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**Sharing between the radio astronomy
service and active services in the frequency
range 275-3 000 GHz**

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Radio astronomy



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REPORT ITU-R RA.2189

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in the frequency range 275-3 000 GHz**

(2010)

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1 Introduction

Certain characteristics of the frequency range 275-3 000 GHz combine to reduce the likelihood of interference between the radio astronomy service and active services in this range. The purpose of this Report is to present a basic introduction to those characteristics and how they affect potential sharing scenarios. Based on the analysis in this Report, there is little chance for interference to radio telescopes from co-frequency terrestrial, airborne, or satellite transmitters, particularly at frequencies above 1 000 GHz. The results of this study are applicable to current and future discussions relating to extending No. 5.565 of the Radio Regulations to frequencies in the 275-3 000 GHz range, and studies related to the advancement of technology at frequencies above 275 GHz¹.

¹ In this Report, “THz frequencies” refers to the range 275-3 000 GHz.

2 Atmospheric absorption

In the range 275-3 000 GHz, propagation through the Earth's atmosphere is strongly affected by absorption due to atmospheric molecules. The molecular species most responsible for the absorption are oxygen (O₂) and water vapour (H₂O). Non-resonant absorption creates a general continuum of absorption that steadily increases with frequency, while exceedingly large values of attenuation are found at specific frequencies corresponding to natural resonances of the molecules. At sea level, the general continuum of absorption is approximately 5 dB/km at 275 GHz, 300 dB/km at 1 000 GHz, and 4 000 dB/km at 3 000 GHz. At specific molecular resonances in this range, the attenuation can be as large as 550 000 dB/km.

Attenuation will decrease with altitude due to lower concentrations of oxygen and water vapour. Figure 1 shows attenuation in dB/km at 4 different altitudes: sea level, 300 m, 1 000 m, and 3 000 m. The curve assumes the 1976 Standard Atmosphere model^{2,3}, with the addition of a column of 2 cm total precipitable water vapour with a scale height of 2 km, at a sea-level relative humidity of 50%. The atmospheric parameters were used in the *am* atmospheric transmission model to compute the absorption curves^{4,5}. Based on the assumed atmospheric characteristics, the following inputs were used in the *am* model:

TABLE 1
Assumed atmospheric properties for calculating absorption
over a horizontal path of 1 km in length

Altitude (m)	Temperature (K)	Pressure (mbar)	Column density of dry air (cm ⁻²)	Column density of water vapour (cm ⁻²)
0	288.15	1013.25	2.55 × 1 024	3.34 × 1 022
300	286.20	977.73	2.47 × 1 024	2.87 × 1 022
1 000	281.65	898.75	2.31 × 1 024	2.03 × 1 022
3 000	268.65	701.09	1.89 × 1 024	7.45 × 1 021

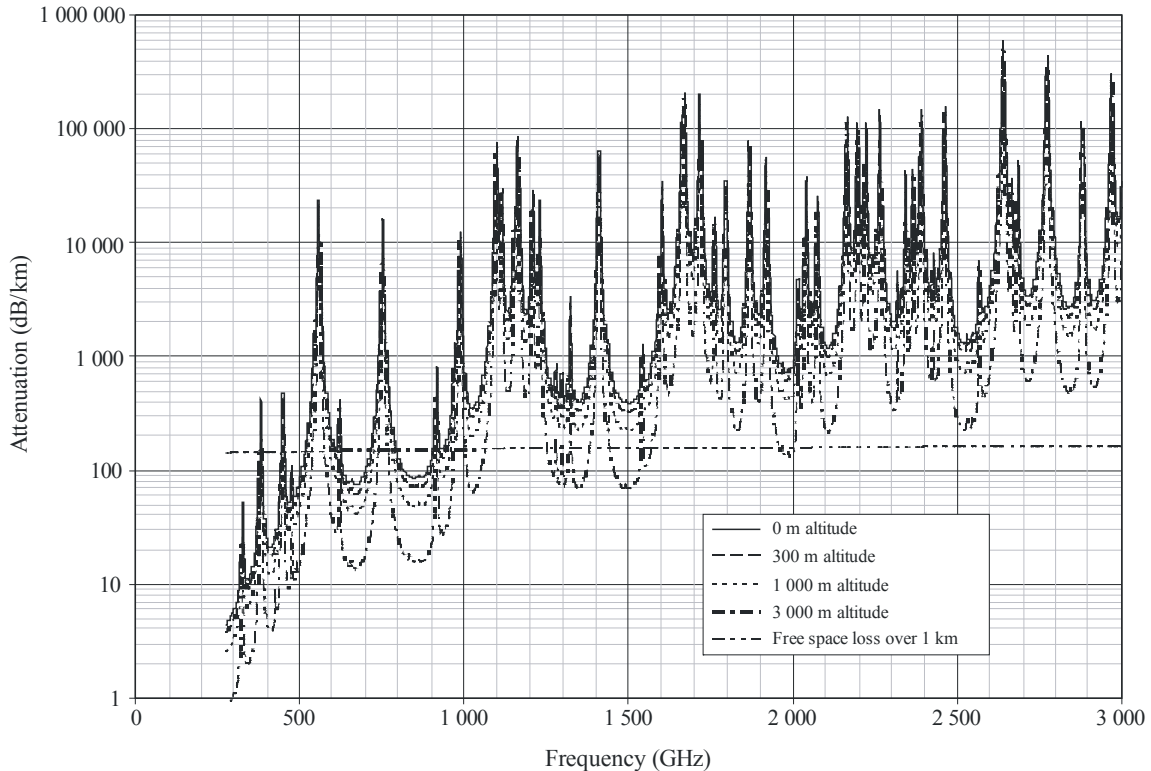
² U.S. Standard Atmosphere [1976] U.S. Government Printing Office, Washington DC, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539.pdf.

