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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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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, and it includes analysis of interference to radio telescopes from co-frequency terrestrial and airborne transmitters. The results of this study are applicable to studies related to the advancement of technology at frequencies above 275 GHz¹.

2 Atmospheric absorption

In the range 275-3 000 GHz, propagation through the Earth's atmosphere is strongly affected by the absorption characteristics of 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. However, the variation of oxygen and water vapour as a function of height yields "windows" with absorption as low as 3 dB/km at higher altitudes. For this reason, sharing studies should take the height above sea level of any proposed operation into account.

Attenuation decreases with height because of lower concentrations of oxygen and water vapour. Figures 1-4 show attenuation in dB/km at five different heights above sea level, 300 m, 1 000 m, 3 000 m, and 5 000 m. The calculation of these attenuation values utilises 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. The water vapour content thus decreases as an exponential function of increasing height. The atmospheric parameters are used in the *am* atmospheric transmission model to compute the absorption curves^{4, 5}.

Additionally, the *am* analysis model is used to evaluate atmospheric absorption over a 1 km horizontal distance at two radio astronomy sites (ALMA⁶ and LMT/GTM⁷), using site-specific,

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

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.

⁶ The ALMA observatory is located in the Atacama Desert in Northern Chile on the Chajnantor Plateau at a height above sea level of 5 km; see <http://www.almaobservatory.org/>.

⁷ The Large Millimetre Telescope Alfonso Serrano / Gran Telescopio Milimétrico Alfonso Serrano (LMT/GTM) is the world's largest single dish millimetre telescope located on the Sierra Negra mountain in Mexico at a height above sea level of 4 580 m; see <http://www.lmtgm.org/>.

50th-percentile, annually-averaged atmospheric characteristics derived from MERRA-2 data⁸, as well as 10th-percentile “ideal” observing conditions. Horizontal attenuation for these sites over 1 km is shown in Figs 1 to 4, with the exception of the LMT/GTM observatory, which does not currently operate above 1 000 GHz. Furthermore, horizontal attenuation is shown as a worst-case scenario. Because the observatories are on mountaintops, most transmitters would likely be at a lower altitude. Additionally, Earth-curvature should be taken into account. This Report highlights the importance of sharing studies at specific geographic locations on a case-by-case basis.

Based on the assumed atmospheric characteristics, the following inputs (Table 1) were used in the *am* model:

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

Conditions	Height above sea level (m)	Temperature (K)	Pressure (hPa)	Column density of dry air (cm ⁻²)	Column density of water vapour (cm ⁻²)
Standard atmosphere	0	288.15	1013.25	2.51×10^{24}	3.34×10^{22}
Standard atmosphere	300	286.20	977.73	2.45×10^{24}	2.87×10^{22}
Standard atmosphere	1 000	281.65	898.75	2.29×10^{24}	2.03×10^{22}
Standard atmosphere	3 000	268.65	701.09	1.88×10^{24}	7.46×10^{21}
Standard atmosphere	5 000	255.68	540.83	1.53×10^{24}	2.74×10^{21}
LMT/GTM average	4 580	274.70	590.00	1.55×10^{24}	8.32×10^{21}
LMT/GTM 10 th percentile conditions ⁹	4 580	271.20	590.00	1.57×10^{24}	8.67×10^{20}
ALMA average	5 050	272.20	554.00	1.57×10^{24}	2.28×10^{21}
ALMA, 10 th percentile conditions ¹⁰	5 050	265.30	554.00	1.51×10^{24}	3.52×10^{20}

The tremendous variation in propagation as a function of atmospheric pressure, temperature, frequency, and water vapour content is clearly evident in Figs 1 to 4.

⁸ *Ibid.* 4, p 21. MERRA-2 is a global atmospheric dataset derived from satellite observations. The data was used by the author of the *am* model to produce a complex layer-by-layer model of the atmosphere specific to the ALMA site. This layer-by-layer model is employed in the present study.

⁹ LMT/GTM 10th percentile conditions typically occur in the northern hemisphere winter during nighttime.

¹⁰ ALMA 10th percentile conditions typically occur in the southern hemisphere winter during nighttime.

FIGURE 1

Atmospheric attenuation computed over horizontal paths of 1 km at five different heights above sea level, as well as annually-averaged and 10th percentile observing conditions at the ALMA and LMT/GTM radio astronomy observatory sites, assuming the atmospheric properties of Table 1

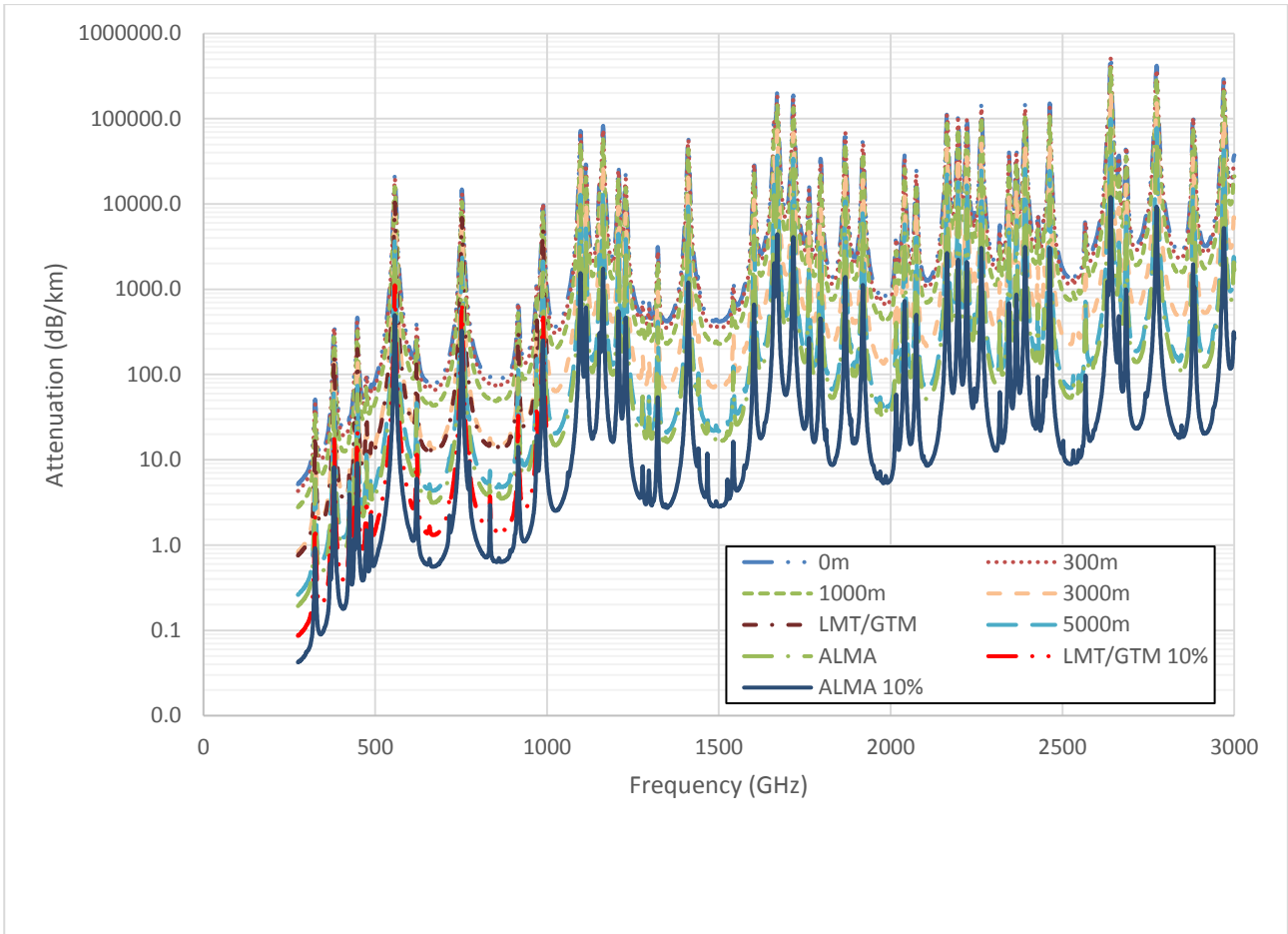


FIGURE 2

Atmospheric attenuation computed over horizontal paths of 1 km at five different heights above sea level, as well as annually-averaged and 10th percentile observing conditions at the ALMA and LMT/GTM radio astronomy observatory sites, assuming the atmospheric properties of Table 1 (frequencies from 275 to 500 GHz shown for clarity)

