ITU-R Recommendations of Particular Importance to Radio Astronomy

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The ITU-R recommendations can be broadly described as a series of documents that state the requirements of the various radio services with regard to the frequencies and other parameters of transmission, propagation, reception, etc. as well as problems arising in 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 of 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: mention of: 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 (2 MHz to 800 GHz); and the use of Moon 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 allocation 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 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: the sensitivity of radio astronomical receiving equipment greatly exceeds that of communications and radar systems; at frequencies below 40 MHz long distance propagation of interference (by ionospheric reflection) occurs; choice of observatory site or local protection (shielding) do not help protect against satellite transmissions; and 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. To make these 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 become 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 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 equal to 32-25 log φ where φ is the angle measured from the main beam axis, for $1° < \varphi < 47.8°$. With this model the 0 dBi level occurs at $\varphi = 19.1°$. 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 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 the19.1°cone is Ω divided by the 2π steradians above the horizon from which interfering signals may be received. For $\varphi = 19.1°$, $\Omega/2\pi = 5.5\%$. 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 calculation of the power flux density corresponding to 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

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

where Δf is the receiver bandwidth, k is Boltzmann's constant ($1.38\text{x}10^{-23}$ 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 factor $\sqrt{(\Delta f\ t)}$. Thus Eq. (1) represents the ratio of the voltages of the interference and rms noise, after averaging. Then if we equate Eq. (1) to 0.1, we can solve for the threshold value of interference,

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

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

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

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 factor $\sqrt{(\Delta f\ t)}$ 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 similar 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 space 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, that is, two spaced antennas and a receiving system that combines their received signals, is modulated by a sinusiodal fringe function as a result in 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 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 autocorrelator 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 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 for 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 of small angular structure and single antenna telescopes fulfill an essential role in observing 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 that 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 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 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 to 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 exceed the levels 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 cases involving non-GSO satellites when full data are not available. However, to take fuller account of 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 number of 10% of time 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 conform with the expected density of units active at any given time. Random choice would also apply to the pointing of there 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 in the path between a radio astronomy observatory and any transmitter of the other service, which usually implies that there is no line-of-sight path between the radio astronomy observatory and the transmitters. 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 in the size of the coordination zone be calculated taking account of the criteria in RA.769, specific characteristics of the sharing service, propagation models 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 line 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. Observations 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 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

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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."

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 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 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. Digital modulation and spread spectrum result from modulation but 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 are concerned with protection of radio-quiet areas of space, RA.479 and RA.1417.

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 radioastronomy service and by passive space research, and consequently 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 to passive services except for a 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 from 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 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. However, the bandwidths for use on the Moon should not be restricted by allocation bandwidths as 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 protection of the 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 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 determine by the diameter of the geostationary orbit. The *recommends* include: that administrations, in making frequency assignments that may affect the 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 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 $1° < \varphi < 47.8°$**,** and -10 dBi for $\varphi > 47.8°$. This applies to antennas of diameter greater that 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 detail 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 which include 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 and for space services 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 $P \leq$ 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 power spectral density the limits for space services are generally 24 dB 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.).