³ Standard atmosphere calculator available at <http://www.luizmonteiro.com/StdAtm.aspx>.

⁴ Paine, Scott, "The *am* Atmospheric Model", Submillimeter Array Technical Memo #152 (Revision 3); available at <http://www.cfa.harvard.edu/~spaine/am/>.

⁵ Recommendation ITU-R P.676 accurately calculates atmospheric attenuation up to a maximum frequency of 1 000 GHz. The *am* model is more rigorous for frequencies above 1 000 GHz. For a consistency check, the data in Fig. 1 and those in Fig. 5 of Recommendation ITU-R P.676 agree well in the region of overlapping frequency coverage. Figure 1 of this Report is based on *am* for the entire range.

FIGURE 1
Atmospheric attenuation computed over horizontal paths of 1 km at four different altitudes, assuming the atmospheric properties of Table 1. For reference, free-space loss over 1 km is also plotted



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Because atmospheric absorption is a strong factor for terrestrial systems at THz frequencies, calculation of path loss between a transmitter and receiver must include this factor. The signal level at the receiver is:

$$P_R = P_T + G_T + G_R - PL - A \quad (1)$$

where:

- P_R : the power at the output port of the receive antenna
- P_T : the power at the input port of the transmit antenna
- G_T : the gain of the transmit antenna in the direction of the receive antenna
- G_R : the gain of the receive antenna in the direction of the transmit antenna
- PL : the “traditional” path loss between transmit and receive antennas due to geometric spreading and terrain blockage
- A : the additional loss factor due to atmospheric absorption.

All terms are expressed in logarithmic units.

Due to extreme atmospheric absorption, typically the only possible interference scenarios involve a transmitter and victim receiver that are line-of-sight to one another, and therefore the PL factor is free-space loss:

$$PL(\text{dB}) = 20 \log D_{\text{km}} + 20 \log f_{\text{GHz}} + 92.44 \quad (2)$$

where:

- D_{km} : the distance between the transmitter and the receiver (km)
- f_{GHz} : the frequency (GHz).

At sea level, the minimum baseline absorption rate is approximately 5 dB/km at 275 GHz (i.e. $A \approx 5 D_{\text{km}}$). Solving for D_{km} at which $PL = A$ shows that atmospheric absorption A will be greater than free-space loss PL for any distance greater than approximately 34 km (free-space loss and atmospheric absorption are both ~ 172 dB at this distance). At 1 000 GHz, the baseline absorption rate is approximately 300 dB/km, and the distance at which free-space loss and atmospheric absorption are the same (~ 150 dB) is approximately 0.5 km. At 3 THz, the baseline absorption rate is approximately 4 000 dB/km, and the corresponding distance at which absorption is greater than the calculated free-space loss is about 33 m (loss/absorption are both ~ 132 dB), although this is less than the near field distance of a small 10 cm diameter antenna and the free-space loss formula breaks down. At specific absorption resonance peaks, these distances shrink dramatically. Consider for example a resonance near 1 411 GHz, where sea level attenuation exceeds 65 000 dB/km. Attenuation exceeds the calculated free-space loss at a distance of only 1.6 m, which is again less than the near field distance of a very small antenna.

At higher elevations the conclusions are similar. At 3 000 m altitude and 275 GHz frequency, the baseline absorption rate is approximately 1 dB/km, and atmospheric attenuation exceeds free-space loss for distances over about 186 km. At 1 000 GHz frequency, the absorption rate is approximately 100 dB/km, and atmospheric attenuation exceeds free-space loss for distances over about 1.6 km. At 3 000 GHz, the baseline absorption rate is approximately 1 000 dB/km, and the distance is about 150 m.