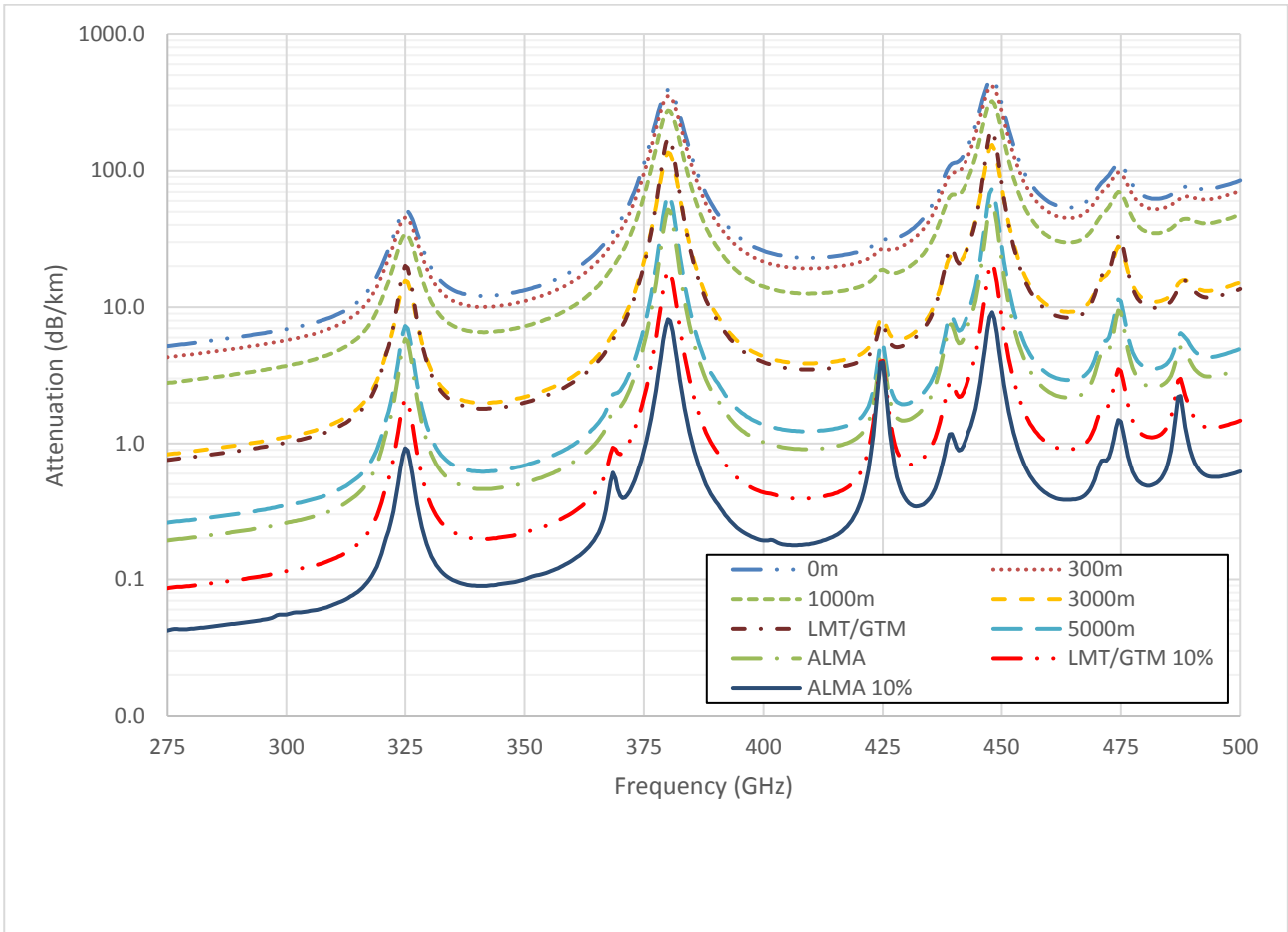


FIGURE 3

Atmospheric attenuation computed over horizontal paths of 1 km at five different heights above sea level, as well as annually-averaged and 10th percentile observing conditions at the ALMA and LMT/GTM radio astronomy observatories, assuming the atmospheric properties of Table 1 (frequencies from 500 to 1 000 GHz shown for clarity)

