i.e. transmitting) radio services, as well as for passive, receive-only services. Methods and techniques are being developed to suppress RFI or mitigate its effects on the victim service. The range of technical and operational measures that can be taken is very large.

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.

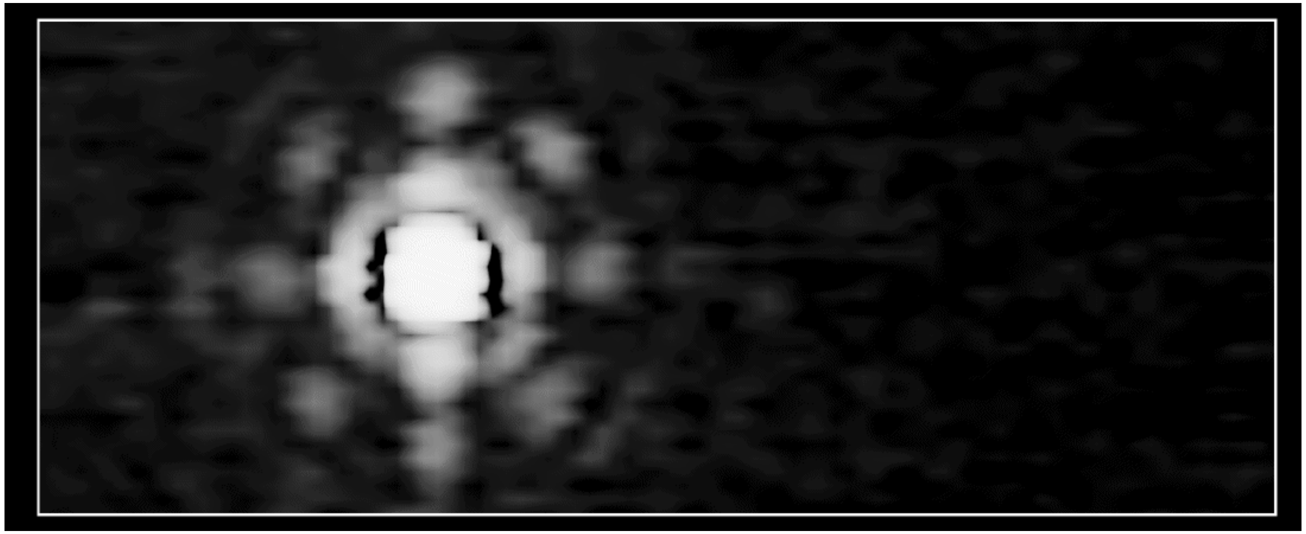


Fig. 2: The beam pattern at 10.6 GHz of the Effelsberg 100 m radio telescope, towards 3C84. field size: 30’ x 12’, flux 20.5 Jy (~ -247 dB(W m^{-2} Hz^{-1})).

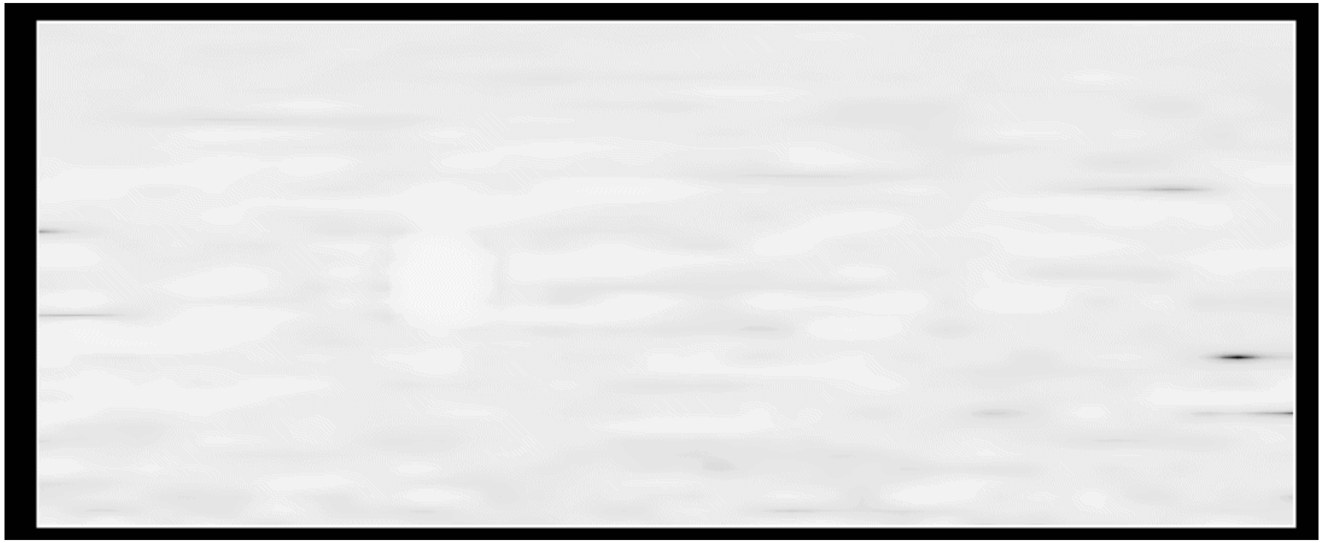


Fig. 3: The same field, with the same source, 3C84, as Fig. 2, 10 degrees away from the satellite.