The conclusion is that for frequencies above about 1 000 GHz, atmospheric absorption is typically a more significant factor than geometric spreading (free space loss). This is especially true for sites that are not on high and dry mountaintops.

3 Antenna beamwidth

In addition to atmospheric absorption, small antenna beam sizes also reduce the chances of accidental interference. The beamwidth of a dish antenna, measured in degrees, is given by the approximate formula:

$$\theta_{\text{deg}} \cong \frac{1720}{\alpha f_{\text{GHz}} d_{\text{cm}}} \quad (3)$$

where:

- θ_{deg} : the approximate beamwidth (degrees)
- f_{GHz} : the frequency (GHz)
- d_{cm} : the antenna's physical diameter (cm)
- α : a parameter (≤ 1) that is effectively the fraction of the diameter of the dish illuminated by the feed.

A given size antenna will produce a smaller beamwidth with increasing frequency; alternatively, at a given frequency, a larger dish will create a smaller beamwidth (assuming α remains constant).

At frequencies near or above 275 GHz, antenna beamwidths are very small, even for small dishes. As an example, a 30 cm diameter dish (about the size of a large dinner plate) will create a beam of only 0.28° at a frequency of 275 GHz, assuming $\alpha = 0.75$. For illustration, 0.28° corresponds to the approximate angular extent of a medium-sized computer monitor when viewed from the opposite end of a 105 m football playing field. At 1 000 GHz, the beamwidth of the same antenna is 0.08°

which corresponds to the angular extent of about 2/3 the diameter of a football when viewed from the opposite end of the playing field. At 3 000 GHz, the beamwidth of the same antenna is about 0.025°. To gauge this angle, it is equivalent to less than the diameter of a tennis ball when viewed from the far end of a football field.

Assuming that the antenna beam and a potential interfering emission source are constrained to be in the same plane (for example, an antenna pointed along a horizontal path and an emission source on the ground), the likelihood that a random point source of emission falls within the main beam of a horizontally-pointed antenna is approximately $\theta_{\text{deg}}/360^\circ$. The computed probability is approximately 4.6×10^{-3} for a 5 cm antenna at 275 GHz, to 6.5×10^{-4} for a 10 cm antenna at 1 000 GHz, to 7×10^{-5} for a 30 cm antenna at 3 000 GHz (see Table 2).

Because of strong absorption in this frequency range, rapid free-space fall-off, and low RF power generation (§ 4), it is likely that if any interference occurs between two active terrestrial systems, it would require their antenna beams to be pointing directly at each other. Given the small beam sizes, the chances that two unrelated horizontally pointed terrestrial antennas have beams that point at each other is very small. Roughly speaking, the chance that one antenna is in the beam of the other is approximately $\theta_{\text{deg}}/360^\circ$, so that the probability P_{2D} that two antennas are simultaneously within the beams of each other is then:

$$P_{2D} \cong \frac{\theta_1 \theta_2}{(360^\circ)^2} = \frac{22.8}{\alpha^2 d_{\text{cm}}^2 f_{\text{GHz}}^2} \quad (4)$$

where for simplicity the last term has assumed that the antennas are identical in size and illumination efficiency. The following table summarizes the resulting probability for various antenna sizes and frequencies, assuming $\alpha = 0.75$.

TABLE 2

Probability, within the same plane, that a point source of emission falls within the main beam of a randomly-pointed antenna ($\theta_{\text{deg}}/360^\circ$), and the probability that two identical unrelated antennas happen to be pointed within each other's beams, as a function of frequency and antenna diameter

Frequency (GHz)	Antenna diameter (cm)	Probability of isotropic source in main beam ($\theta_{\text{deg}}/360^\circ$)	Probability of main beam coupling (P_{2D})
275	5	5×10^{-3}	2×10^{-5}
275	10	2×10^{-3}	5×10^{-6}
275	30	8×10^{-4}	6×10^{-7}
1 000	5	1×10^{-3}	2×10^{-6}
1 000	10	6×10^{-4}	4×10^{-7}
1 000	30	2×10^{-4}	5×10^{-8}
2 000	5	6×10^{-4}	4×10^{-7}
2 000	10	3×10^{-4}	1×10^{-7}
2 000	30	1×10^{-4}	1×10^{-8}
3 000	5	4×10^{-4}	2×10^{-7}
3 000	10	2×10^{-4}	5×10^{-8}
3 000	30	7×10^{-5}	5×10^{-9}