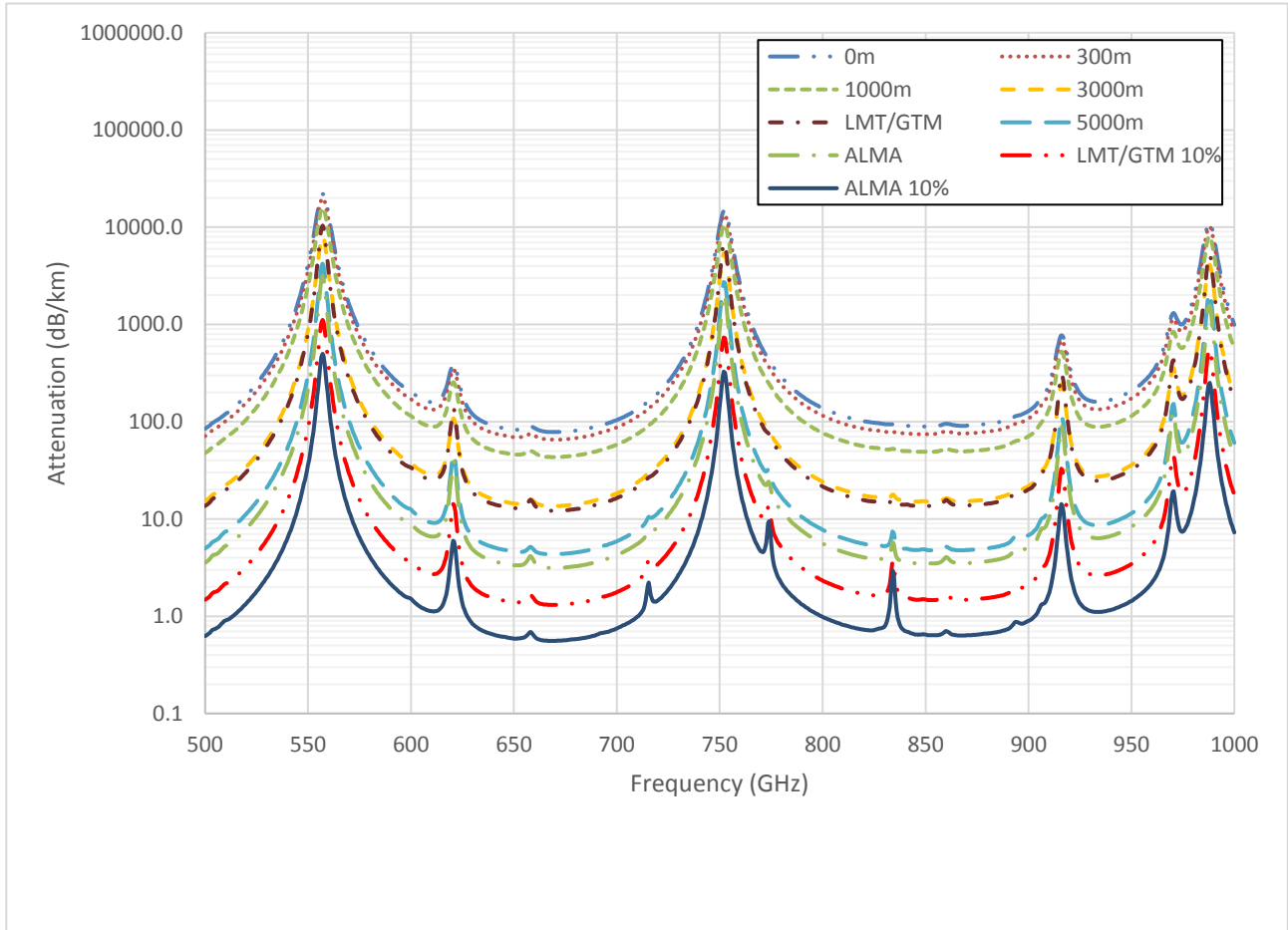
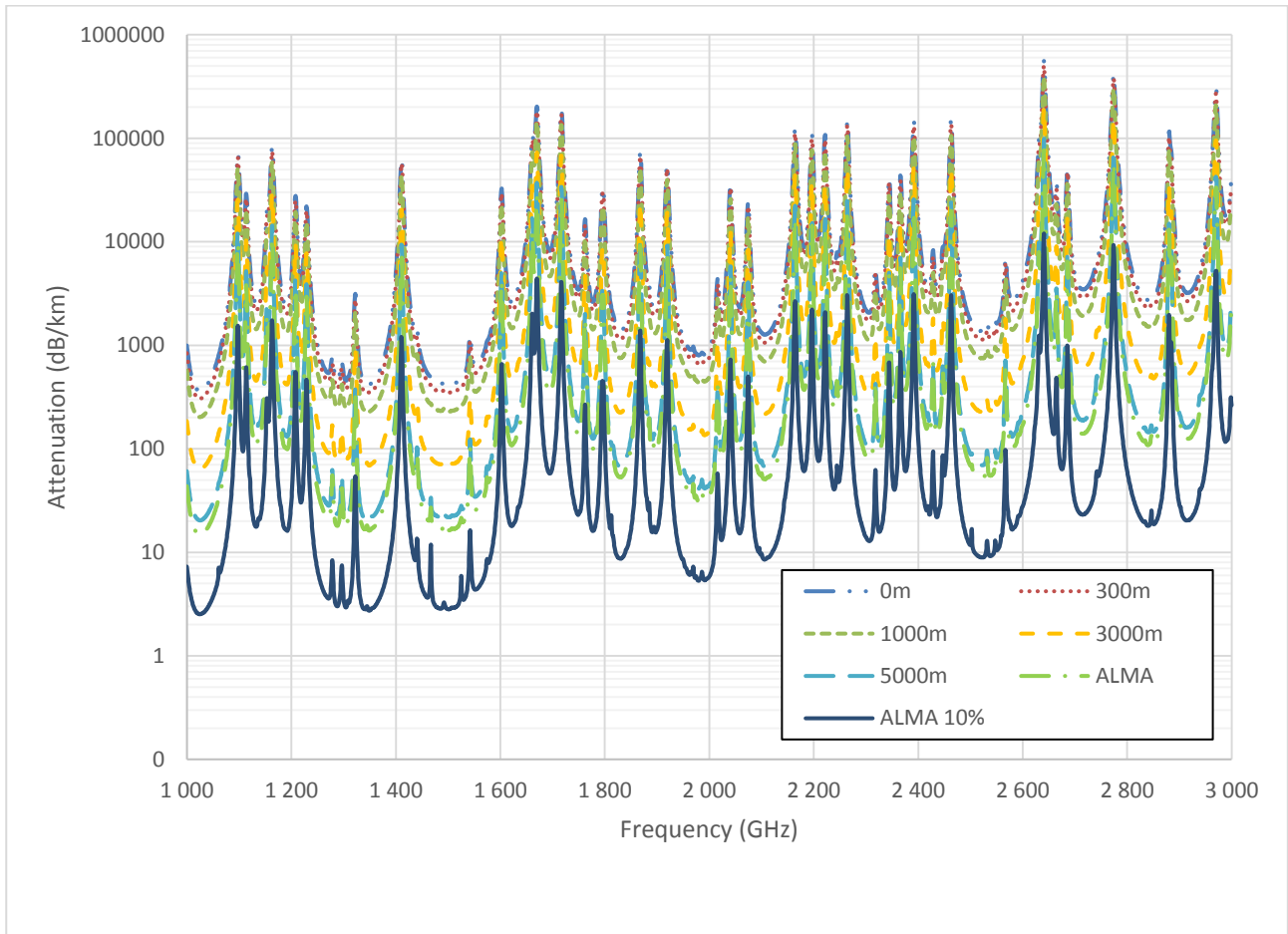


FIGURE 4

Atmospheric attenuation computed over horizontal paths of 1 km at five different heights above sea level, assuming the atmospheric properties of Table 1 (frequencies from 1 000 to 3 000 GHz shown for clarity)



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

$$P_R = P_T + G_T + G_R - PL - A \tag{1}$$

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.

For 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 and height). 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.

Though there is significant variability over the frequency range, at greater heights and particularly at sites with favourable atmospheric characteristics for radio astronomy observations, atmospheric absorption decreases markedly. At 5 000 m above sea level and a frequency of 275 GHz, the baseline absorption rate is approximately .25 dB/km. At a frequency of 1 000 GHz, the absorption baseline rate is approximately 20 dB/km, and at 3 000 GHz, the baseline absorption rate ranges from approximately 165 dB/km to 1 000 dB/km.

At the ALMA site, calculated horizontal-path atmospheric absorption in observing “windows” ranges from approximately 0.2 dB/km at 275 GHz, to 3.5 dB/km near 500 GHz, and to 6.5 dB/km near 950 GHz.

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. However, most RAS facilities operating in this frequency range are in fact located on high and dry mountaintops, so the atmospheric absorption approaches free space loss at these sites and sharing studies need to take this into consideration.

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.

An antenna of a specific size will have a smaller beamwidth with increasing frequency; alternatively, at a given frequency, a larger dish will have 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 will have a beam of only 0.28 degrees at a frequency of 275 GHz, assuming $\alpha = 0.75$. If 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).

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 because of strong absorption in this frequency range, rapid free-space fall-off, and low RF power generation (§ 4). 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 two-dimensional case, it has been assumed the antennas are identical. The three-dimensional probability computes to the following values as a function of frequency and antenna size. While the probability of a random source falling within the main beam of an antenna is very small, at sufficiently high power it could damage sensitive and expensive electronics in the radio astronomy receivers which operate at cryogenic temperatures of a few K. Radio astronomy receivers may be particularly vulnerable to damage from pulses of short duration. Sharing studies should examine methods to ensure that the very low probability of main-beam coupling does not occur if it has the potential to be damaging.

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}

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 pointing directly at one another is

exceedingly small. The number and pointing angles of receiving dishes at a given observatory site, however, may need to be taken into consideration, especially as certain bright astronomical sources are observed with greater frequency for calibration.

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 must be taken into account. Consider as an example a 50 m radio telescope dish like the LMT/GTM located 1 km from a terrestrial transmit antenna. The radio dish has an angular size θ_{rel} of approximately $(50 \text{ m}/1\,000 \text{ m}) = 0.05 \text{ radian} = 2.9 \text{ degrees}$ as seen from the antenna. This is much larger than the angular extent of the transmit beam, so it is the controlling factor when considering the computed likelihood of the beam being pointed towards 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. This example highlights the importance of coordination zones around radio astronomy facilities in this frequency range.

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 utilised a primary reflector of 3.5 m in diameter equipped with various infrared and radio detectors, including one instrument (HIFI) that covered 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, was 0.007 degrees, 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 with lower-frequency devices; however, high electron mobility transistor (HEMT) and other relevant technologies continue to see active effort and improvement.^{11, 12} For the purposes of this Report, evaluation of potential received signals at radio astronomy sites was completed using transmitter powers (P_T) of -20 dBW, -10 dBW, and 0 dBW. It should be noted that as new millimetre- and sub-millimetre-wave generation and amplification technology develops, the use of higher transmission powers will, of necessity, require further evaluation.

5 Sharing between active services and radio astronomy

To examine possible interference scenarios for radio telescopes because of transmitters in the 275-3 000 GHz range, it is necessary to define a signal level that could be considered sufficiently high to cause harmful 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 extrapolation of the values in Table 1 of Recommendation ITU-R RA.769 to the range 275-3 000 GHz is made. In Recommendation ITU-R RA.769, discrete values of the harmful interference levels for continuum observations are provided for all of the allocated radio astronomy

¹¹ X.B. Mei *et al.*, "Sub-50NM InGaAs/InAlAs/InP HEMT for sub-millimeter wave power amplifier applications," 2010 22nd International Conference on Indium Phosphide and Related Materials (IPRM), Kagawa, 2010, pp. 1-3.

¹² V. Radisic *et al.*, "A 10-mW Submillimeter-Wave Solid-State Power-Amplifier Module," in IEEE Transactions on Microwave Theory and Techniques, vol. 58, no. 7, pp. 1903-1909, July 2010.

