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Threshold interference levels for the protection of space-based radio astronomy observations

RA Series

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REPORT ITU-R RA.2403-0

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1 Introduction

Space-based radio astronomy observations provide information that cannot be obtained with Earth-based radio telescopes:

a) In some regions of the radio spectrum the atmosphere or the ionosphere blocks partially, or completely, cosmic radio waves from reaching the Earth's surface.

b) Radio telescopes in space, when used in combination with Earth-based ones, enable observations at extremely high angular resolution, far higher than what can be obtained with Earth-based interferometry only.

c) Space observations make possible the achievement of very high sensitivity in the measurement of the cosmic microwave background (CMB) radiation.

Radio astronomy observations from space are made for two reasons:

i) to get above the atmosphere that absorbs cosmic radiation in certain bands, particularly below ~ 10 MHz and, except in the atmospheric windows, above ~ 60 GHz. Such observations are usually carried out from spacecraft in halo orbit around the Lagrange L_2 point (see: e.g., Recommendation ITU-R RA.1417), with the telescope pointed towards the source being studied, and away from the Earth, to minimize the possibility of interference, and

ii) to carry out very high angular resolution Very Long Baseline Interferometry (VLBI) observations between a ground-based and a space-based telescope. For these observations highly elliptical Molniya type orbits are used mostly by the radio telescope in space with very distant aphelion that allows for the widest possible antenna spacing with those on Earth, as well as intermediate spacings needed to determine source structure.

In those portions of the spectrum where the Earth's atmosphere is transparent to radio waves, space- and Earth-based radio astronomy observations can be made in the same bands. The threshold levels of interference detrimental to radio astronomy observations, given in Recommendation ITU-R RA.769, were developed for Earth-based observations. In portions of the spectrum that can be observed only by space-based radio telescopes, no protection criteria have been developed specifically for space-based radio astronomy observations.

2 Sensitivity of radio astronomy observations in space

The methodology presented in § 2.1 for calculation of the threshold levels for interference detrimental to space-based radio astronomy observations is the same as for ground-based observations. When a frequency band can only be observed from space, the detrimental interference levels used are calculated according to the methodology in the Recommendation ITU-R RA.769. As with Recommendation ITU-R RA.769 the current Report uses the Rayleigh-Jeans approximation in the calculation of *pfd* values. A more rigorous calculation for the higher frequencies would use the Planck's law but the results differ by no more than 0.6 dB.

In Tables 1 to 3 the values used for receiver temperature, T_R, for frequencies below 1 GHz provided in Recommendation ITU-R RA.769 were amended. These are more representative of state-of-the-art space-borne receivers than the values given for ground-based receivers in Recommendation ITU-R RA.769. This change makes a small difference of less than 3 dB on the sensitivity value. In addition, for the antenna temperature we used the galactic and cosmic background radiation as given by Recommendation ITU-R P.372-11.

2.1 General considerations and assumptions used in the calculation of interference levels

2.1.1 Detrimental-level interference criterion

The methodology of the sensitivity calculations for radio astronomy observations in space is similar to that for Earth-based observations developed in Recommendation ITU-R RA.769. The primary parameter in calculations of the levels of interference detrimental to radio astronomy observations is the power flux density (*pfd)* of the observing system, determined by the system temperature. For Earth-based observations above 15 GHz, the atmosphere makes a large contribution to the system temperature. When radio astronomy observations are carried out in space, outside the atmosphere, the lower system temperature that result from the absence of atmospheric contribution to it results, in turn, in lower detrimental interference levels. Following the method described in Annex 1 to Recommendation ITU-R RA.769, the detrimental-interference levels are calculated as a function of observing frequency and provided in Tables 1, 2 and 3 for continuum (broadband), spectral line (narrow band) and Very Long Baseline Interferometry (VLBI) observations, respectively.

Following Recommendation ITU-R RA.769, the sensitivity of a radio astronomy observation can be defined in terms of the smallest change ΔP in the power level P at the radiometer input that could be detected and measured. The sensitivity equation is:

$$\frac{\Delta P}{P} = \frac{1}{\sqrt{\Delta f_0 t}} \qquad (1)$$

where:

- P and ΔP: spectral power density of the noise and variation of spectral power density
- Δf_0: bandwidth observed
- t: integration time.