Similar considerations can be made for satellite antennas, where the probabilities are even smaller because the antennas are not constrained to operate in one plane. In the satellite case, beam solid angles (in steradians or square degrees) are taken into account. For small beams, the fraction of a sphere occupied by the beam (terrestrial or satellite) is given by:

$$\frac{\Omega}{4\pi} \cong \frac{1}{4\pi} \cdot \pi \left(\frac{\theta_{\text{deg}}/57.3}{2} \right)^2 = 1.9 \times 10^{-5} \theta_{\text{deg}}^2 = \frac{56.3}{\alpha^2 d_{\text{cm}}^2 f_{\text{GHz}}^2} \quad (5)$$

where Ω is the beam solid angle in steradians, the factor of 57.3 is for conversion of the beamwidth from degrees to radians, and 4π is the number of steradians in a sphere. Equation (5) is then the fraction of a sphere covered by the beam, which is the inverse of the antenna's isotropic gain:

$$G(\text{dBi}) = 10 \log \left(\frac{4\pi}{\Omega} \right) = 20 \log \alpha + 20 \log d_{\text{cm}} + 20 \log f_{\text{GHz}} - 17.5 \quad (6)$$

The probability that a random source of emission falls within the main beam is $\sim \Omega/4\pi$, which, for a 10 cm antenna, equals 1.0×10^{-5} at 275 GHz, 1.0×10^{-6} at 1 000 GHz, and 1.0×10^{-7} at 3 000 GHz (see Table 3). The probability that two unrelated antennas are randomly pointed at each other is $\sim (\Omega_1/4\pi) (\Omega_2/4\pi)$:

$$P_{3D} \cong \frac{3170}{\alpha^4 d_{\text{cm}}^4 f_{\text{GHz}}^4} \quad (7)$$

where for simplicity as in the 2-dimensional case, it has been assumed the antennas are identical. The 3-dimensional probability computes to the following values as a function of frequency and antenna size.

TABLE 3

Probability that a random source of emission falls within the main beam of an antenna ($\Omega/4\pi$), and the probability that two identical antennas happen to be pointed directly within each other's beams, $P_{3D} = (\Omega/4\pi)^2$, as a function of frequency and antenna diameter. The gain of the antenna, $= 10\log(4\pi/\Omega)$, is also listed

Frequency (GHz)	Antenna diameter (cm)	G (dBi)	$\Omega/4\pi$	Probability of main beam coupling (P_{3D})
275	5	43	5×10^{-5}	3×10^{-9}
275	10	49	1×10^{-5}	2×10^{-10}
275	30	58	1×10^{-6}	2×10^{-12}
1 000	5	54	4×10^{-6}	2×10^{-11}
1 000	10	60	1×10^{-6}	1×10^{-12}
1 000	30	70	1×10^{-7}	1×10^{-14}
2 000	5	60	1×10^{-6}	1×10^{-12}
2 000	10	66	3×10^{-7}	6×10^{-14}
2 000	30	76	3×10^{-8}	8×10^{-16}
3 000	5	64	4×10^{-7}	2×10^{-13}
3 000	10	70	1×10^{-7}	1×10^{-14}
3 000	30	79	1×10^{-8}	2×10^{-16}

The conclusion is that for reasonable assumptions of antenna size in the frequency range 275-3 000 GHz, the likelihood that a random source of emission falls within the main beam of a directional antenna is very small; the chance of two directional antennas having their main beams pointed directly at one another is exceedingly small.

These conclusions are relevant to the possibility that active antennas are pointed in the direction of a radio observatory; however, additional considerations of the angular extent of the radio telescope as seen by the active antenna have to be taken into account. Consider as an example a 100 m radio telescope dish located 1 km from a terrestrial transmit antenna. The radio dish has an angular size θ_{tel} of about $(100 \text{ m}/1\,000 \text{ m}) = 0.1 \text{ radian} = 5.7^\circ$ as seen from the antenna. This is much larger than the angular extent of the transmit beam, so it is the controlling factor as to the computed likelihood of the beam being pointed toward the radio telescope. It is assumed that in such cases, the transmit antenna is located within or close to an area that is under the control of the radio astronomy observatory itself, so that local coordination can solve potential problems.

In space, radio astronomy antennas are generally as large as economically feasible in order to provide significant collecting area. For example, the European Space Agency's Herschel telescope utilizes a primary reflector of 3.5 m in diameter equipped with various infrared and radio detectors, including one instrument (HIFI) covering the range of 480-1 910 GHz (non-continuous). At 1 000 GHz, the beamwidth of the 3.5 m antenna, assuming 75% feed coverage, is 0.007° , providing excellent immunity to main beam coupling with any potential man-made interference, since the beam covers only about one billionth of a sphere. In addition, the spacecraft itself is some 1.5 million km from Earth, further reducing chances of receiving man-made interference.