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:

$$S_H = -277.26 + 25.1 \log(f_{\text{GHz}}) \text{ dB} \left(\frac{\text{W}}{\text{m}^2\text{Hz}} \right) \quad (8)$$

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). Recommendation ITU-R RA.769 also includes protection criteria values for spectral line observations. These values, designed to protect observations of narrow bandwidth signals, are substantially more stringent than the continuum values used in the derivation of equation (8).

In Recommendation ITU-R RA.769, the assumed bandwidth over which the interference is received for continuum observations is 8 GHz (a typical bandwidth for state-of-the-art millimetre wave radio telescopes), so the corresponding power density in $\text{dB}(\text{W}/\text{m}^2)$ can be obtained by adding $10 \times \log(8 \times 10^9)$ to S_H . 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 dBW. Assuming the fit of equation (8) is used to extrapolate values of S_H to the 275-3 000 GHz range, the following values for harmful levels of interference to the radio astronomy service are obtained:

TABLE 4

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

Frequency (GHz)	$P_H = S_H \times 8 \text{ GHz} \times \frac{\lambda^2}{4\pi}$ (dBW)	$S_H \times 8 \text{ GHz}$ (dB(W/m ²))	S_H (dB(W/m ² Hz))
275	-187	-117	-216
1 000	-184	-103	-202
2 000	-183	-95	-194
3 000	-182	-91	-190

For comparison purposes, similar calculations based upon current, state-of-the-art receivers deployed at the ALMA Observatory result in threshold levels of interference for radio astronomy continuum (8 GHz bandwidth) and spectral line observations (1 MHz bandwidth) as listed in Tables 5 and 6.

TABLE 5

**Threshold levels of interference to radio astronomy continuum observations for ALMA
(values as of 2018)**

Centre frequency ⁽¹⁾ f_c (MHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity (noise fluctuations)		Threshold interference levels		
			Temperature ΔT (mK)	Power spectral density, ΔP (dB(W/Hz))	Input power ΔP_H (dBW)	pfd $S_H \Delta f$ (dB(W/m ²))	Spectral pfd S_H (dB(W/(m ² · Hz)))
275 000	20	75	0.024	-274.8	-185.8	-115.9	-214.9
345 000	30	100	0.032	-273.5	-184.5	-112.2	-211.3
405 000	60	215	0.069	-270.2	-181.2	-107.6	-206.6
432 000	73	275	0.087	-269.2	-180.2	-106.0	-205.0
500 000	110	385	0.124	-267.7	-178.6	-103.2	-202.2
605 000	165	1 600	0.441	-262.2	-173.1	-96.0	-195.1
675 000	100	690	0.198	-265.6	-176.6	-98.6	-197.6
710 000	150	1 240	0.347	-263.2	-174.2	-95.7	-194.7
790 000	170	2 660	0.708	-260.1	-171.1	-91.7	-190.7
870 000	110	1 270	0.345	-263.2	-174.2	-94.0	-193.0
940 000	160	2 260	0.605	-260.8	-171.8	-90.8	-189.9

TABLE 6

**Threshold levels of interference harmful to radio astronomy spectral-line observations for
ALMA
(values as of 2018)**

Frequency f (MHz)	Minimum antenna noise temperature T_A (K)	Receiver noise temperature T_R (K)	System sensitivity (noise fluctuations)		Threshold interference levels		
			Temperature ΔT (mK)	Power spectral density ΔP_S (dB(W/Hz))	Input power ΔP_H (dBW)	pfd $S_H \Delta f$ (dB(W/m ²))	Spectral pfd S_H (dB(W/(m ² · Hz)))
275 000	20	75	2.12	-225.3	-175.3	-105.4	-165.4
345 000	30	100	2.91	-224	-174	-101.8	-161.8
405 000	60	215	6.15	-220.7	-170.7	-97.1	-157.1
432 000	73	275	7.78	-219.7	-169.7	-95.5	-155.5
500 000	110	385	11.07	-218.2	-168.2	-92.7	-152.7
605 000	165	1 600	39.47	-212.6	-162.6	-85.6	-145.6
675 000	100	690	17.66	-216.1	-166.1	-88.1	-148.1
710 000	150	1 240	31.08	-213.7	-163.7	-85.2	-145.2
790 000	170	2 660	63.28	-210.6	-160.6	-81.2	-141.2
870 000	110	1 270	30.86	-213.7	-163.7	-83.5	-143.5
940 000	160	2 260	54.11	-211.3	-161.3	-80.4	-140.4

5.1 Terrestrial transmitter into terrestrial radio telescope

It is assumed that interference occurs if:

$$P_R = P_T + G_T + G_R - PL - A \geq P_H \tag{9}$$

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 harmful to radio astronomy observations (see Table 4).

An interesting 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 great height above sea level. As the most sensitive radio telescopes operating in this frequency range are situated at approximately 5 000 m above sea level, 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 5 000 m above sea level 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 (9)) would occur can be computed for -20 dB, -10 dB, and 0 dBW transmitter power. The results are plotted in Fig. 5 for 275-1 000 GHz, and in Fig. 6 for 1 000-3 000 GHz.

FIGURE 5

Horizontal distance at 5 000 m above sea level beyond which a transmitted signal at frequencies between 275 and 1 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Rec. ITU-R RA.769, based upon assumptions described in the text

