International Telecommunication Union

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Radiocommunication Sector of ITU

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(09/2009)

Astronomical use of frequency band 50-350 THz and coexistence with other applications

RA Series

Radio astronomy

International Telecommunication Union

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Note*: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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1 Introduction

The infrared and near-infrared Parts of the electromagnetic Spectrum are of large and growing interest for astronomical research. Thermal emission from dust at temperatures of a few Kelvins to hundreds of Kelvins, which is the case for most dust clouds and larger rocky bodies, is strong in these bands, which makes them ideal for studies of star and planet formation and interstellar dust clouds. Molecules important in the chemical processes taking place in these clouds produce many spectral lines in the infrared and near-infrared wavelength range.

Consequently this Part of the Spectrum has become of high astronomical interest and has led to the implementation of large ground-based facilities for observing in those frequency bands to which the troposphere is adequately transparent, and airborne and spaceborne facilities for observations at other frequencies.

This Report is intended to provide background information relevant to the task of making bands in this part of the electromagnetic spectrum accessible to future active services while ensuring that astronomical observations are adequately protected.

2 Atmospheric transmissivity

Although only Part of the Spectral Range of interest is accessible from ground-based observatories, the larger size and much greater flexibility for accommodating new projects and equipment changes makes them still a very attractive option, even in bands where there is significant atmospheric absorption. Even then, ground-based facilities are highly expensive, so most major observatories are constructed and operated by national or international consortia, at the best available sites. To maximize the amount of usefully accessible spectrum, the ground-based facilities are located at high-altitude locations, such as Mauna Kea in Hawaii (altitude about 4 200 m). Figure 1 shows a plot of atmospheric transmissivity at the site of the Gemini North Telescope on Mauna Kea. The transmissivity (α) of the atmosphere is the ratio of the power received at the telescope to that incident upon the top of the atmosphere. The corresponding attenuation is given by:

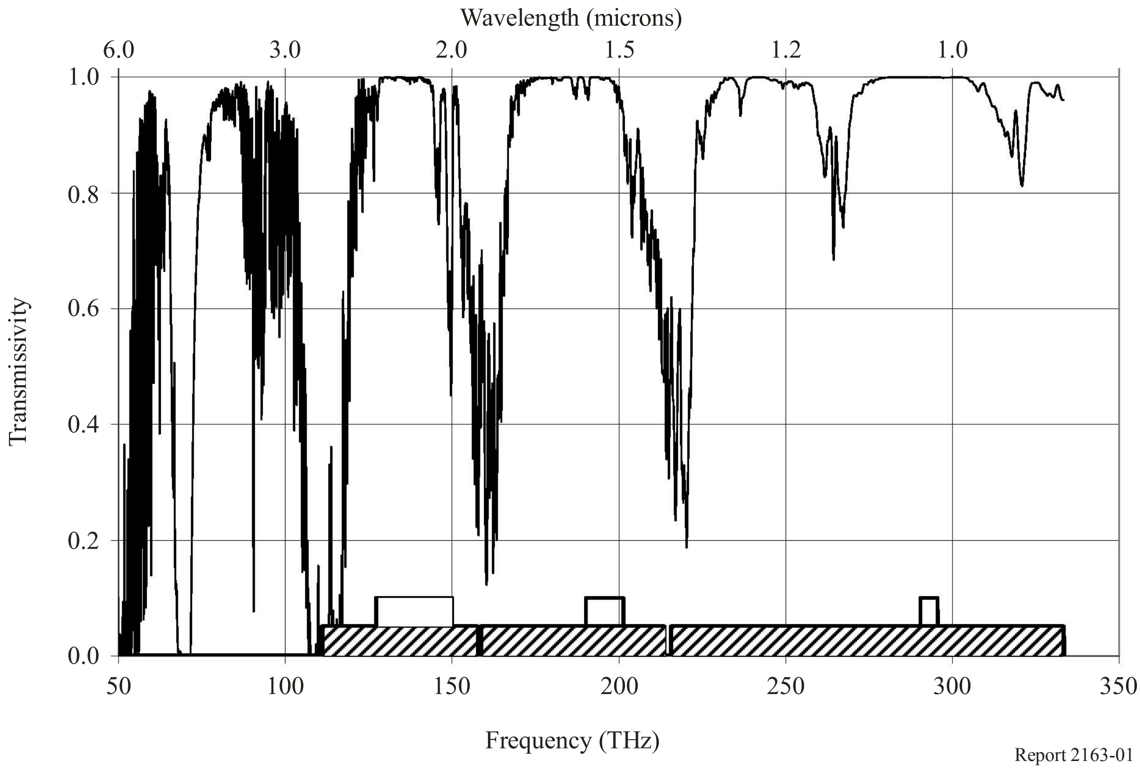
$$L = -10 \log (\alpha) \qquad \text{dB}$$