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

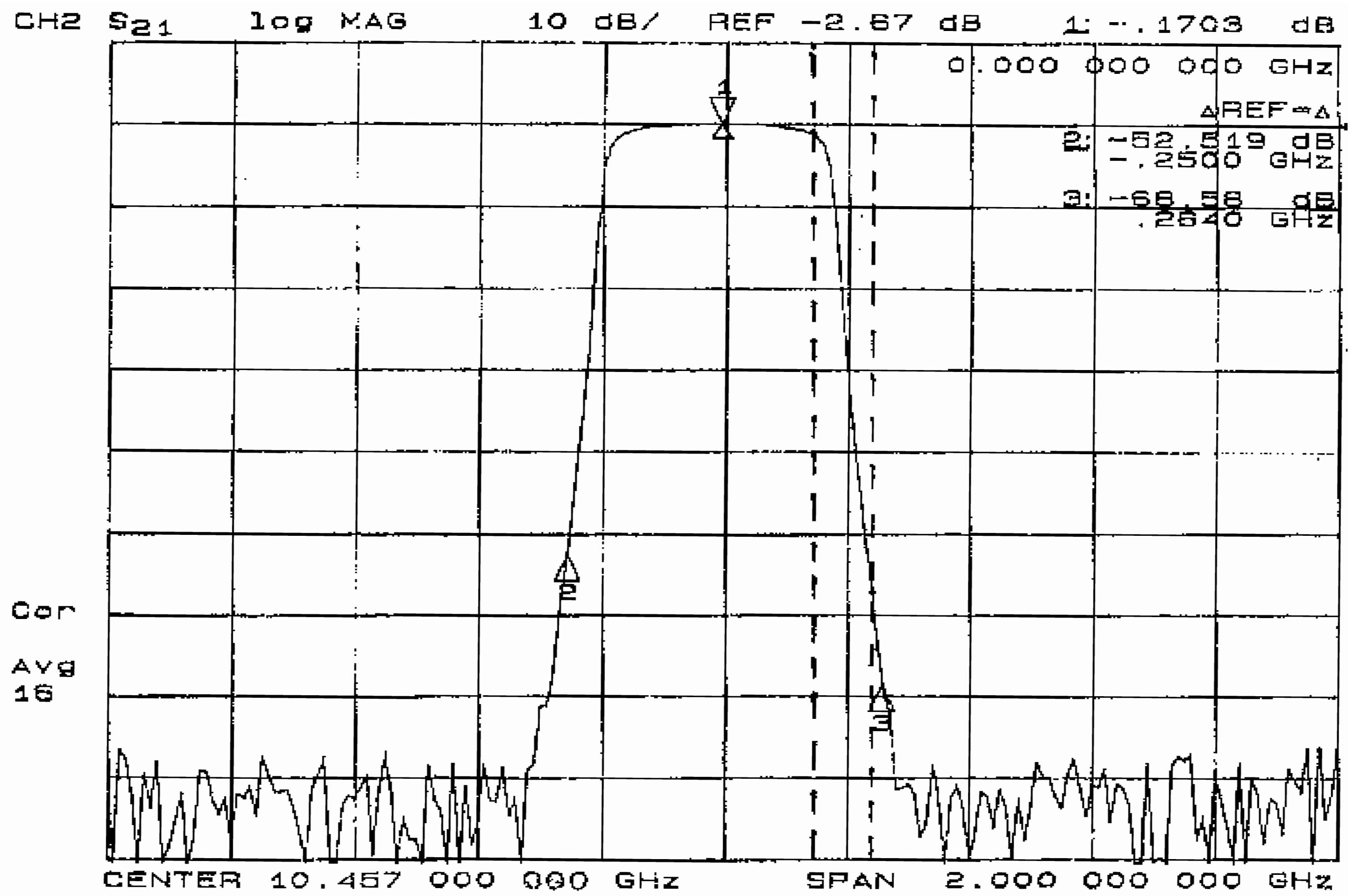


Fig. 4: A scan across one of the 10.7 GHz filters deployed to put 70 dB of attenuation between the receiver and the satellite TV channel. The radio astronomy band, shown dotted, is entirely consumed within the rolloff of the filter as guard band. Marker 1 is at -0.17 dB, marker 2 at -62.22 dB, and marker 3 at -80 dB.