P and ΔP in equation (1) can be expressed in temperature units, using the Boltzmann constant k:

$$\Delta P = k\,\Delta T; \quad \text{and} \quad P = k\,T \qquad (2)$$

Thus we may express the sensitivity equation as:

$$\Delta T = \frac{T}{\sqrt{\Delta f_0 t}} \qquad (3)$$

where:

$$T = T_A + T_R$$

For one polarization of the radio telescope, T is the sum of T_A (the antenna noise temperature, which is the sum of the contributions of the cosmic background noise, the noise from the Earth's atmosphere and radiation from the Earth) and T_R is the receiver noise temperature. Again following Recommendation ITU-R RA.769, the detrimental interference threshold level ΔP_H, is defined as the interference power within the bandwidth Δf that introduces an error of 10% in the measurement of ΔP (or ΔT), i.e.:

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

The interference can also be expressed in terms of the *pfd* incident on the antenna, either in the entire allocated bandwidth or as a spectral power flux density (*spfd*), S_H, in a unit (1 Hz) bandwidth. The values given are 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 is the frequency). The gain of an isotropic radiator, 0 dBi, is used as a general representative value for the sidelobe level.

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

$$20 \log f - 158.5 \text{ dB} \tag{5}$$

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

2.1.2 Integration time

Following Recommendation ITU-R RA.769, an integration time of 2 000 s is used.

2.1.3 Antenna response pattern

Following Recommendation ITU-R RA.769, interference is assumed to enter via a 0 dBi sidelobe.

2.1.4 Bandwidth

The astronomical observations are typically either made over the whole bandwidth, termed continuum observations, or as spectral line observations in a search for atomic or molecular signatures of the astronomical object. Following Recommendation ITU-R RA.769, Equation (1) shows that observations of the highest sensitivity are obtained when radio astronomers make use of the largest possible bandwidth. Consequently, in Table 1 (continuum observations), Δf is assumed to be the width of the allocated radio astronomy bands for frequencies up to 71 GHz.

Above 71 GHz a value of 8 GHz is used, which is the bandwidth generally used in practice. In Table 2 (spectral line observations) a channel bandwidth Δf equal to the Doppler shift in frequency corresponding to 3 km/s in velocity is used for entries below 71 GHz. This value represents a compromise between the desired high spectral resolution and the sensitivity. There are a very large number of astrophysically important lines above 71 GHz, as shown in Recommendation ITU-R RA.314, but only a few representative values for detrimental levels are given in Table 2 for the range 71-275 GHz.

The channel bandwidth used to compute the detrimental levels above 71 GHz is 1 000 kHz (1 MHz). This value was chosen for practical reasons. While it is slightly wider than the spectral channel width customarily used at these frequencies, it is used as the standard reference bandwidth for space services above 15 GHz.

2.1.5 Receiver noise temperature and antenna noise temperature

When making space-based radio astronomy observations at frequencies above 15 GHz, the contribution to the system temperature by the Earth's atmosphere is negligible, and therefore for space-based observations, the contribution of the Milky Way Galaxy to the background noise is the major external contribution to the antenna noise temperature. The antenna noise temperature includes the background temperature, for which the value used for space-based observations is that of the cosmic microwave background (CMB) emission, i.e. approximately 2.7 K.

The receiver noise temperatures in Tables 1 and 2 are representative of the systems in use in radio astronomy. For frequencies above 1 GHz these are cryogenically cooled amplifiers or mixers. The quantum effect places a theoretical lower limit of hf/k on the noise temperature of such devices, where h and k are the Planck and Boltzmann constants, respectively. This limit becomes important at frequencies above 100 GHz, where it is equal to 4.8 K. Practical mixers and amplifiers for bands at 100 GHz provide higher noise temperatures, greater than hf/k by a factor of about four. Thus, for frequencies above 100 GHz, noise temperatures equal to 4 hf/k are used in Tables 1 and 2.

2.2 Special cases

The detrimental total power (*pfd*) and spectral *pfd* levels shown in Tables 1 and 2 assume that interference is received through a 0 dBi sidelobe, and should be regarded as the general detrimental interference limits for high sensitivity radio astronomy observations from space, when the interference does not enter through the near sidelobes.

2.2.1 The response of interferometers and arrays to radio interference

Two effects reduce the response to interference in case of observations made with interferometers and arrays. 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 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 3, based on the values of T_A and T_R given in Table 1. Frequencies in Table 3 are those from Recommendation ITU-R RA.769, and frequencies above 100 GHz for which Earth- and space-based observations are planned.

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 radio astronomy.