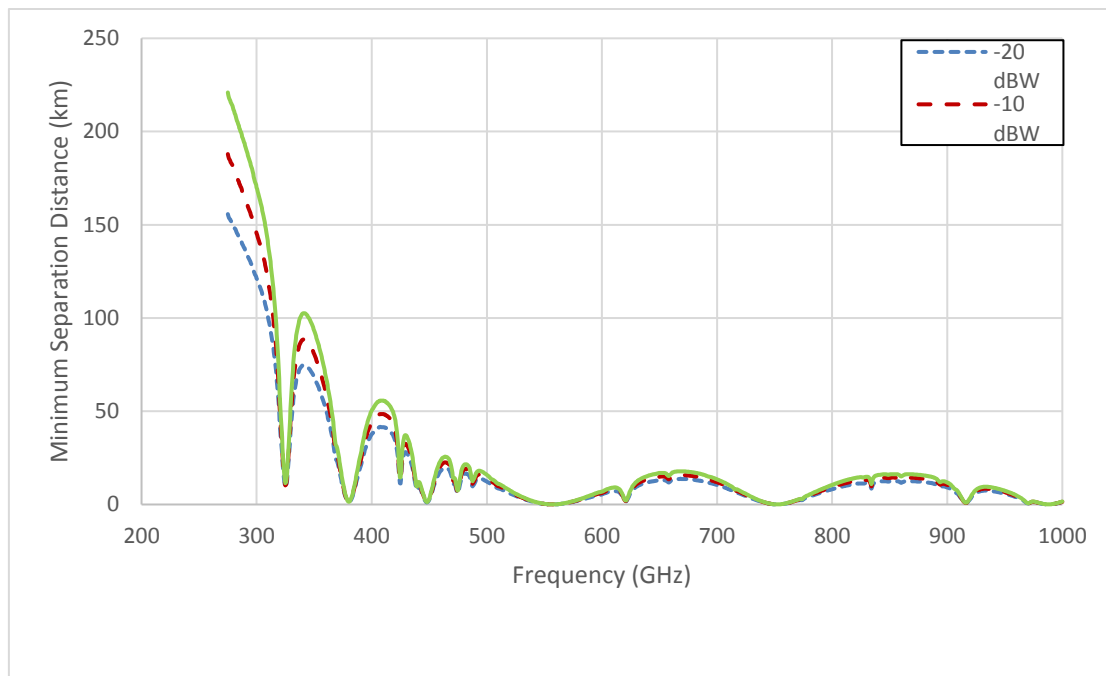
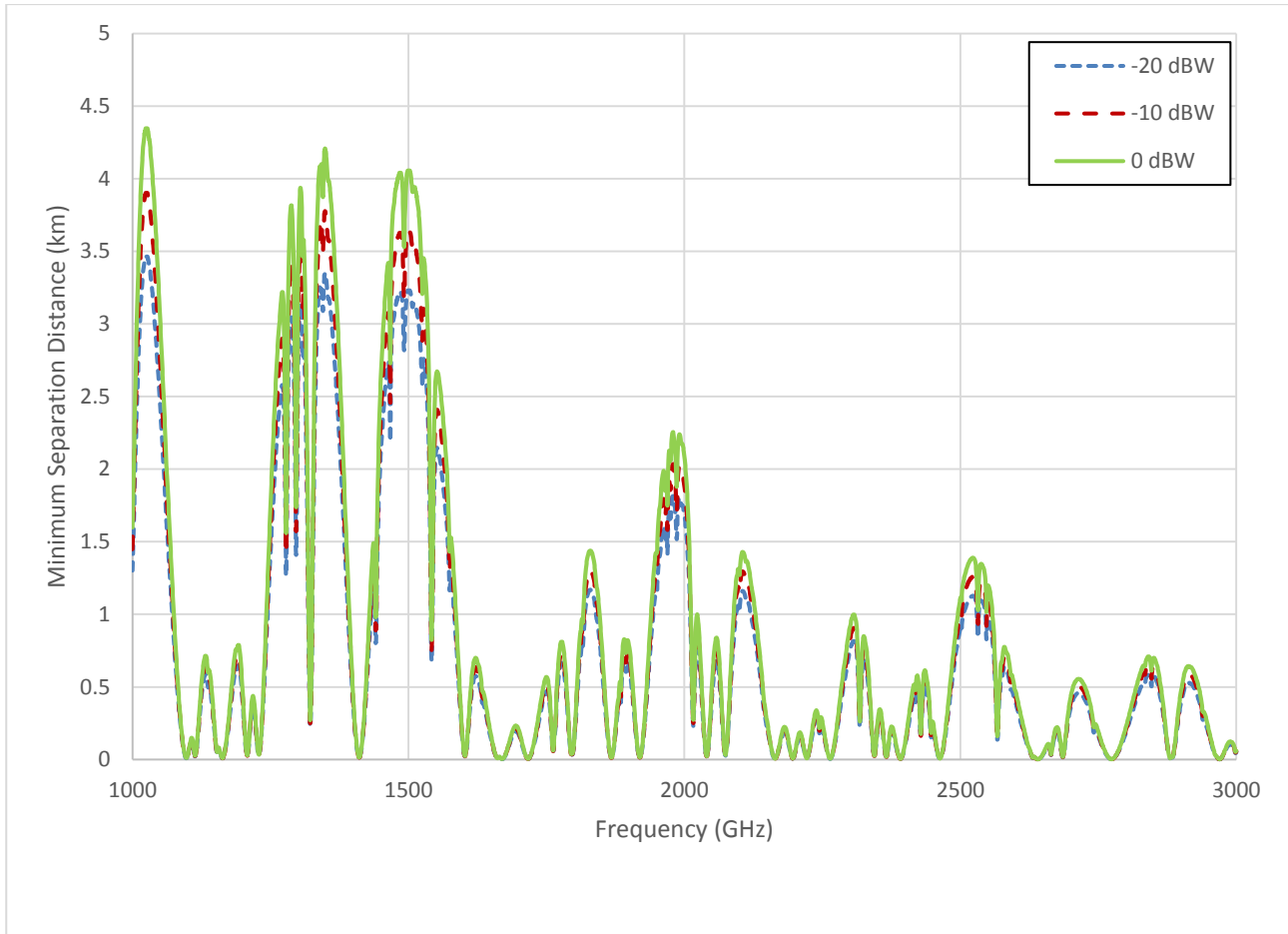


FIGURE 6

Horizontal distance at 5 000 m above sea level beyond which a horizontally-transmitted signal at frequencies between 1 000 and 3 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Rec. ITU-R RA.769, based upon assumptions described in the text



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 scenario of both transmitter and telescope located on a high and dry mountaintop. At lower altitudes, attenuation is much larger and the interference distance becomes even smaller, but radio telescopes operating in this frequency range would not likely be located in such areas.

Figure 7 depicts horizontal separation distances for avoidance of harmful interference to the ALMA radio astronomy site for 275 to 1 000 GHz, under the conditions noted above.

FIGURE 7

Horizontal distance beyond which a horizontally-transmitted signal at frequencies between 275 and 1 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Rec. ITU-R RA.769 for the ALMA radio telescope site under average annual conditions, based upon assumptions described in the text

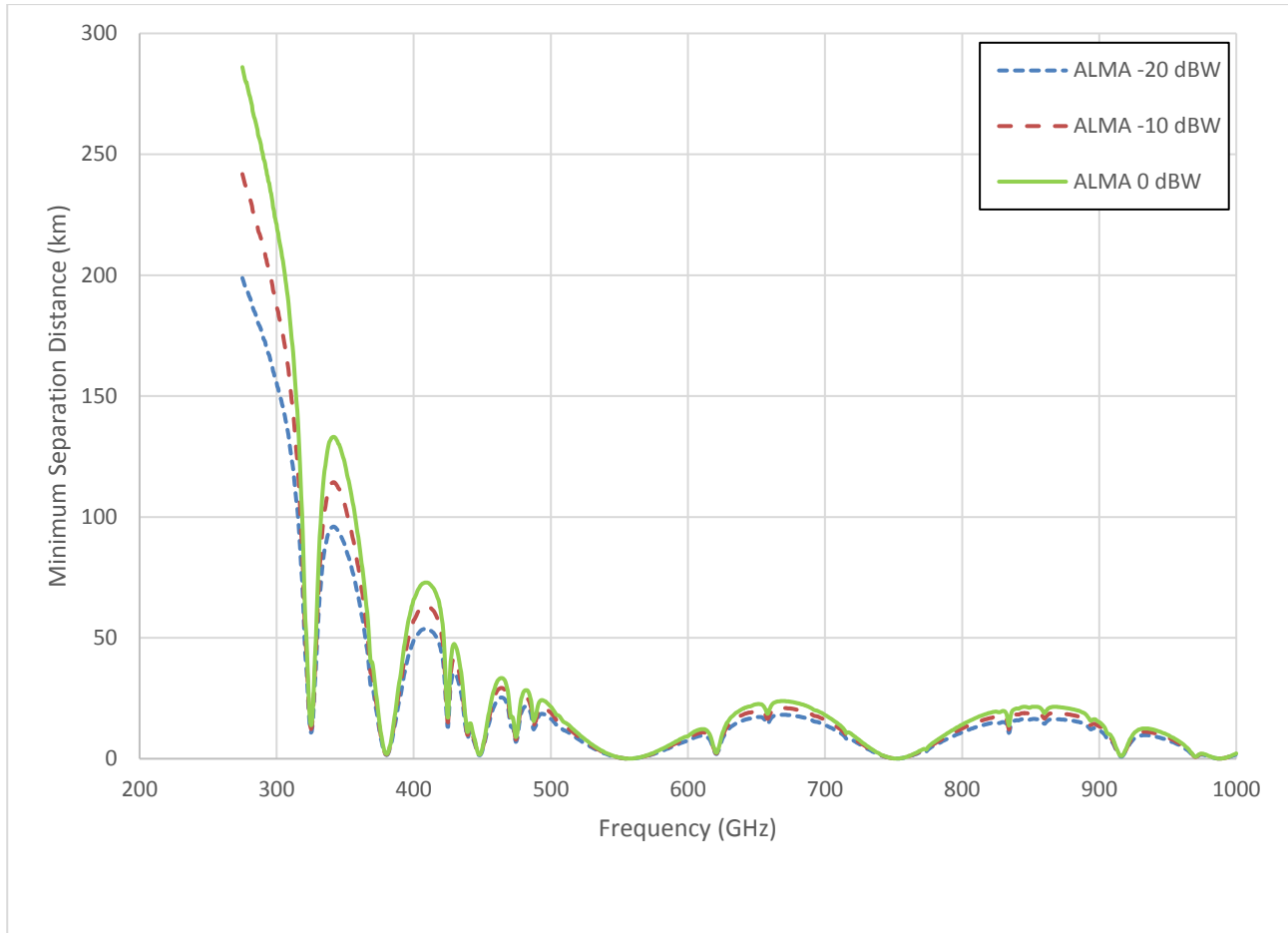


Figure 8 depicts a comparison of horizontal separation distances required to not exceed power levels given in Recommendation ITU-R RA.769 for the ALMA site under annually-averaged and “ideal” 10th percentile observing conditions, with a hypothetical site at sea level, using 0 dBW transmitter power. This Figure clearly shows the large difference in atmospheric attenuation characteristics between sea-level and observatory-level heights. The separation distance at sea level and 275 GHz would be approximately 20 km, but at the height of ALMA this distance increases by a factor of 10 to 50 depending on the weather conditions. As above, direct illumination of the receiver site by the transmitter is assumed.