4 RF power generation

State-of-the-art components generate low RF power in the range 275-3 000 GHz compared to lower-frequency devices. Maximum power output from solid state multipliers is limited to approximately 1 mW (0 dBm) at 1 000 GHz; at 3 000 GHz, the maximum output power is approximately 10 μ W (-20 dBm)⁶. Photonic generation of submillimetre wavelength radiation is possible using very short optical laser pulses, akin to the process of creating lower-frequency radio waves using spark gap transmitters. Photonic technology is presently limited to about 10 μ W (-20 dBm) in power at 1 THz in frequency⁷. While vacuum tube devices may be able to generate higher power levels than solid-state multipliers or photonic devices, they are not widely used. In this Report, the maximum RF power level between 275-3 000 GHz is assumed to follow the empirical formula:

$$P_T = 0.01(1000 - f_{\text{GHz}}) \quad \text{dBm} \quad (8)$$

5 Sharing between active services and radio astronomy

To examine possible interference scenarios to radio telescopes due to transmitters in the 275-3 000 GHz range, it is necessary to define a signal level that could be considered sufficiently high to cause detrimental effects to radio astronomy observing. At frequencies below 275 GHz, such levels are derived in Recommendation ITU-R RA.769. For the purpose of this Report, a coarse

⁶ EISELE, H. [2002] Conventional and Novel Approaches to RF Power Generation with Two-Terminal Devices at Terahertz Frequencies. *Proceedings of the Tenth IEEE International Conference on Terahertz Electronics*, Cambridge, UK, p. 13 (see esp. Figure 10).

⁷ NAGATSUMA, T. [2009] Generating Millimeter and Terahertz Waves. *IEEE Microwave Magazine*, Vol 10, No. 4, p. 64 (see esp. Figure 9).

extrapolation of the Recommendation ITU-R RA.769 values to the range 275-3 000 GHz is made. In Recommendation ITU-R RA.769, discrete values of the detrimental interference level are provided for all of the allocated radio astronomy bands. If a linear least squares fit to the discrete values for the radio astronomy continuum bands in the range 89-270 GHz is made, those levels are well represented by the formula:

$$S_H = -247.26 + 25.11 \log(f_{\text{GHz}}) \text{ dB} \left(\frac{\text{mW}}{\text{m}^2 \text{Hz}} \right) \quad (9)$$

where the correlation coefficient for the linear least squares fit is $r = 0.998$. This formula is used to extrapolate the values into the range 275-3 000 GHz (see Table 4).

In Recommendation ITU-R RA.769, the assumed bandwidth over which the interference is received is 8 GHz (a typical bandwidth for state-of-the-art millimetre wave radio telescopes), so the corresponding power density in $\text{dB}(\text{mW}/\text{m}^2)$ can be obtained by multiplying S_H by 8 GHz. Further, Recommendation ITU-R RA.769 assumes that the power is received in a 0 dBi side lobe of the radio telescope antenna, so that the corresponding effective collecting area is $\lambda^2/4\pi$, and this factor can be used to translate the power density to an effective received power (P_H) in dBm. Assuming the fit of equation (9) is used to extrapolate values of S_H to the 275-3 000 GHz range, the following values for detrimental levels of interference to the radio astronomy service are obtained:

TABLE 4

**Example values of interference levels detrimental to the radio astronomy service,
extrapolated from values provided in Recommendation ITU-R RA.769
for allocated radio astronomy bands between 89-270 GHz**

Frequency (GHz)	S_H dB(mW/m ² Hz)	$S_H \times 8 \text{ GHz}$ dB(mW/m ²)	$P_H = S_H \times 8 \text{ GHz} \times \lambda^2/4\pi$ (dBm)
275	-186	-87	-157
1 000	-172	-73	-154
2 000	-164	-65	-153
3 000	-160	-61	-152

5.1 Terrestrial transmitter into terrestrial radio telescope

It is assumed that interference occurs if:

$$P_R = P_T + G_T + G_R - PL - A \geq P_H \quad (10)$$

where:

P_R : the power received at the radio telescope site

P_T : the transmitter power of the interferer

G_T : the gain of the transmit antenna (equation (6))

G_R : the gain of the radio telescope in the direction of the transmitter, which is assumed to be 0 dBi in accordance with Recommendation ITU-R RA.769

PL : free-space loss (equation (2))

- A : the atmospheric attenuation (see Fig. 1)
- P_H : the level of interference detrimental to radio astronomy observations (see Table 4).

