RECOMMENDATION ITU-R RA.769-1

PROTECTION CRITERIA USED FOR RADIOASTRONOMICAL MEASUREMENTS

(Question ITU-R 145/7)

(1992-1995)

The ITU Radiocommunication Assembly,

considering

a) that the development of radioastronomy has led to major technological advances, particularly in receiving techniques, and to improved knowledge of fundamental radio-noise limitations of great importance to radiocommunication, and promises further important results;

b) that radioastronomers have made useful astronomical observations from the Earth's surface at frequencies as low as 2 MHz, as high as 800 GHz, and from space platforms at frequencies which extend down to lower than 10 kHz;

c) that protection from interference is essential to the advancement of radioastronomy and the associated measurements;

d) that the sensitivity of radioastronomical receiving equipment, which is still steadily improving, greatly exceeds the sensitivity of communications and radar equipment;

e) that propagation conditions at frequencies below about 40 MHz are such that a transmitter operating anywhere on the Earth might cause interference detrimental to radioastronomy;

f) that some transmissions from spacecraft introduce problems of interference to radioastronomy and that these cannot be avoided by choice of site for an observatory or by local protection;

g) that certain types of radioastronomical observation require long periods of uninterrupted recording, sometimes up to several days;

h) that interference to radioastronomy can be caused by terrestrial transmissions reflected by the Moon, by aircraft, and possibly by artificial satellites;

j) that some types of high-resolution interferometric observations require simultaneous reception, at the same radio frequency, by receiving systems located in different countries or on different continents;

k) that some degree of protection can be achieved by appropriate frequency assignments on a national rather than an international basis;

l) that the World Radiocommunication Conferences have made improved allocations for radioastronomy, but that protection in many bands, particularly those shared with other radio services, will need careful planning;

m) that technical criteria concerning interference detrimental to the radioastronomy service have been developed, which are those set out in Tables 1, 2, 3 and 4,

recommends

1 that radioastronomers should be encouraged to choose sites as free as possible from interference;

2 that administrations should afford all practicable protection to the frequencies used by radioastronomers in their own and neighbouring countries, taking due account of the levels of interference given in Annex 1;

3 that administrations, in seeking to afford protection to particular radioastronomical observations, should take all practical steps to reduce to the absolute minimum, all unwanted emissions falling within the band of the frequencies to be protected for radioastronomy, particularly those emissions from aircraft, spacecraft and balloons;

4 that when proposing frequency allocations, administrations take into account that it is very difficult for the radioastronomy service to share frequencies with any other service in which direct line-of-sight paths from the transmitters to the observatories are involved. Above about 40 MHz sharing may be practicable with services in which the transmitters are not in direct line-of-sight of the observatories, but coordination may be necessary, particularly if the transmitters are of high power.

ANNEX 1

Sensitivity of radioastronomy systems

1 General considerations

The simplest way to define the sensitivity of an observation in radioastronomy is to state the smallest power level change ΔP at the radiometer input which can, with high certainty, be detected and measured by the radiometer. The sensitivity equation is:

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{\Delta f_0 \, t}} \tag{1}$$

where P and ΔP refer to noise powers, Δf_0 stands for the bandwidth and t is the integration time. Equation (1) also holds if P and ΔP are power spectral densities. Thus ΔP, the noise fluctuation in power spectral density in the sensitivity equation (1), is related to the total system sensitivity (noise fluctuations) expressed in temperature units through the Boltzmann constant, k, as shown in equation (2):

$$\Delta P = k \ \Delta T; \quad \text{also} \quad P = k \ T \tag{2}$$

and we may express the sensitivity equation as:

$$\Delta T = \frac{T}{\sqrt{2 \Delta f_0 \, t}} \tag{3}$$

where:

$$T = T_A + T_R$$

and represents the sum of T_A (the antenna noise temperature contribution from the cosmic background, the Earth's atmosphere and radiation from the Earth) and T_R, the receiver noise temperature. Equations (1) or (3) can be used to estimate the sensitivities and interference levels for radioastronomical observations. The results are listed in Tables 1 and 2: an observing (or integration) time t of 2 000 s is assumed. In Table 1 (continuum observations), Δf is assumed to be the bandwidth of the allocated radioastronomy bands. In Table 2 (spectral line observations) Δf is the channel bandwidth (corresponding to a velocity of 3 km/s) typical of a spectral line system.