FIGURE 8

Horizontal distances beyond which a horizontally-transmitted signal at frequencies between 275 and 1 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Rec. ITU-R RA.769 for transmitters at sea level and the ALMA radio telescope site, based upon assumptions described in the text

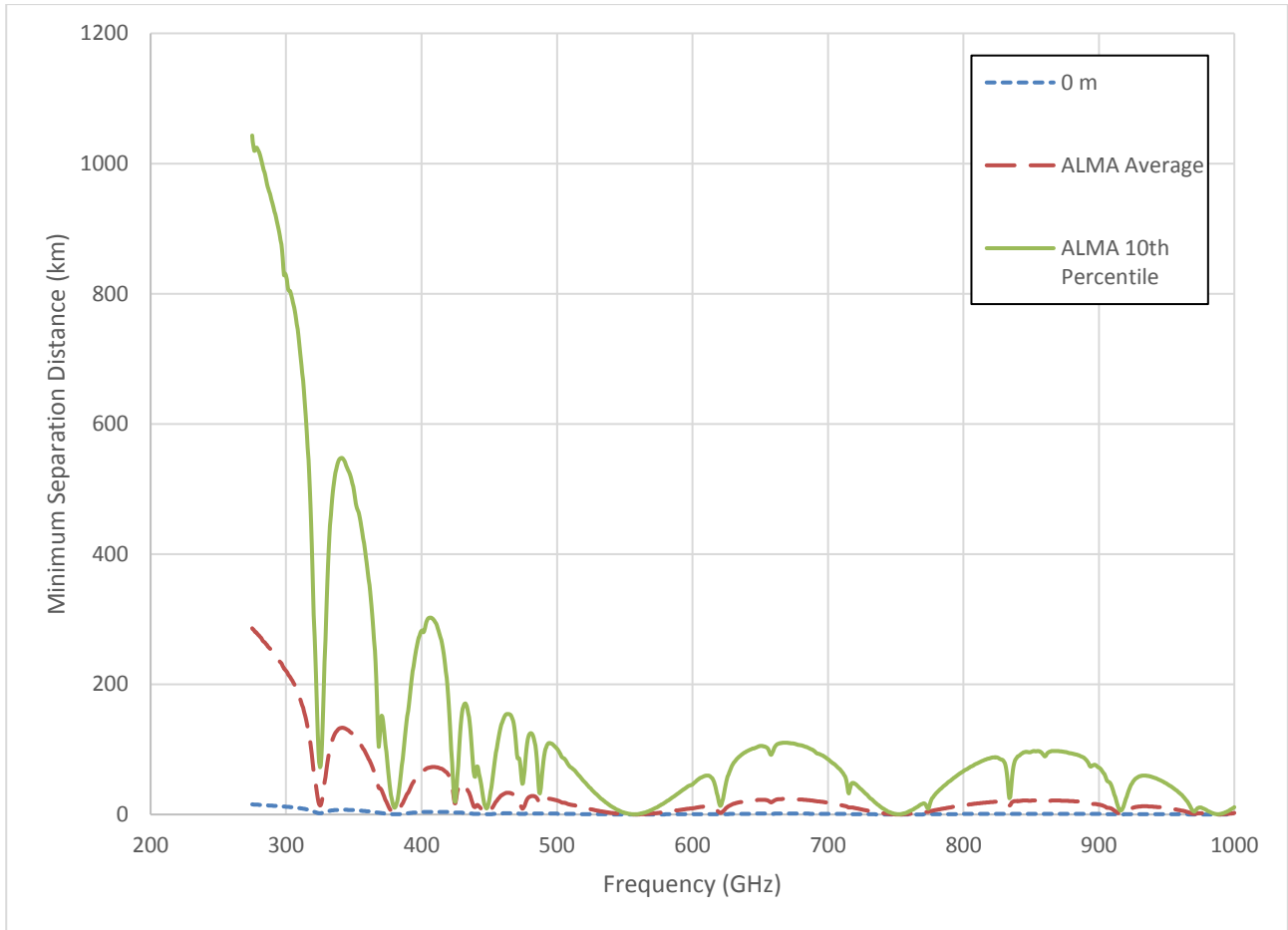
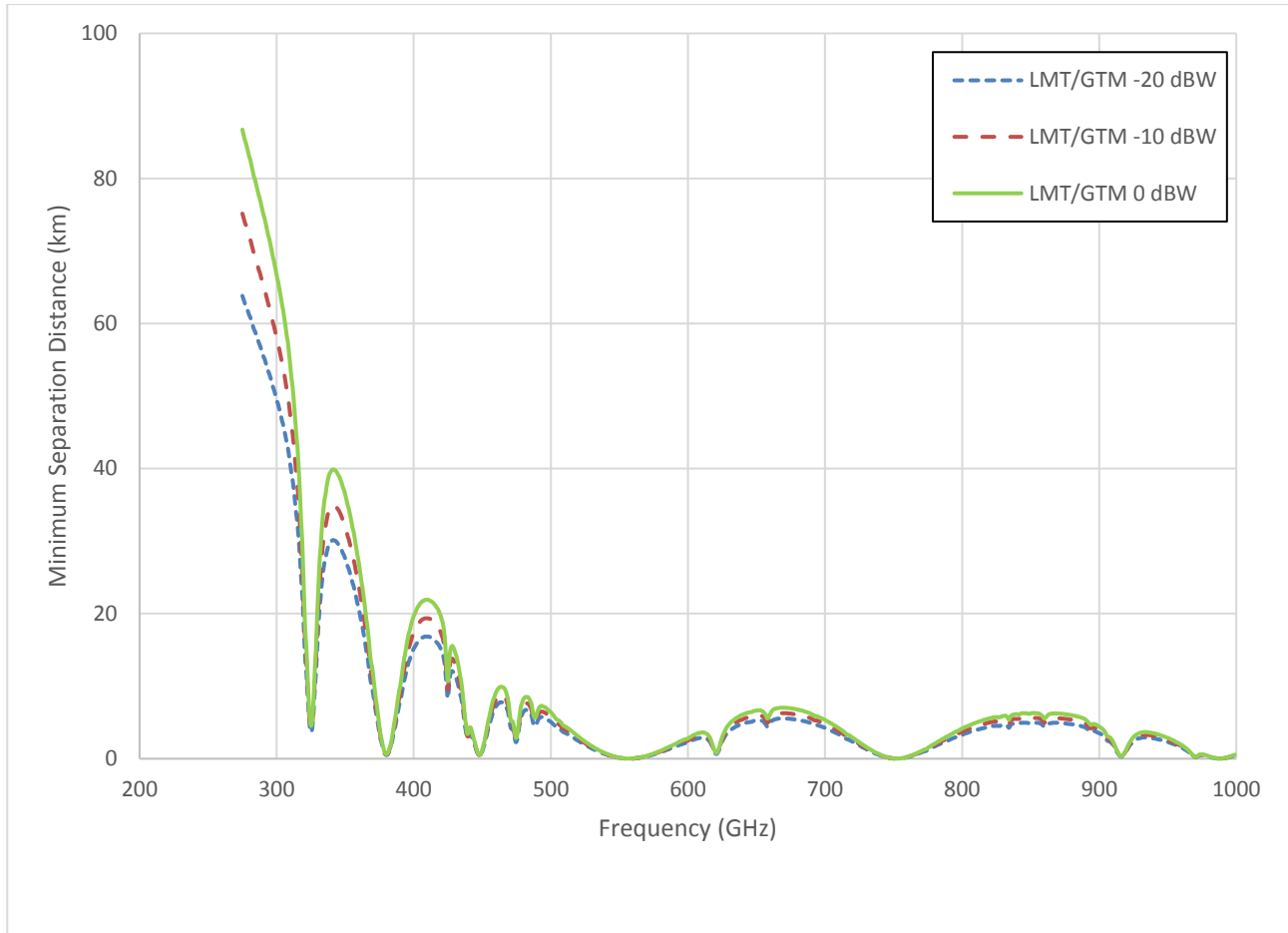


Figure 9 depicts horizontal separation distances for avoidance of harmful interference to the LMT/GTM radio astronomy site for 275 to 1 000 GHz, under the conditions noted above.