The graph shows the atmospheric transmissivity at the summit of Mauna Kea Hawaii as measured at the site of the United Kingdom Infra-Red Telescope (UKIRT). The thick-lined, cross-hatched blocks close to the frequency axis represent the frequency ranges that are covered by the principal detectors on the Gemini North Telescope, which is located close to UKIRT, the thin-lined, open blocks span the bands used as (continuum observation) examples in this study. The instrumentation on the Gemini North telescope was used because it represents the front-line instruments now in use for astronomical observations.

The Gemini telescopes and most other infrared facilities are imagers. An image of the patch of sky seen by the telescope is focused on an array of detectors. Each of these detectors is equivalent to the feed on a conventional, single-antenna radio telescope. The detector array can be used for broad-band imaging or spectral imaging, with the pass-band being chosen by an appropriate filter being placed in front of the detector array. At a typical observing wavelength of 1.65 microns, the half-power beamwidth of an 8-m antenna is about 0.05 arc-s, although phase scintillation due to the atmosphere degrades this value. However, with respect to the reception of interference, the angle of note is the solid angle in the sky seen by the entire detector array, which may be a substantial fraction of a degree across.

FIGURE 1

Zenithal atmospheric transmissivity as measured at the United Kingdom Infra-red Telescope on Mauna Kea, Hawaii. Unity indicates full transmission with no (minimal) loss, zero indicates complete absorption



3 Noise

In radio telescopes operating at lower frequencies, the sensitivity is ultimately limited by the combination of sky noise, ground noise, interference where present and noise produced in the receiver system. The combination of these values is the basis for calculation of the interference thresholds listed in Recommendation ITU-R RA.769. That listing gives threshold values for both continuum (integrating the power over the whole band allocation) and spectral observations, where the bandwidth used is that of a spectrometer channel.

For telescopes operating at frequencies above 50 THz (1 Terahertz, or THz is equal to 10^{12} Hz) the situation is different:

1 most optical/infra-red telescopes are imagers, using charge-coupled device (CCD) arrays at the focus of the dish/mirror, whereas most single-antenna radio telescopes are single-pixel devices, although this is now changing;

2 the noise levels in radio telescopes using bands currently allocated to the radio astronomy service are dictated by a combination of ground, sky and receiver noise. In infra-red telescopes the detector noise is generally negligible compared with the noise from the sky (the troposphere);

3 because the sky noise comprises multiple spectral lines from atmospheric gases, continuum noise thresholds are larger than those in spectral observations because the continuum bandwidth covers multiple spectral line noise peaks whereas the narrow channel bandwidths used in spectral observations can often be fitted into the low-noise valleys between the noise peaks, so the difference is not merely a factor of (*bandwidth ratio*)$^{1/2}$;

4 the main lobe of the "antenna pattern" often has a half-power bandwidth less than an arc-second, so the main lobe and the inner side lobes are all closely grouped in the sky. Telescopes are usually in buildings, so interference is not usually picked up by back lobes (unless locally generated); it gets in through the aperture in the dome where the telescope looks out;

5 some of the formulae used in conventional radio astronomy are invalid for THz frequencies. For example, the frequently-used Rayleigh-Jeans approximation to the black body may or may not be applicable, depending upon what is being observed.

These factors suggest an alternative approach would be more appropriate in considering protection criteria and interference thresholds.

4 Interference thresholds

Since the noise level is largely dictated by sky noise rather than detector noise, the sensitivity of the telescope is essentially dictated by the size of the mirror/antenna. The approach to defining thresholds is therefore based on observations made using a telescope (Gemini North, located on Mauna Kea, Hawaii). We then use these to produce quantities that are independent of the telescope and can therefore be applied generically in the same manner as the thresholds in Recommendation ITU-R RA.769 are applicable at longer wavelengths.