A “close-to-worst-case” terrestrial scenario for interference to the radio astronomy service from an active system in the 275-3 000 GHz range would be a transmitter running maximum available RF power into a relatively large transmit antenna pointing directly at a radio telescope, with both transmitter and telescope at a high elevation. To simulate this scenario and determine the distance at which the existence of the transmitter could be problematic for the radio telescope, it will be assumed that the radio telescope and the transmitter are both at 3 000 m altitude, that the transmitter is running maximum available power (equation (8)), and that the transmit antenna is 30 cm in diameter with $\alpha = 0.75$. Under these assumptions, the distance at which interference (as defined by equation (10)) would occur can be computed. The results are plotted in Fig. 2 for 275-1 000 GHz, and in Fig. 3 for 1 000-3 000 GHz.

FIGURE 2

Distance beyond which a transmitted signal at frequencies between 275 and 1 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Recommendation ITU-R RA.769, based upon near-worst-case assumptions described in the text

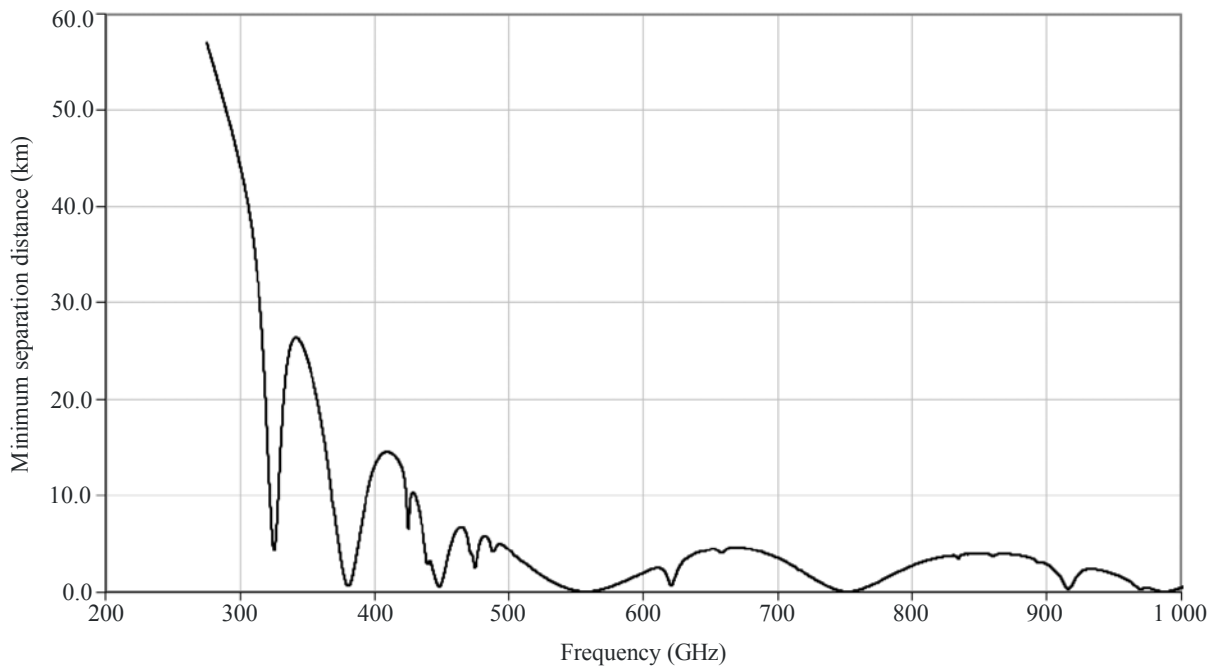
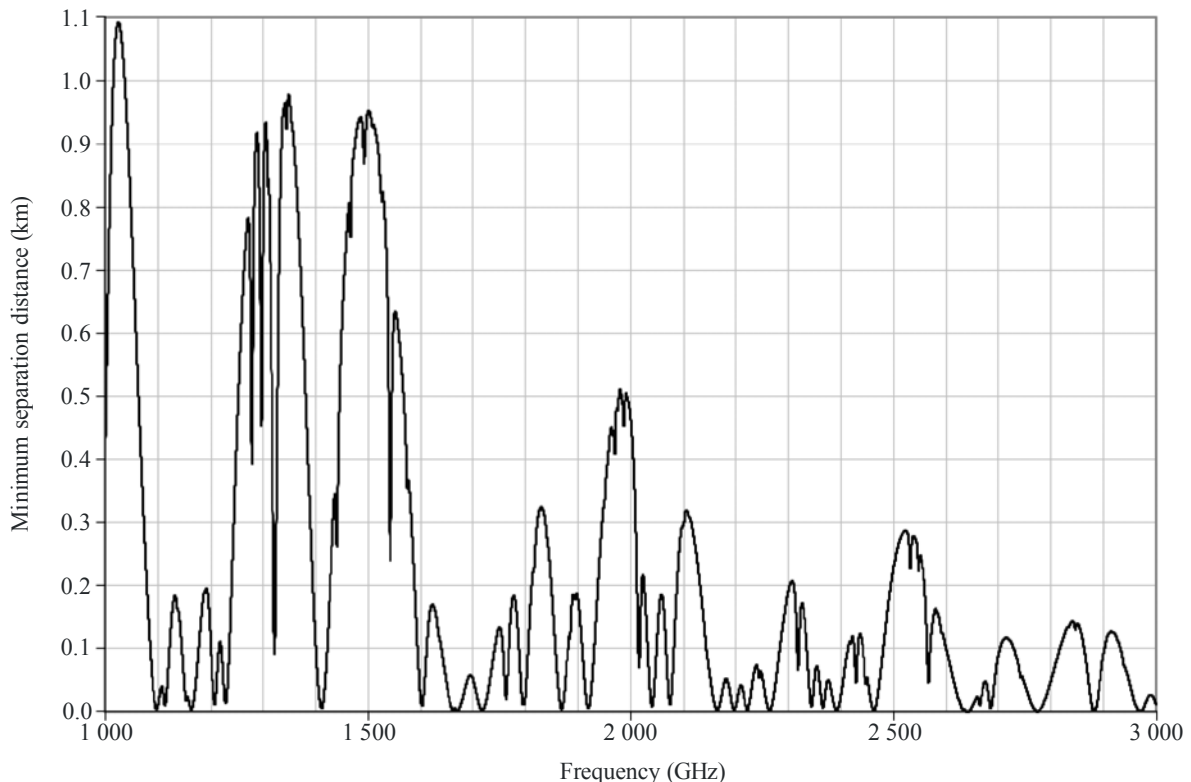