The interference threshold levels given in Tables 1 and 2 are expressed as the interference level which introduces an error of 10% in the measurement of ΔP (or ΔT), i.e.:

$$\Delta P_H = 0.1 \, \Delta P \ \Delta f \tag{4}$$

In summary, the appropriate columns in Tables 1 and 2 may be calculated using the following methods:

– ΔT, using equation (3),

– ΔP, using equation (2),

– ΔP_H, using equation (4).

The interference can also be expressed in terms of the power flux-density incident at the antenna, either in the total bandwidth or as a spectral power flux-density S_H per 1 Hz of bandwidth. For convenience, the values are given for an antenna having a gain, in the direction of arrival of the interference, equal to that of an isotropic antenna (which has an effective area of $c^2/4\pi f^2$, where c is the speed of the light and f the frequency).

Values of $S_H \Delta f$ (dB(W/m^2)), are derived from P_H by adding:

$$20 \log f - 38.6 \qquad \text{dB} \tag{5}$$

where f (MHz). S_H is then derived by subtracting 10 log Δf to allow for the bandwidth.

The calculated sensitivities and interference levels presented in Tables 1 and 2 are based on assumed integration times of 2 000 s. Integration times actually used in astronomical observations cover a wide range of values. Continuum observations made with telescopes operating singly (rather than in interferometric arrays) are reasonably well represented by the integration time of 2 000 s. It is representative of good quality observations. There are many occasions when this time is exceeded by an order of magnitude. There are also certain types of observations, such as observations of solar bursts, for which the greatest attainable sensitivity may not be required. On the other hand 2 000 s is less representative of spectral line observations. Improvements in receiver stability and the increased use of correlation spectrometers have resulted in the more frequent use of longer integration times. Spectral line observations lasting several hours are quite common. A more representative value would be 10 h with a consequent improvement in sensitivity of 6 dB over those values in Table 2.

Changes in receiving systems can be expected to give improved performance in the future. At the high frequency end of the spectrum now being used by radioastronomers, improvements in receiver technology are likely to have their largest effect. If receiver temperatures of 10 K can be achieved at frequencies in excess of 30 GHz then improvements in sensitivity of approximately 6 dB will result.

The levels given in Tables 1 and 2 are applicable to terrestrial sources of interfering signals, and are valid for intentional as well as unwanted emissions. The harmful power flux-density and spectral power flux-density shown in Tables 1 and 2 are based on the 0 dBi side-lobe case and should be regarded as the general interference criteria for high sensitivity radioastronomy observations, when the interference does not enter the near side lobes.

To simplify the task of finding the interference threshold levels for any band, the results from Tables 1 and 2 have been extracted as appropriate in Table 3.

A model of the typical side-lobe levels for large paraboloid antennas in the frequency range 2 to 10 GHz is given in Recommendation ITU-R SA.509. In this model, the side-lobe level decreases with angular distance (degrees) from the main beam axis, and is equal to $32 - 25 \log \varphi$ (dBi) for $1° < \varphi < 48°$. A level of 0 dBi occurs at 19° from the main beam axis. A source of interference of power flux-density equal to the threshold values given in Table 1 would be harmful if such an antenna was pointed within 19° of it. Thus, in some situations, interference below the harmful thresholds in Table 1 can be a problem to radioastronomers.

2 Special cases

2.1 Interference from geostationary satellites

Interference from geostationary satellites is a case of particular importance. Because the power levels in Tables 1 and 2 were calculated assuming 0 dBi antenna gain, interference detrimental to radioastronomy will be encountered when a reference antenna, such as described in Recommendation ITU-R SA.509, is pointed within 19° of a satellite radiating at levels in accordance with those listed in the tables. A series of similar transmitters located at intervals of 30° around the geostationary-satellite orbit (GSO) would preclude radioastronomy observations with high sensitivity from a band of sky 38° wide and centred on the orbit. The loss of such a large area of sky would impose severe restrictions on radioastronomy observations.