In general a measurement of an astronomical quantity consists of the value plus superimposed noise. In typical observations made at THz systems using the Gemini North Telescope, a measurement is deemed valid when it stands out above the background noise by about 5 times the r.m.s. noise level. Due to the low noise levels produced by the detectors, the noise degrading the desired measurement is almost entirely due to sky noise entering the main beam of the antenna pattern.

The interference threshold spfd corresponding to the methodology described in Recommendation ITU-R RA.769 is given by:

$$S_0 = S - 17 \text{ dB} + G_0$$

where S corresponds to the detection threshold spfd for the detector, which is defined as 5-σ above the noise and G_0 is the boresight gain of the telescope dish/mirror in dB. There is a 7 dB difference between the defined detection criterion and the r.m.s. background noise fluctuation spfd, which corresponds to 1-σ. The acceptable level of interference as defined according to the methodology in Recommendation ITU-R RA.769 is 10 dB below that value. This approach is used in estimating the spfd thresholds tabulated below. The mirrors on the Gemini telescopes have a diameter of 8 m and we assume here an aperture efficiency of 50%. The spectral power flux-densities are in units dB(W/m · Hz). Whereas at the longer wavelengths it is general practice to express the position of a wave in the electromagnetic spectrum in terms of the frequency of the wave, in infra-red and near-infrared astronomy it is the convention to use wavelength. The tables show the band parameters in terms of wavelength, as received from the infra-red astronomy community contributing to this Report, and also in terms of frequency. Conveniently, the frequencies f_L and f_H in THz are given by 300 divided by the wavelength in microns.

Continuum observations											
	Wavelength (μ)				Frequency (THz)				Threshold spfd		
Band	λ_L	λ_C	λ_H	**BW**	f_L	f_C	f_H	**BW**	**Gain**	**5-σ**	**spfd**
J	1.15	1.24	1.33	0.18	225.56	243.22	260.87	35.31	143	−326	−199
H	1.49	1.64	1.78	0.29	168.54	184.94	201.34	32.80	141	−320	−197
K	2.00	2.18	2.36	0.36	127.12	138.56	150.00	22.88	138	−324	−202
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)

Spectral line observations											
	Wavelength (μ)				Frequency (THz)				Threshold spfd		
Band	λ_L	λ_C	λ_H	**BW**	f_L	f_C	f_H	**BW**	**Gain**	**5-σ**	**spfd**
J	1.15	1.24	1.33	2.5E-4	225.56	243.22	260.87	0.048	143	–324	–197
H	1.49	1.64	1.78	3.2E-4	168.54	184.94	201/34	0.036	141	–324	–200
K	2.00	2.18	2.36	4.3E-4	127.12	138.56	150.00	0.027	138	–324	–202
L	3.43	3.78	4.13	6.7E-4	72.64	80.05	87.46	0.014	133	–324	–207
M	4.55	4.67	4.79	9.4E-4	62.63	64.28	65.93	0.013	132	–324	–209
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)

(1) Band designation. Unfortunately the band designations in this wavelength regime duplicate some of those applied at lower frequencies.

(2) Lower wavelength limit of detector operating band.

(3) Wavelength of centre of detector operating band.

(4) Upper wavelength limit of detector operating band.

(5) "Wavelength bandwidth", difference in wavelength between the lower and upper operating wavelength limits for the detector.

(6) Lower frequency limit of detector operating band.

(7) Centre frequency of the detector operating band.

(8) Upper frequency limit of the detector operating band.

(9) Frequency Bandwidth covered by the detector.

(10) The gain of the 8-m mirror/antenna of a Gemini Telescope at the operating frequency, assuming an aperture efficiency of 50%.

(11) The spectral power flux-density of an observed signal exceeding the rms noise level by a factor of 5, for an integrating time of 2 000 s.

(12) Using the antenna gain and the 5-sigma detection spectral power flux-density, we obtain this value for the level of additional noise or interference that received through the far side lobes, would degrade the rms noise fluctuation by 10%.