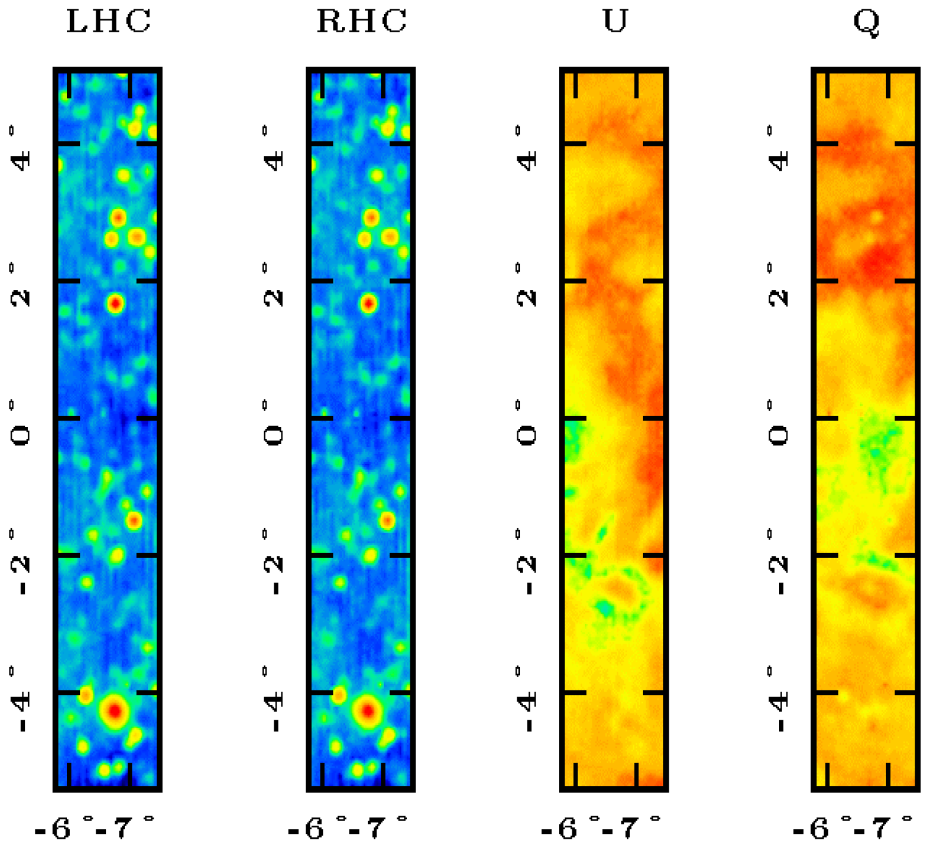


Fig. 5: An Effelsberg 1395 MHz, map of a piece of sky using a 14 MHz bandpass, simultaneously in both left and right circular polarizations, together with the resulting Stokes U & Q maps. The observation was made on 12 February2002, at UT 20.23 Ö 21.44.