FIGURE 3

Distance beyond which a transmitted signal at frequencies between 1 000 and 3 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Recommendation ITU-R RA.769, based upon near-worst-case assumptions described in the text



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The conclusion is that for frequencies in the 1 000-3 000 GHz range, a transmitter would have to be in the immediate vicinity of a telescope to cause interference, assuming the worst-case scenario of both transmitter and telescope located on a high and dry mountaintop. At lower elevations attenuation is much larger and the interference distance becomes even smaller, but radio telescopes operating in this frequency range would never be located in such areas.

5.2 Airborne transmitter into radio telescope

Airborne sources of interference to radio telescopes are transient because the airplanes are moving with respect to the radio telescope. This is especially true for frequencies in the 275-3 000 GHz range because very high slant-path atmospheric absorption limits the possibility of interference only to when an airplane is almost directly overhead and with an antenna that is pointed directly toward the ground. Because an airplane will be moving very quickly with respect to the ground, and the THz-range beam is very narrow, interference will be very short duration.

The assumed interference scenario is:

- Radio astronomy observatory located at an elevation of 3 000 m.
- Airplane flying at an altitude of 10 000 m.
- Transmitter antenna with 5 cm diameter with 75% illumination efficiency pointing directly downward.
- Airplane flies directly over the centre of the radio telescope, at a speed of 600 km/h.
- Frequency of 275 GHz.

This scenario represents a near-worst-case situation because: the transmit antenna is of relatively small size (wide beam); the frequency is at the lower limit of the band under consideration, creating the widest antenna beam; and the airplane flies directly over the telescope at a relatively low speed, maximizing the duration of interference.

The free space loss over 7 000 m at 275 GHz is 175 dB (equation (2)). The maximum achievable e.i.r.p. with the specified antenna is 50 dBm (equation (8) and Table 3). The resulting signal level at the radio telescope is –125 dBm. The transmit antenna beam width is $1.7^\circ = 0.029$ rad (equation (3)). The airplane is 7 000 m above the radio telescope, so the projected beam on the ground is $0.029 * 7\ 000\text{ m} = 204\text{ m}$ wide. The interfering beam then sweeps over the telescope for a duration of $(0.204\text{ km}) / (600\text{ km/h}) = 0.0003\text{ h}$, or 1.22 s. The Recommendation ITU-R RA.769 interference threshold is –157 dBm averaged over a 2000 s integration period (see Table 4). The average interference level from the plane is $-125\text{ dBm} + 10\log(1.22\text{ s}/2000\text{ s}) = -125\text{ dBm} - 32\text{ dB} = -157\text{ dBm}$, which exactly equals the Recommendation ITU-R RA.769 threshold level. However, no allowances for atmospheric attenuation have been included, and it is assumed that the airplane flies *directly* over the centre of the telescope. Taking these factors into account, the received power and the duration of the power will, in reality, be significantly less. A change of course by the airplane of more than $\sim 1/5$ km would result in essentially no interference being observed.