FIGURE 9

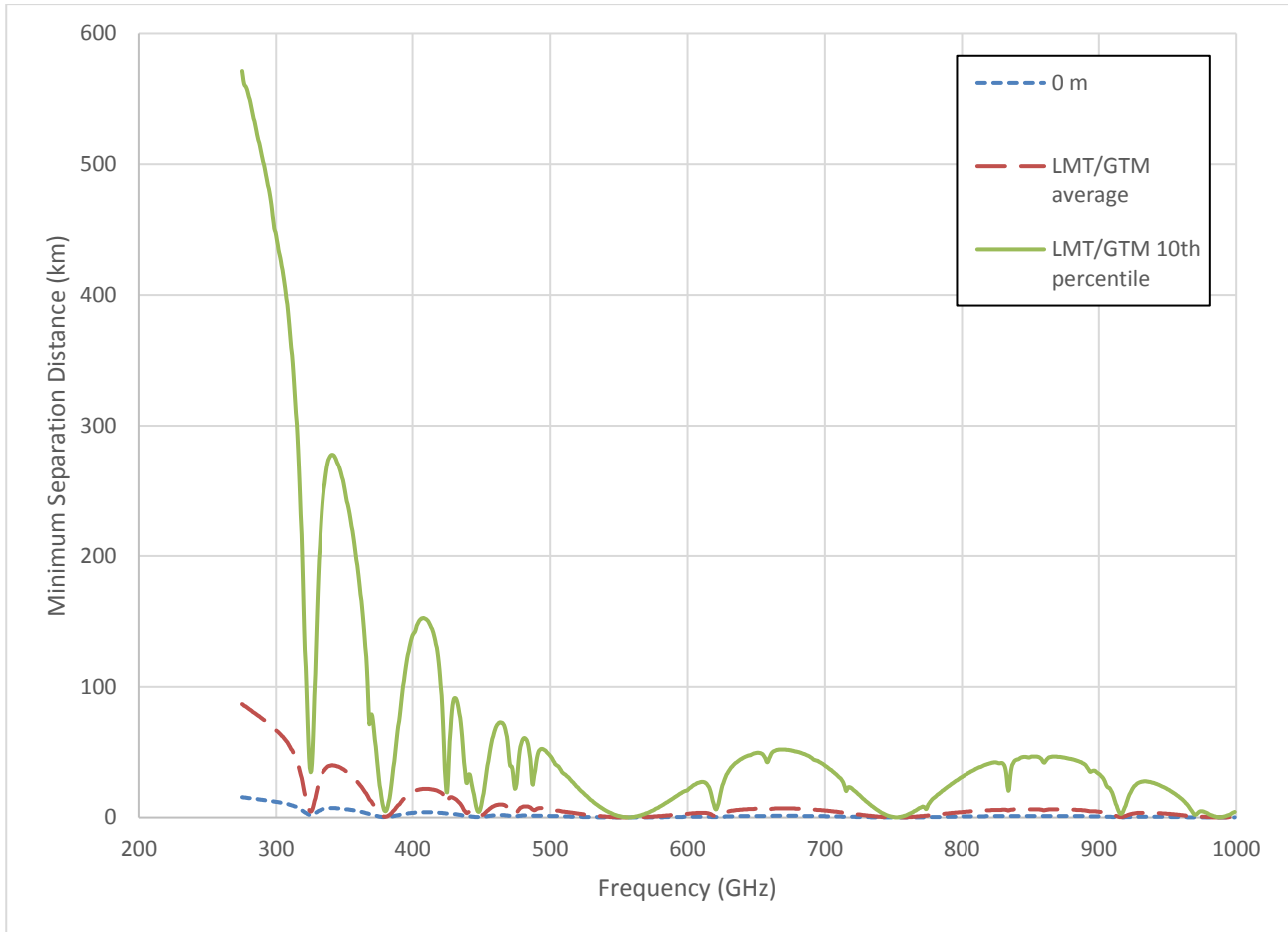
Horizontal distance beyond which a horizontally-transmitted signal at frequencies between 275 and 1 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Rec. ITU-R RA.769 for the LMT/GTM radio telescope site under average annual conditions, based upon assumptions described in the text



As with Fig. 8, Fig. 10 depicts a comparison of horizontal separation distances required to avoid levels above those given in Recommendation ITU-R RA.769 for the LMT/GTM site under annually-averaged and “ideal” 10th percentile observing conditions, with a hypothetical site at sea level, using 0 dBW transmitter power. This Figure clearly shows the large difference in atmospheric attenuation characteristics between sea-level and observatory-level heights. The separation distance at sea level and 275 GHz would be approximately 13 km, but at the height of LMT/GTM this distance increases by a factor of 10 to 50 depending on the weather conditions. As above, direct illumination of the receiver site by the transmitter is assumed.

FIGURE 10

Horizontal distances beyond which a horizontally-transmitted signal at frequencies between 275 and 1 000 GHz would not exceed radio astronomy interference thresholds extrapolated from Rec. ITU-R RA.769 for transmitters at sea level and the LMT/GTM radio telescope site, based upon assumptions described in the text