In general, it would not be practical to suppress the unwanted emissions from satellites to below the harmful level when the main beam of a radio telescope is pointed directly towards the satellite. A workable solution is suggested by observing the projection of the GSO in celestial coordinates as viewed from the latitudes of a number of major radioastronomy observations (see Recommendation ITU-R RA.517). If it were possible to point a radio telescope to within 5° of the orbit without encountering detrimental interference, then for that telescope a band of sky 10° wide would be unavailable for high-sensitivity observations. For a given observatory this would be a serious loss. However, for a combination of existing radio telescopes located at northern and southern latitudes, operating at the same frequencies, the entire sky would be accessible. A value of 5° should therefore be regarded as the requirement for minimum angular spacing between the main beam of a radioastronomy antenna and the GSO.

In the model antenna response of Recommendation ITU-R SA.509, the side-lobe level at an angle of 5° from the main beam is 15 dBi. Thus, to avoid interference detrimental to a radio telescope pointed to within 5° of the transmitter, the satellite emissions must be reduced 15 dB below the power flux-densities given in Tables 1 and 2. When satellites are spaced at intervals of only a few degrees along the GSO, the emission levels associated with the individual transmitters must be even lower to meet the requirement that the sum of the powers of all the interfering signals received should be 15 dB below ΔP_H in Tables 1 and 2.

It is recognized that the emission limitations discussed above cannot, in practice, be achieved so as to enable sharing of the same frequency band between radioastronomy and down-link transmissions from satellites to take place. The limitations are, however, applicable to unwanted emission from the satellite transmitters which fall within the radioastronomy bands listed in Tables 1 and 2. These emission limitations have implications for the space services responsible for the interference, which require careful evaluation. Furthermore, the design of new radioastronomy antennas should strive to minimize the level of side-lobe gain near the main beam as an important means of reducing interference from transmitters in the GSO.

2.2 The response of interferometers and arrays to radio interference

Two effects reduce the response to interference. These are related to the frequency of the fringe oscillations that are observed when the outputs of two antennas are combined, and to the fact that the components of the interfering signal received by different and widely-spaced antennas will suffer different relative time delays before they are recombined. The treatment of these effects is more complicated than that for single antennas in § 1. Broadly speaking the major effect is that the effective integration time over which interference affects the measurement is reduced from the total time of observation to the mean time of one natural fringe oscillation. This typically ranges from some seconds for a compact array with the longest projected spacing $L' \sim 10^3\ \lambda$, where λ is the wavelength, to less than 1 ms for intercontinental arrays with $L' \sim 10^7\ \lambda$. Thus, 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.

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)). In this case, the above considerations do not apply. 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 to prevent serious errors in the measurement of the amplitude of the cosmic signals. The interference levels for typical VLBI observations are given in Table 4.

It must be emphasized that the use of large interferometers and arrays is generally confined to studies of discrete high brightness sources, with angular dimensions no more than a few tenths of a second of arc for VLBI. For more general studies of radio sources, the results in Tables 1 and 2 apply and are thus appropriate for the general protection of radioastronomy.

TABLE 1

Threshold levels of interference detrimental to radioastronomy continuum observations