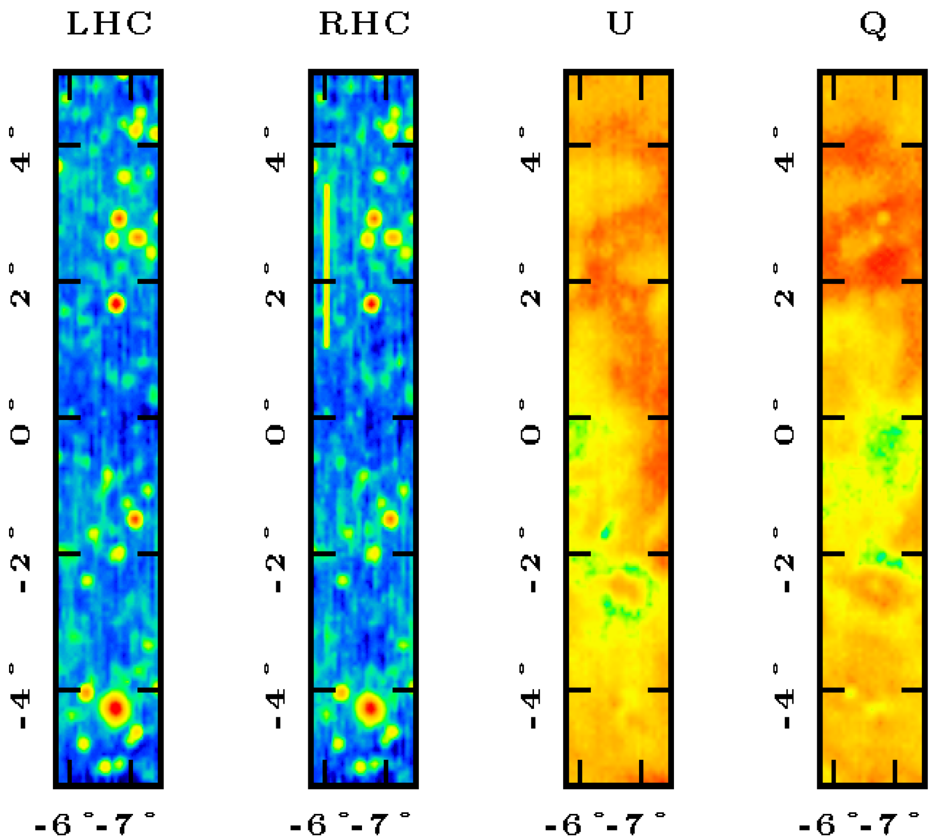


Fig. 6: An Effelsberg 1408 MHz, map of the same piece of sky and at the same time as that in Fig. 5 using a 14 MHz bandpass, simultaneously in both left and right circular polarizations, together with the resulting Stokes U & Q maps. But note here that interference occurs in just one polarization for 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!

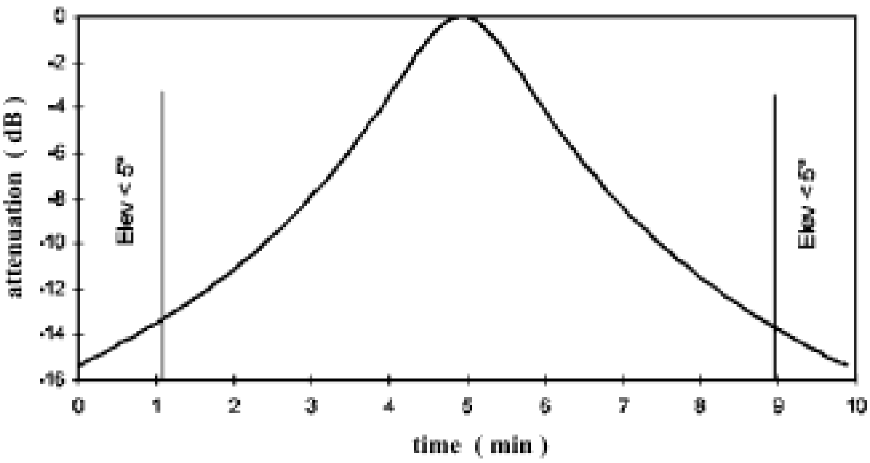


Fig. 7: GTS slant range attenuation during the overhead passage of the ISS.

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

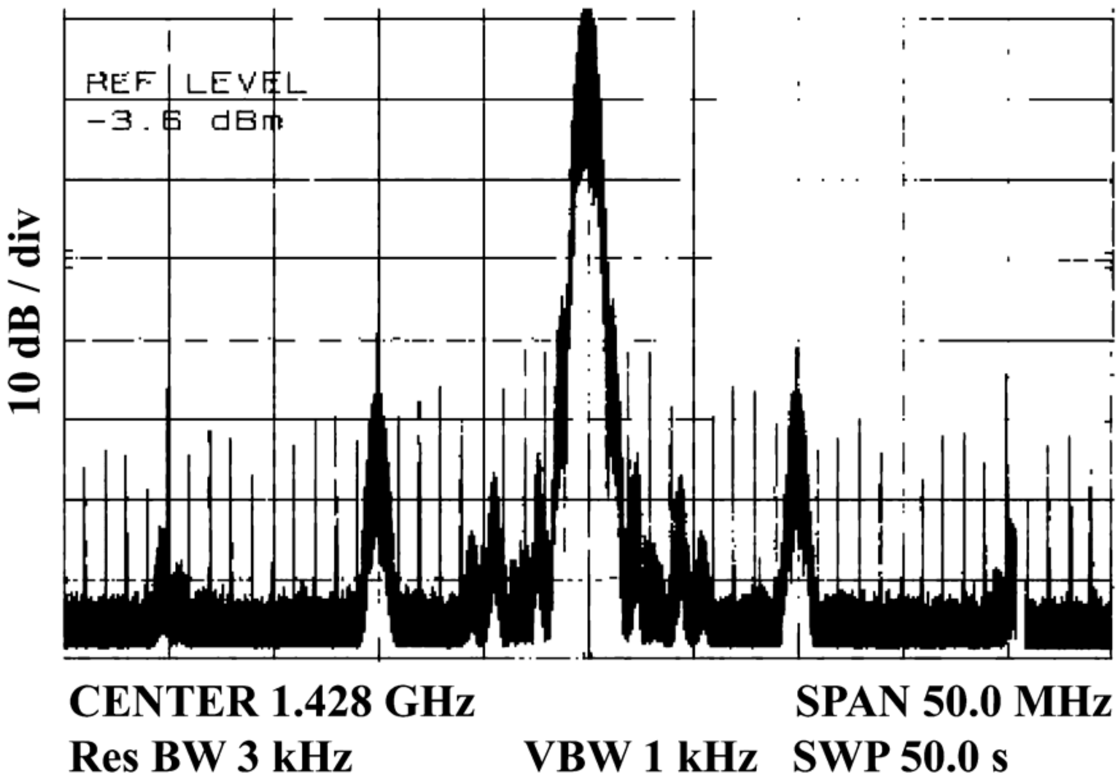


Fig. 8: A GTS transmitter 1.4 GHz Power Spectrum Plot, of 50 MHz span, without a filter.