While interference from a THz transmitter operated aboard a high-altitude helicopter hovering stationary directly over a radio telescope could, conceivably, exceed the extrapolated Recommendation ITU-R RA.769 detrimental interference threshold level, the possibility of this scenario occurring, at least without prior coordination, is remote at best.

The conclusion is that airborne interference to a radio astronomy observatory is unlikely.

5.3 Satellite transmitter into radio telescope

For computing the possibility of interference from non-GSO satellites into a radio telescope, the same methodology as § 5.2 is used. The following assumptions are employed:

- circular orbit;
- transmitter antenna of 5 cm diameter and 75% illumination efficiency pointed directly downward, with maximum available transmit power (7 dBm), resulting in 50 dBm e.i.r.p.;
- satellite passes directly over the centre of the radio telescope;
- frequency of 275 GHz.

The circular orbit speed V_c of a satellite with an orbital radius of R_S (km) is:

$$V_c(\text{km/s}) = 631/\sqrt{R_S} \quad (11)$$

Assuming the near-worst-case scenario of a telescope located on the equator and a satellite orbiting eastward in an orbit with 0 deg inclination, the relative speed of the telescope and the satellite is:

$$V_R = V_E - V_c(R_E / R_S) \quad (12)$$

where:

R_E : the radius of the Earth

V_E : the equatorial rotation speed of the Earth (about 0.5 km/s).

The size of the satellite transmitter's beam projected on the ground is $0.029(R_S - R_E)$, and the amount of time it takes for the beam to sweep over the radio telescope is $0.029(R_S - R_E)/V_R$.

TABLE 5

Average power received by a radio telescope during a single overhead pass of a transmitting satellite at 275 GHz assuming a -157 dBm transmit e.i.r.p.

Altitude (R_S-R_E) (km)	V_R (km/s)	Projected beam size (km)	Time to pass over radio telescope	Fraction of 2000 s (dB)	Free space loss (dB)	Average power (dBm)	Margin
500	6.6	14.5	2.2 s	-30	195	-175	18
1 000	5.9	29	4.9 s	-26	201	-177	20
2 000	4.8	58	12.1 s	-22	207	-179	22
4 000	3.3	116	34.7 s	-17	213	-181	24
8 000	1.9	232	2 min	-12	220	-181	24
10 000	1.5	290	3 min 19 s	-10	221	-180	23
15 000	0.8	435	8 min 49 s	-6	224	-180	23
20 000	0.5	580	20 min 22 s	-2	227	-179	22
30 000	0.1	870	2 h 6 min	0	231	-180	23
35 786	0	1 038	N/A (geosynchronous)	0	232	-182	25

The competing factors of projected beam size, relative speed, and free space loss combine to produce a relatively constant margin (last column of Table 5) over the extrapolated Recommendation ITU-R RA.769 interference threshold levels. Assuming no additional losses due to atmospheric attenuation, and assuming that the satellite passed directly over the telescope, the average signal level during a 2 000 s integration is 18 or more dB below the interference threshold.

6 Conclusions

Sharing between radio astronomy and active services in the range 275-3 000 GHz is not problematic.

On the ground, assuming nearly worst-case conditions, a terrestrial link in the 275-1 000 GHz range would have to be at a high altitude running maximum available power through a large dish pointing directly at a telescope to produce a signal at the telescope that may have a detrimental impact on radio astronomy observing. Above 1 000 GHz, the interferer would have to be within 1 km distance running maximum power and pointed directly at the telescope to exceed interference thresholds; most likely, such a closely-located link would be under the control of the radio observatory itself, or would be subject to informal local coordination with the affected observatory.

If considering interference from airborne transmitters, the small beamwidth of the interferer and the high level of slant-path atmospheric attenuation would require that the plane fly directly over the radio telescope to create interference. A single pass from a transmitter at 275 GHz and flying 7 000 m or more above the observatory would not exceed the Recommendation ITU-R RA.769 interference level. Course deviations by the airplane of more than $\sim 1/5$ km could result in essentially no interference being observed.

For interference by satellites, the competing factors of projected beam size, relative speed, and free space loss combine to produce a relatively constant margin over the extrapolated Recommendation ITU-R RA.769 interference threshold levels. Assuming no additional losses due to atmospheric attenuation, and assuming that the satellite passed directly over the telescope, the average signal level during a 2 000 s integration is 18 or more dB below the interference threshold. Even signal levels from geostationary satellites are not expected to be sufficient to produce interference.

The conclusions reached in this Report do not apply to frequencies below 275 GHz where significantly greater transmit powers are possible with currently available technology. Atmospheric attenuation is also relatively low at most frequencies below 275 GHz compared to absorption at THz frequencies. Some conclusions may change in the future if substantially more transmit power generation becomes achievable at THz frequencies.