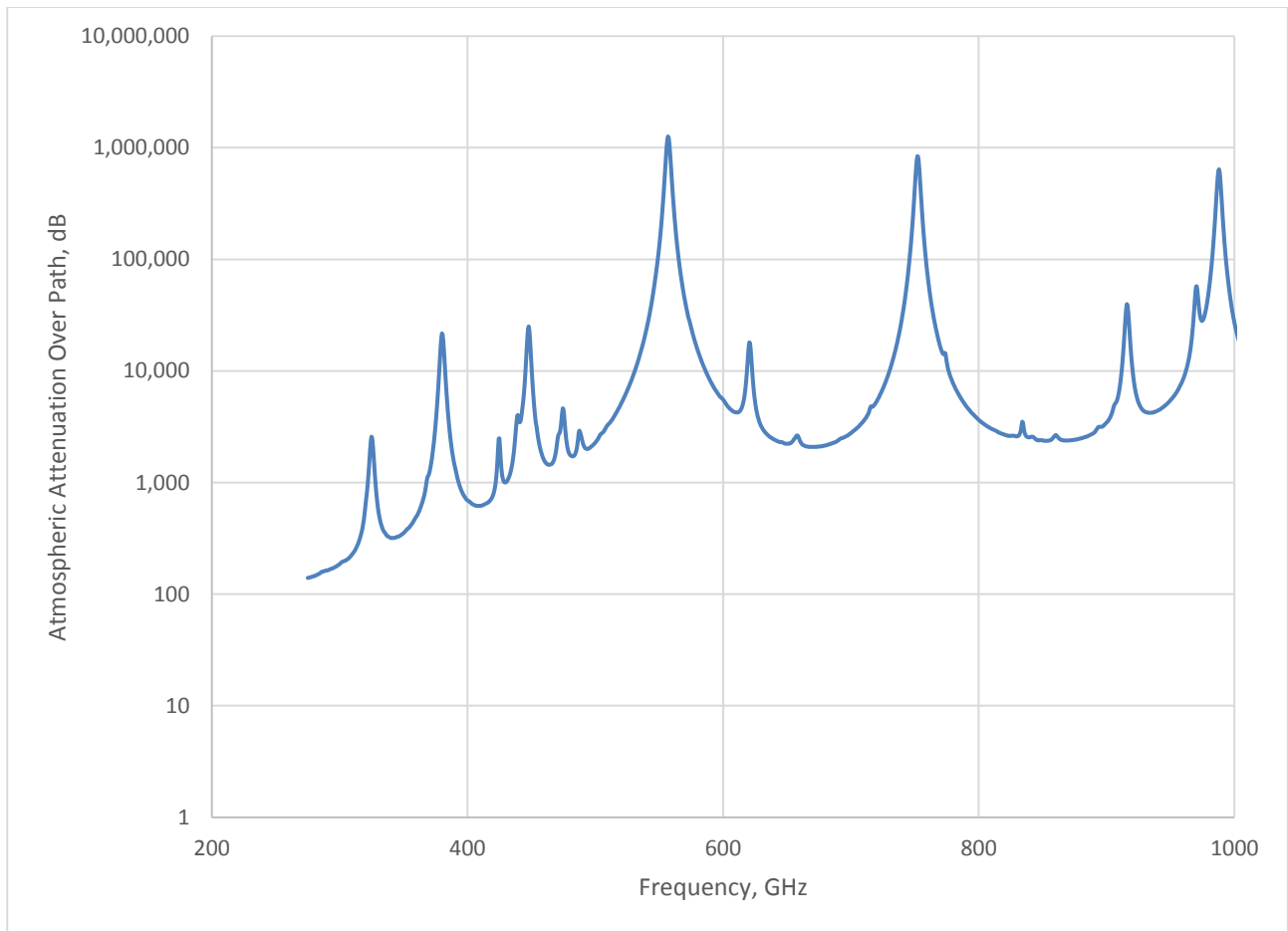
5.2 Case study: Puebla City to LMT/GTM

The Large Millimetre Telescope (LMT/GTM) is located in Mexico on the Sierra Negra mountain at 4 580 m above sea level. It is possible for the receivers of radio telescopes, located on mountaintop sites, to be illuminated by transmitters at lower altitudes. In this case study, we will examine the signal strength necessary to exceed receiver limits from a transmission site located at Puebla City, Mexico, a city of approximately 1.6 million inhabitants at 2 147 m above sea level and a distance of 94 km. The distance and respective heights result in a transmission angle through the atmosphere of 88.5° from the zenith.

Atmospheric attenuation for the path between Puebla City and LMT/GTM, calculated using the *am* software under annual average conditions, is depicted in Fig. 11.

FIGURE 11

Atmospheric attenuation versus frequency from Puebla City, Mexico to LMT/GTM site



As can be seen in the Figure, minimum atmospheric losses in this frequency range are encountered at 275 GHz, and are approximately 140 dB. Note that the attenuation in dB is plotted on a logarithmic scale because of the extreme range of attenuation.

The following additional conditions were assumed:

- No obstructions to line-of-sight transmissions
- Transmitter antenna consisting of a 30 cm dish with illumination factor (α) of 0.75

Using these conditions, a single transmitter would exceed the extrapolated radio astronomy limit at 275 GHz if utilizing greater than 3.08×10^7 Watts (30.8 MW) transmit power, as described in § 5.

Note that this value could be reduced substantially by the use of higher transmitter antenna gain (e.g. larger transmitter dish antenna) or lower atmospheric attenuation arising from reduced local relative humidity (in other words, measurement during relatively dry conditions). Additionally, aggregating signals from large numbers of devices may require additional analysis.

The results of this case study illustrate the stark contrast between protection of radio astronomy sites at great heights above sea level from transmitters located at similar heights and transmitters located at lower altitudes. When considering the latter, separation distances as a function of transmit power may be substantially reduced.

5.3 Airborne transmitter into radio telescope

Airborne sources of interference to radio telescopes are usually transient because they are moving with respect to the radio telescope. For aircraft moving very quickly with respect to the ground, the interference will be of very short duration because the THz-range beam is very narrow.

5.3.1 Scenarios

Analyses of potential interference into radio astronomy observatories at two sites are presented in this section. For both analyses, the scenario includes the following characteristics:

- Aircraft flying at a height of 10 000 m above sea level.
- Transmitter antenna with 5 cm diameter with 75% illumination efficiency pointing directly downward.
- Aircraft flies directly over the centre of the radio telescope, at a speed of 600 km/h.
- Frequency of 275 GHz.

5.3.1.1 ALMA

This section provides an analysis of potential aeronautical interference at the ALMA radio astronomy site. The ALMA radio astronomy observatory is located at a height of 5 050 m above sea level.

The free space and atmospheric loss between the aircraft and the ALMA site, i.e. over a height difference of 4 950 m at 275 GHz is 155 dB (equation (2)). The resulting signal level at the radio telescope, with a transmitter operating at 0 dBW, is -112 dBW. The transmit antenna beam width is $1.7^\circ = 0.029$ rad (equation (3)), resulting in a projected beam on the ground of width $0.030 * 4\,950 \text{ m} = 144$ m wide. The interfering beam then sweeps over the telescope for a duration of $(0.144 \text{ km}) / (600 \text{ km/h}) = 0.00024$ h, or 0.86 s. The Recommendation ITU-R RA.769 interference threshold is -187 dBW averaged over a 2000 s integration period (see Table 4). The average interference level from the aircraft is -113 dBW + $10 \log(0.86 \text{ s}/2000 \text{ s}) = -113$ dBW -34 dB = -147 dBW; i.e. 40 dB greater than the Recommendation ITU-R RA.769 threshold level. Reducing transmitter power to -20 dBW would reduce this received interference level to -166 dBW. Typical atmospheric attenuation for the ALMA site at 275 GHz, as calculated by the *am* model using annually-averaged MERRA-2 data, would be less than 0.5 dB for the 5 km vertical distance between transmitter and receiver.

5.3.1.2 LMT/GTM

This section provides an analysis of potential aeronautical interference at the LMT/GTM radio astronomy site, located at 4 580 m above sea level. The analysis methodology is similar to that conducted for the ALMA site, above.

Using the methodology described in § 5.3.1.1, the average interference level from the aircraft is -114 dBW + $10 \log(0.94 \text{ s}/2\,000 \text{ s}) = -114$ dBW -33 dB = -147 dBW. This is 40 dB greater than the Recommendation ITU-R RA.769 threshold level. Reducing transmitter power to -20 dBW would reduce this received interference level to -167 dBW. Typical atmospheric attenuation for the LMT/GTM site at 275 GHz, as calculated by the *am* model using annually-averaged MERRA-2 data, would be less than 1.5 dB for the 5.4 km vertical distance between transmitter and receiver.

5.3.2 Aeronautical analysis conclusions

Off-axis (slant path) transmissions, assuming the main beam illuminated the radio astronomy receiver, would incur greater free space and atmospheric losses; however, because of greater slant path distance between transmitter and receiver, such illumination would also involve longer main-beam coverage of the radio astronomy site as the aircraft passed by. Under the given conditions, direct illumination of the radio astronomy sites from almost any location within sight of the

receiver, horizon to horizon, at -20 dBW or 0 dBW transmitter power, would produce power levels at the sites that meet or exceed the threshold.

Greater atmospheric and free-space attenuation and narrower transmitter beamwidth at higher frequencies or lower observatory altitudes would reduce the interfering signal. Conversely, under ideal 10th percentile observing conditions, less atmospheric loss would result in higher signal levels at the radio astronomy site from the aeronautical emitter than calculated here.

While airborne interference to radio astronomy in this frequency range is unlikely, as sidelobe transmitter power levels would be significantly lower and aircraft flight speeds are likely to be greater than in this scenario, direct illumination of radio astronomy sites by airborne transmitters in this frequency range may be a source of harmful interference. Such illumination should be avoided.

5.4 Satellite transmitter into radio telescope

The methodology for evaluating potential interference from space stations into Radio Astronomy receivers may be found in Recommendations ITU-R S.1586 for the Fixed-Satellite Service, and ITU-R M.1583 for the Mobile Satellite Service, using the extrapolated power thresholds described in equation (8).

6 Conclusions

Sharing between radio astronomy and active services in the range 275-3 000 GHz is possible if atmospheric characteristics as a function of height above sea level, as well as transmitter antenna directivity, are taken into account.

This study reviewed several scenarios to evaluate the potential of harmful interference to radio astronomy sites. In this frequency range, such sites are located at high altitudes with significantly lower atmospheric attenuation than at sea level. Situations in which direct illumination of radio astronomy sites from the greatest distances could result in harmful interference generally involve transmitters at similar or greater heights. In these cases, greater geographic separation, or avoidance of direct illumination, could resolve interference issues. This Report highlights the importance of sharing studies at specific geographic locations on a case-by-case basis.

Direct illumination of radio astronomy sites by transmitters close to sea level, if geometrically possible, would likely involve far greater atmospheric absorption effects, and therefore decreased geographic separation requirements for a given transmitter power.

For airborne transmitters, direct illumination of high-altitude radio astronomy sites could result in levels of interference greater than those deemed acceptable, as derived from Recommendation ITU-R RA.769.

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, and atmospheric attenuation near sea level is generally lower.