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

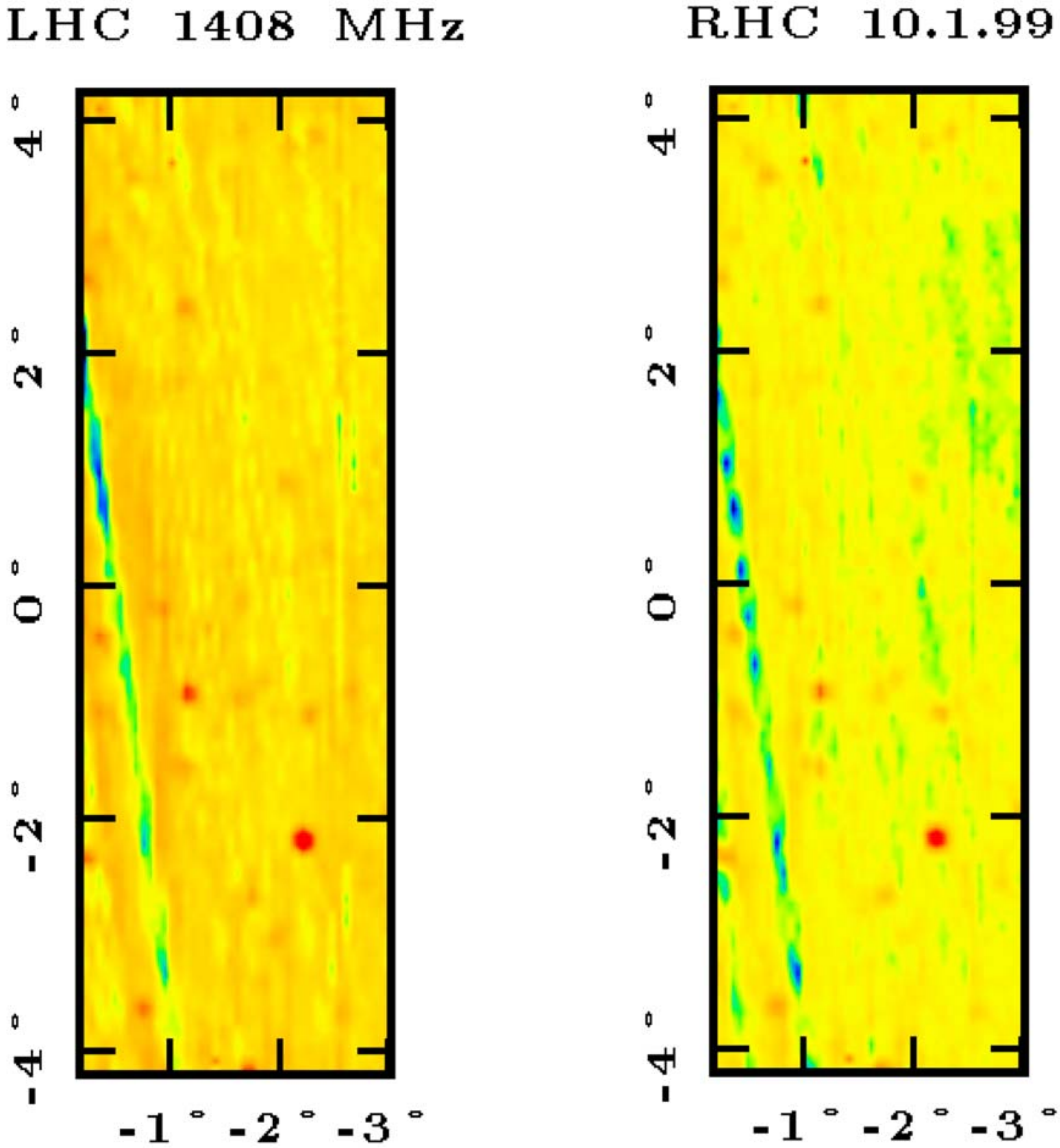


Fig. 9: 1408 MHz LHC & RHC simultaneous maps from Effelsberg.