Centre frequency[(1)] f_c (MHz)	Assumed bandwidth Δf_A (MHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity[(2)] (noise fluctuations)		Harmful interference levels[(2) (3)]		
				Temperature ΔT (mK)	Power spectral density ΔP (dB(W/Hz))	Input power ΔP_H (dBW)	Power flux-density $S_H \Delta f_A$ (dB(W/m^2))	Spectral power flux-density S_H (dB(W/(m^2 · Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
13.385	0.05	60 000	100	4 250	– 222	– 185	– 201	– 248
25.610	0.120	20 000	100	917	– 229	– 188	– 199	– 249
73.8	1.6	1 000	100	14	– 247	– 195	– 196	– 258
151.525	2.95	200	100	2.76	– 254	– 199	– 194	– 259
325.3	6.6	40	100	0.86	– 259	– 201	– 189	– 258
408.05	3.9	25	100	1.00	– 259	– 203	– 189	– 255
611	6.0	15	100	0.74	– 260	– 202	– 185	– 253
1 413.5	27	10	20	0.091	– 269	– 205	– 180	– 255
1 665	10	10	20	0.15	– 267	– 207	– 181	– 251
2 695	10	10	20	0.15	– 267	– 207	– 177	– 247
4 995	10	10	20	0.15	– 267	– 207	– 171	– 241
10 650	100	12	20	0.05	– 272	– 202	– 160	– 240
15 375	50	15	30	0.10	– 269	– 202	– 156	– 233
23 800	400	15	50	0.051	– 271	– 195	– 147	– 233
31 550	500	18	100	0.083	– 269	– 192	– 141	– 228
43 000	1 000	25	100	0.063	– 271	– 191	– 137	– 227
89 000	6 000	30	150	0.037	– 273	– 185	– 125	– 222
110 500	11 000	40	150	0.029	– 274	– 184	– 121	– 222
166 000	4 000	40	150	0.048	– 272	– 186	– 120	– 216
224 000	14 000	40	200	0.032	– 274	– 182	– 114	– 215
270 000	10 000	40	200	0.038	– 273	– 183	– 113	– 213

(1) Calculation of interference levels is based on the centre frequency shown in this column although not all regions have the same allocations.

(2) An integration time of 2 000 s has been assumed; if integration times of 15 min, 1 h, 2 h, 5 h or 10 h are used, the relevant values in the table should be adjusted by + 1.7, – 1.3, – 2.8, – 4.8 or – 6.3 dB respectively.

(3) The interference levels given are those which apply for measurements of the total power received by a single antenna. Less stringent levels may be appropriate for other types of measurements, as discussed in § 2.2. For transmitters in the geostationary orbit, the levels need to be adjusted by –15 dB, as explained in § 2.1.

TABLE 2*

Threshold levels of interference detrimental to radioastronomy spectral-line observations

Frequency f (MHz)	Assumed spectral line channel bandwidth Δf_c (kHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity[(1)] (noise fluctuations)		Threshold interference levels [(1)] [(2)]		
				Temperature ΔT (mK)	Power spectral density ΔP (dB(W/Hz))	Input power ΔP_H (dBW)	Power flux-density $S_H \Delta f_c$ (dB(W/m^2))	Spectral power flux-density S_H (dB(W/(m^2 · Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
327	10	40	100	22.1	– 245	– 215	– 204	– 244
1 420	20	10	20	3.35	– 253	– 220	– 196	– 239
1 612	20	10	20	3.35	– 253	– 220	– 194	– 238
1 665	20	10	20	3.35	– 253	– 220	– 194	– 237
4 830	50	10	20	2.12	– 255	– 218	– 183	– 230
14 500	50	15	30	1.84	– 256	– 214	– 169	– 221
22 200	250	40	50	2.85	– 254	– 210	– 162	– 216
23 700	250	40	50	2.85	– 254	– 210	– 161	– 215
43 000	500	25	100	2.80	– 254	– 207	– 153	– 210
48 000	500	30	100	2.91	– 254	– 207	– 152	– 209
88 600	1 000	30	150	2.85	– 254	– 204	– 144	– 204
98 000	1 000	40	150	3.00	– 254	– 204	– 143	– 203
115 000	1 000	50	150	3.16	– 254	– 204	– 141	– 201
140 000	1 500	40	150	2.45	– 255	– 203	– 139	– 200
178 000	1 500	40	150	2.45	– 255	– 203	– 136	– 198
220 000	2 500	40	200	2.40	– 255	– 201	– 133	– 197
265 000	2 500	40	200	2.40	– 255	– 201	– 131	– 195

* This table is not intended to give a complete list of spectral-line bands, but only representative examples throughout the spectrum.