(13) In the case of spectral line observations, the bandwidth in this column is the wavelength interval covered by one spectrometer channel. The bandwidth in the continuum case is simply the difference between the low and high frequencies or wavelengths defining the operating band. In the case of spectral observations the channel bandwidth is the bandwidth of the spectrometer sensor. This is given in microns, so the equivalent bandwidth in THz is:

$$\Delta f = \frac{300}{\lambda - \Delta\lambda/2} - \frac{300}{\lambda + \Delta\lambda/2}$$

where λ is the wavelength of that channel and $\Delta\lambda$ is its bandwidth in microns (as per table).

5 Current observing sites

There are many telescopes in the world with the capability to make observations in the THz bands, and the number is increasing. Telescopes with mirrors as large as 30 m are under development. However, the number of sites combining high-altitude, low levels of manmade interference and good accessibility is comparatively small. The list below shows current sites around the world where THz telescopes are in operation, under construction or envisaged. North latitudes and East Longitudes are labelled +, and South latitudes and West longitudes are labelled.

Site	Country	Latitude	Longitude	Height (m)
AAO	Australia	–31:16:37	+149:03:58	1 164
Almeria	Spain	+37:13:25	−02:32:46	2 168
Apache Point	USA	+32:46:49	−105:49:13	2 788
Armazones	Chile	−24:35:52	−70:11:46	2 701
Las Campanas	Chile	−29:00:54	−70:44:12	2 722
Canary Islands	Spain	+28:45:24	−17:53:30	2 400
Cerro Pachon	Chile	−30:14:27	−70:44:12	2 722
Cerro Tololo	Chile	−30:10:09	−70:48:21	2 200
Chajnator	Chile	−23:01:22	−67:45:18	5 062
Dome Circe	Antarctica	−75:06:00	+123:21:00	3 233
Flagstaff	USA	+35:05:49	−111:32:09	2 163
Kitt Peak	USA	+31:57:30	−111:38:48	2 096
Mauna Kea	USA	+19:49:16	−155:28:06	4 205
Mount Graham	USA	+32:42:06	−109:52:19	1 926
Mount Hopkins	USA	+31:41:18	–110:53:05	2 617
Paranal	Chile	−24:37:38	–70:24:15	2 635
Pic du Midi	France	+42:56:11	+00:08:34	2 877
San Pedro	USA	+30:45:00	–115:13:00	2 830
La Silla	Chile	−29:15:15	–70:44:22	2 400

6 Mitigation

The interference situation is quite different at THz frequencies than is the case at the lower frequencies usually addressed in radio spectrum management. Propagation is essentially line-of-sight and antennas are highly directional. Generally the telescopes are mounted in metal buildings, which provide screening so that external interference can only reach the telescope through the dome opening.

Specularly-reflected inter-satellite laser link signals (or ground-based laser transmissions to the satellites) could damage or destroy the detectors on the telescope. However, if the inter-satellite signals are at frequencies for which the atmospheric attenuation is high, this problem might be avoided. Ground-stations using Earth-to-space and space-to-Earth links at frequencies in the low-loss windows can avoid causing problems by appropriate spatial separation.

Although the “antenna beams” are individually narrow, so that beam-beam coupling for an individual beam would be low, most of these telescopes are imagers, with an array of many pixels at the focus, “seeing” collectively a patch of sky that could be a substantial fraction of a degree across. Therefore, the chance of beam-beam coupling destroying one or more of the detectors in the array detector is much higher (roughly proportional to the number of detectors in the array).

Spatial separation is the best mitigative option. Since telescopes observing at frequencies above 100 THz are based at isolated, high-altitude sites, there are few suitable places in the world, and in general these are far from population concentrations (Mauna Kea in Hawaii is a possible exception). It is, therefore, feasible to avoid transmitting towards such sites. Providing spatial separation is large enough, the low-attenuation windows in the atmosphere may be used both by active and passive services.

7 Conclusion

There are as yet no known active systems using THz frequencies. However, the technology is now available and applications are being discussed. Options for avoiding interference with astronomical applications in these bands are fairly easily implemented and practicable, so it should be easy to consider these issues at the early stages of system development to avoid future problems. For example, inter-satellite links could use wavelengths that are highly absorbed by the troposphere, and links between Earth and space could employ geographic separation from observatory sites.