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

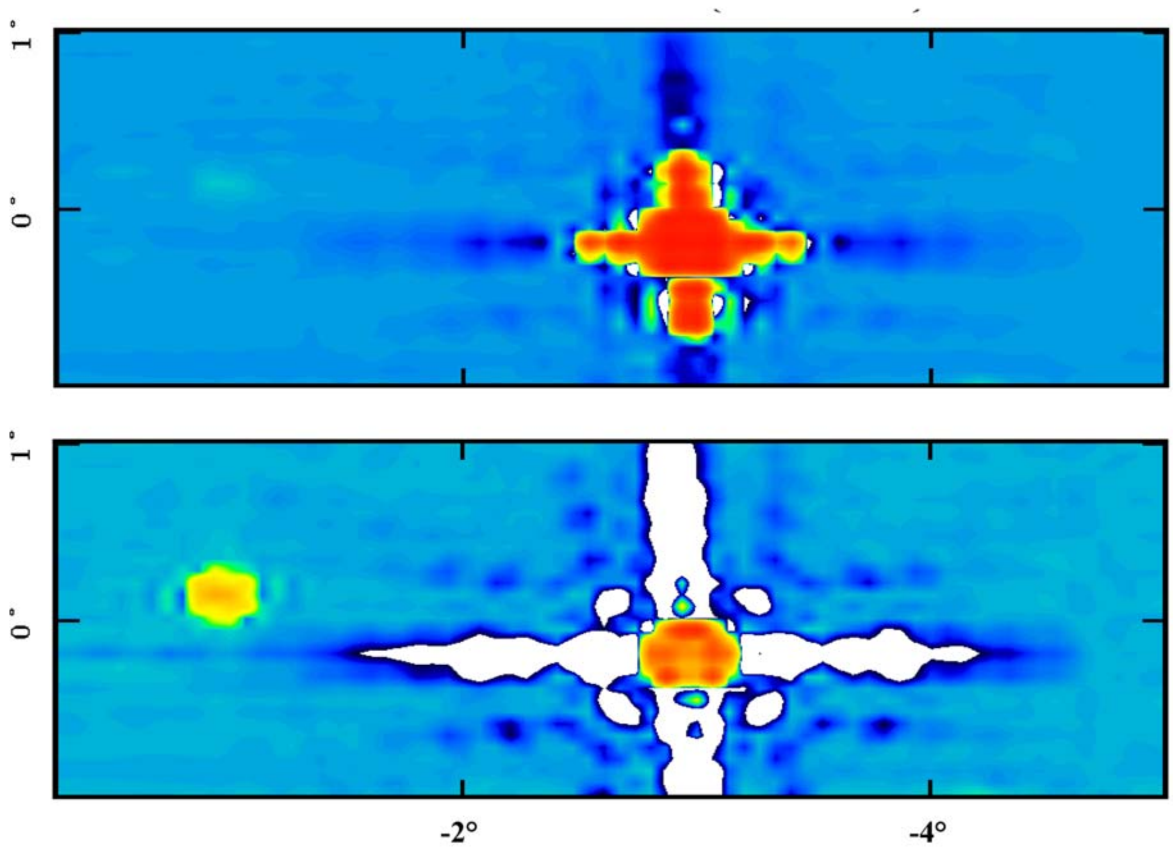


Fig. 10: The LHC (top) and RHC simultaneous maps of AFRISAT without a filter.

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!