(1) An integration time of 2 000 s has been assumed; if assignation times of 15 min, 1 h, 2 h, 5 h or 10 h are used, the relevant values in the table should be adjusted by + 1.7, – 1.3, – 2.8, – 4.8 or – 6.3 dB respectively.

(2) The interference levels given are those which apply for measurements of the total power received by a single antenna. Less stringent levels may be appropriate for other types of measurements, as discussed in § 2.2. For transmitters in the geostationary orbit, the levels need to be adjusted by – 15 dB, as explained in § 2.1.

COLUMN DESCRIPTIONS FOR TABLES 1 AND 2

Column

(1) Centre frequency of the allocated radioastronomy band (Table 1) or nominal spectral line frequency (Table 2).

(2) Assumed or allocated bandwidth (Table 1) or assumed typical channel widths used for spectral line observations (Table 2).

(3) Minimum antenna noise temperature includes contributions from the ionosphere, the Earth's atmosphere and radiation from the Earth.

(4) Receiver noise temperature representative of a good radiometer system intended for use in high sensitivity radioastronomy observations.

(5) Total system sensitivity in millikelvins as calculated from equation (1) using the combined antenna and receiver noise temperatures, the listed bandwidth and an integration time of 2 000 s.

(6) Same as (5) above, but expressed in noise power spectral density using the equation $\Delta P = k \, \Delta T$, where $k = 1.38 \times 10^{-23}$ (J/K) (Boltzmann's constant). The actual numbers in the table are the logarithmic expression of ΔP.

(7) Power level at the input of the receiver considered harmful to high sensitivity observations (ΔP_H). This is expressed as the interference level which introduces an error of not more than 10% in the measurement of ΔP; $\Delta P_H = 0.1 \, \Delta P \, \Delta f$. The numbers in the table are the logarithmic expression of ΔP_H.

(8) Power flux-density in a spectral line channel needed to produce a power level of ΔP_H in the receiving system with an isotropic receiving antenna. The numbers in the table are the logarithmic expression of $S_H \, \Delta f$.

(9) Spectral power flux-density in a spectral line channel needed to produce a power level ΔP_H in the receiving system with an isotropic receiving antenna. The numbers in the table are the logarithmic expression of S_H.

TABLE 3

Simplified table of interference threshold levels extracted from Tables 1 and 2

Radioastronomy band	Power flux-density (dB(W/m^2))	Spectral power flux-density (dB(W/(m^2 · Hz)))
13.36-13.41 MHz	–201	–248
25.55-26.70 MHz	–199	–249
73.0-74.6 MHz	–196	–258
150.05-153.0 MHz	–194	–259
322.0-328.6 MHz	–204	–258
406.1-410.0 MHz	–189	–255
608-614 MHz	–185	–253
1 400-1 427 MHz	–196	–255
1 610.6-1 613.8 MHz	–194	–238
1 660-1 670 MHz	–194	–251
2 690-2 700 MHz	–177	–247
4 990-5 000 MHz	–171	–241
10.6-10.7 GHz	–160	–240
15.35-15.4 MHz	–156	–233
22.1-22.5 GHz	–162	–233
23.6-24.0 GHz	–161	–233
31.3-31.8 GHz	–141	–228
42.5-43.5 GHz	–153	–227
86-92 GHz	–144	–222
105-116 GHz	–141	–222
164-168 GHz	–136	–216
182-185 GHz	–135	–216
217-231 GHz	–133	–215
265-275 GHz	–131	–213

TABLE 4

Threshold interference levels for VLBI observations

Centre frequency, f_c[(1)] (MHz)	Interference level, S_H (dB(W/(m^2 · Hz)))
325.3	–215
611	–211
1 413.5	–209
2 695	–204
4 995	–198
10 650	–192
15 375	–187
23 800	–182
43 000	–173
86 000	–166

(1) Interference levels at other frequencies used for VLBI may be obtained by interpolation.