TABLE 1

Threshold levels of interference detrimental to radio astronomy continuum observations made in space

Centre frequency f_c MHz (1)	Assumed BW=Δf [MHz] (2)	Min Ant Noise Tem T_A [K] (3)	Receiver noise Temp, T_R [K] (4)	Tempera ture ΔT [mK] (5)	Power Spectral density ΔP [dBW/Hz] (6)	Input Power ΔP_H [dBW] (7)	pfd$\Delta S_H \Delta f$ [dBW/m^2] (8)	Spectral pfdΔS_H [dBW/m^{2}Hz] (9)
325.3	6.6	36	10	0.400	–263	–204	–193	–261
408.05	3.9	23	10	0.374	–263	–207	–193	–259
611	6	10	10	0.183	–266	–208	–191	–259
1 413.5	27	2.7	10	0.055	–271	–207	–182	–257
1 665	10	2.7	10	0.090	–269	–209	–183	–253
2 695	10	2.7	10	0.090	–269	–209	–179	–249
4 995	10	2.7	10	0.090	–269	–209	–174	–244
10 650	100	2.7	10	0.028	–274	–204	–162	–242
15 375	50	2.7	15	0.056	–271	–204	–159	–236
22 355	290	2.7	30	0.043	–272	–198	–149	–234
23 800	400	2.7	30	0.037	–273	–197	–148	–234
31 550	500	2.7	30	0.031	–274	–197	–146	–233
43 000	1 000	2.7	30	0.022	–276	–196	–142	–232
89 000	8 000	2.7	30	0.008	–279	–190	–130	–229
150 000	8 000	2.7	30	0.008	–279	–190	–125	–224
224 000	8 000	2.7	43	0.011	–278	–189	–120	–220
270 000	8 000	2.7	50	0.013	–277	–188	–118	–217
660 000	8 000	2.7	127	0.032	–273	–184	–107	–206
870 000	8 000	2.7	167	0.042	–272	–183	–103	–202

TABLE 2

Threshold levels of interference detrimental to radio astronomy spectral line observations made in space

Centre frequency f_c kHz (1)	Assumed BW=Δf [kHz] (2)	Min Ant Noise Tem T_A [K] (3)	Receiver noise Temp, T_R [K] (4)	Temperature ΔT [mK] (5)	Power Spectral density ΔP [dBW/Hz] (6)	Input Power ΔP_H [dBW] (7)	pfd$\Delta S_H \Delta f$ [dBW/m^2] (8)	Spectral pfdΔS_H [dBW/m^{2}Hz] (9)
327	10	36	10	8.05	–250	–220	–208	–248
1 420	20	2.7	10	2.01	–256	–223	–198	–241
1 612	20	2.7	10	2.01	–256	–223	–197	–240
1 665	20	2.7	10	2.01	–256	–223	–197	–240
4 830	50	2.7	10	1.27	–258	–221	–185	–232
14 488	150	2.7	15	1.02	–259	–217	–172	–224
22 200	250	2.7	30	1.46	–257	–213	–165	–219
23 700	250	2.7	30	1.46	–257	–213	–164	–218
43 000	500	2.7	30	0.99	–259	–212	–158	–215
48 000	500	2.7	30	0.99	–259	–212	–157	–214
88 600	1 000	2.7	30	0.73	–260	–210	–150	–210
150 000	1 000	2.7	30	0.73	–260	–210	–145	–205
220 000	1 000	2.7	43	1.0	–259	–209	–140	–200
265 000	1 000	2.7	50	1.2	–258	–208	–138	–198

COLUMN DESCRIPTIONS FOR TABLES 1 AND 2

Column

1) Centre frequency of the radio astronomy 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 Milky Way Galaxy background.

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

5) Total system sensitivity (mK) 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) *pfd* 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 *pfd* 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. To obtain the corresponding power levels in a reference bandwidth of 4 kHz or 1 MHz add 36 dB or 60 dB, respectively.

TABLE 3

Threshold interference levels for VLBI observations

Centre frequency (MHz)	**Threshold level (dB(W/m^2· Hz)))**
325.3	–220
611	–218
1 413.5	–213
2 695	–207
4 995	–200
10 650	–196
15 375	–191
23 800	–184
43 000	–180
86 000	–173
230 000	–163
660 000	–150
870 000	–146

3 Summary

The threshold levels in this Report are the detrimental interference levels for the protection of space-based RAS applications.