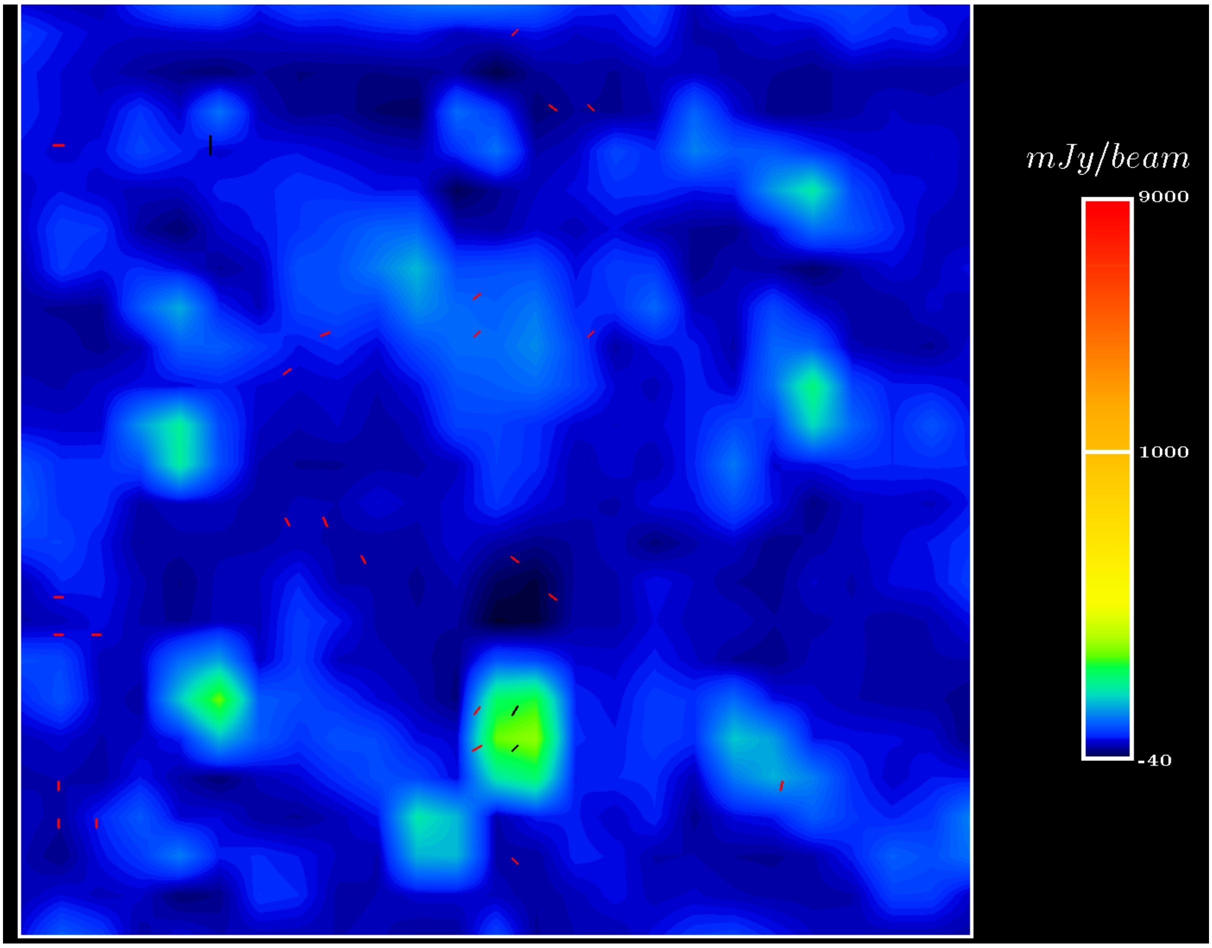


Fig. 11: An Effelsberg 1387 - 1402 MHz map of the location of AFRISAT after the filters have been installed.

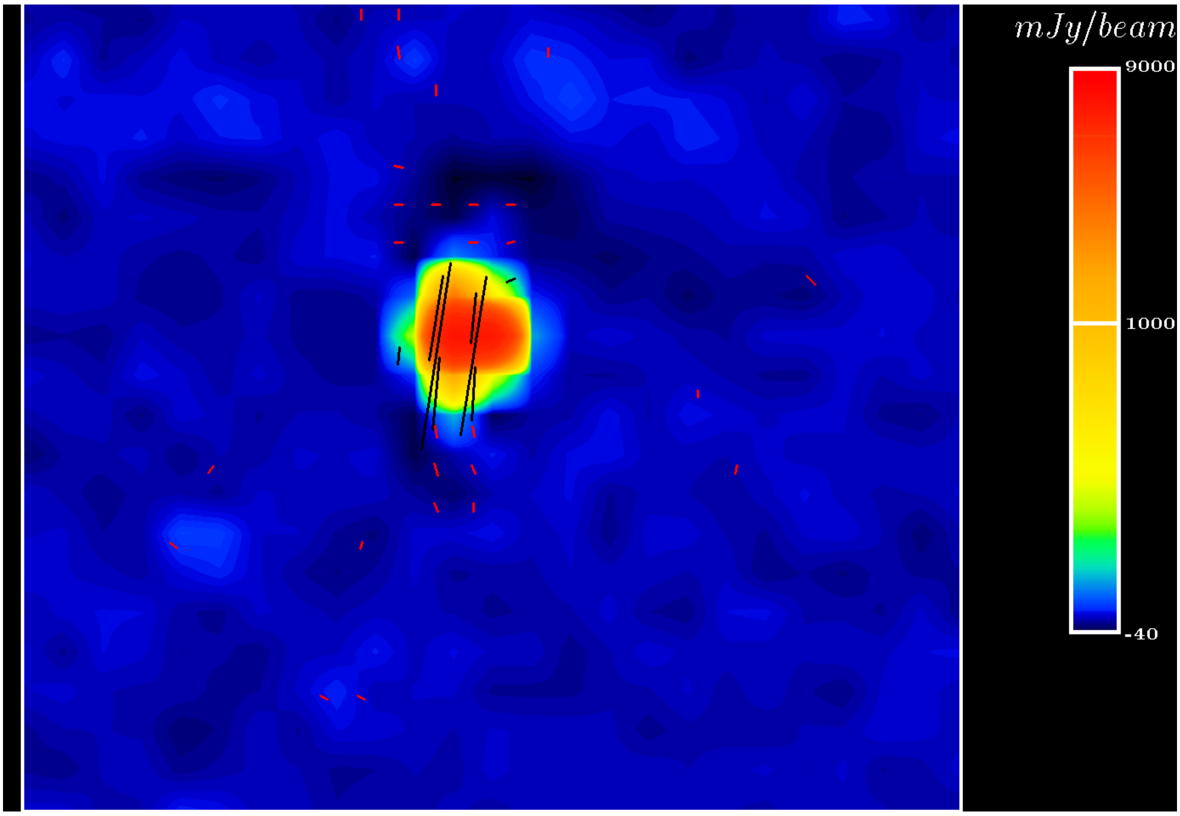
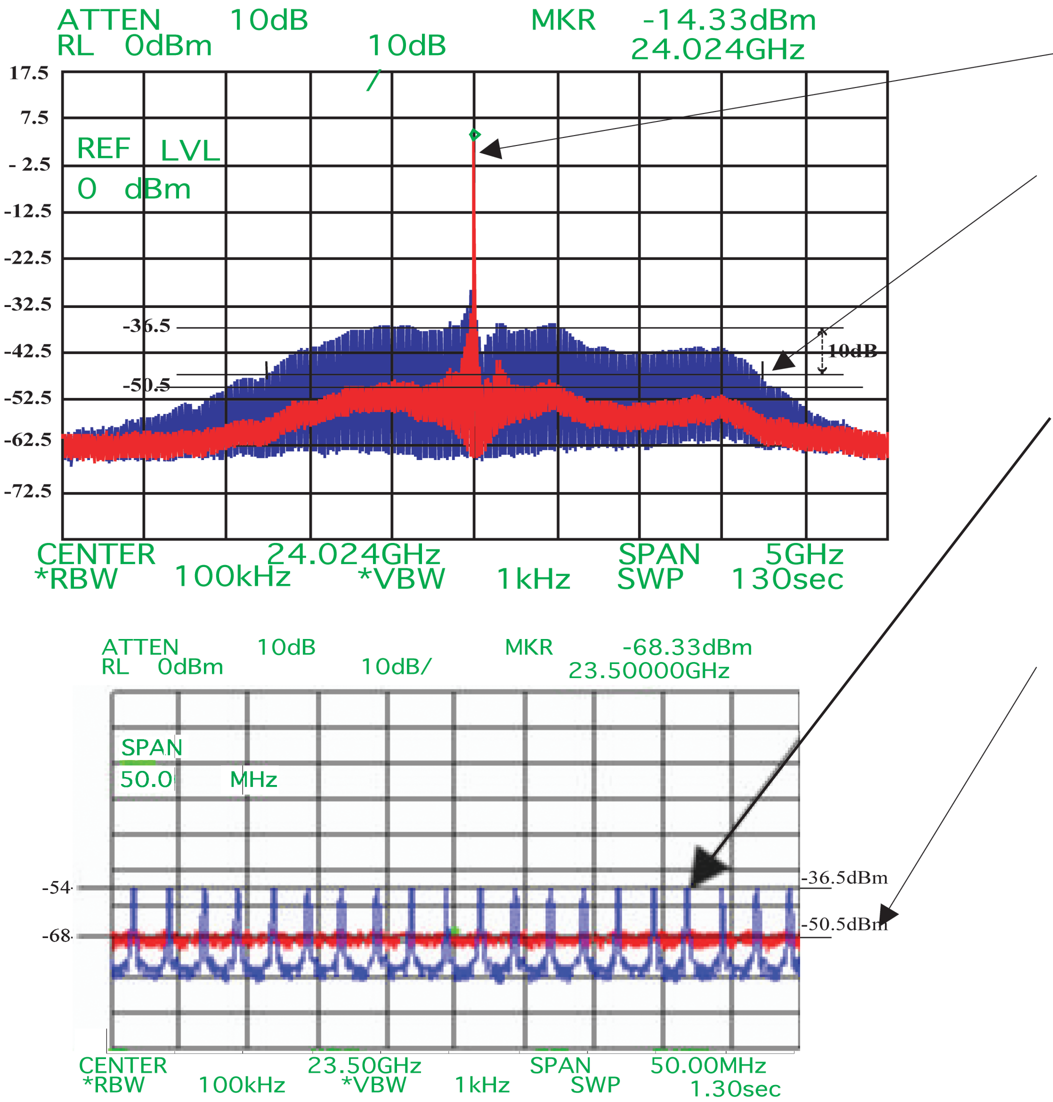


Fig. 12: An Effelsberg 1653 - 1667 MHz map of the location of AFRISAT after the filters have been installed.



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-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.