

## RECOMMENDATION ITU-R RA.1630-0\*, \*\*

**Technical and operational characteristics of ground-based astronomy systems for use in sharing studies with active services between 10 THz and 1 000 THz\*\*\***

(2003)

The ITU Radiocommunication Assembly,

*considering*

- a) that the spectral range between 400 THz and 750 THz has been utilized for astronomical observations for centuries and, just in the last 30 years, technical advances have made it possible to fully explore the entire spectral range between 10 THz and 1 000 THz;
- b) that observations between 10 THz and 1 000 THz provide data critical to answering certain fundamental questions of astronomy that cannot be answered by astronomical observations carried out below 275 GHz alone;
- c) that the spectrum between 10 THz and 1 000 THz is also used for astronomical research as well as many other applications;
- d) that the technology for astronomical observations in the spectrum between 10 THz and 1 000 THz is continuously evolving;
- e) that ground-based astronomical observations in the visible range, between 400 THz and 750 THz, are also conducted routinely by amateur astronomers;
- f) that frequencies between 10 THz and 1 000 THz are now being used for data links, range measuring devices, and other active systems on ground-based and space-borne platforms, and as these systems are rapidly expanding and increasing in number, the likelihood of interference between active and passive systems is likely to increase;
- g) that many applications of active and passive systems operating between 10 THz and 1 000 THz are very similar to those being used at lower frequencies in the electromagnetic spectrum;
- h) that while there are significant differences between the technologies used in this part of the spectrum compared with lower frequencies (e.g. counting photons vs. integrating power over time), there are also many similarities (e.g. both are used for continuum and spectral line observations);
- j) that it is timely to consider the nature of protective measures and sharing considerations to ensure that ground-based astronomical telescopes can continue to operate without interference,

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\* This Recommendation should be brought to the attention of the International Astronomical Union (IAU) and the International Union of Radio Science (URSI).

\*\* Radiocommunication Study Group 7 made editorial amendments to this Recommendation in the year 2017 in accordance with Resolution ITU-R 1.

\*\*\* 1 THz = 1 000 GHz.

*recognizing*

a) that use and sharing of the spectrum between 10 THz and 1 000 THz has not been studied within the ITU-R,

*recommends*

1 that astronomers take into account the possibility of interference from transmitters operating between 10 THz and 1 000 THz in their choices of observatory sites and in the design of instrumentation;

2 that astronomers provide the appropriate Radiocommunication Study Groups with information on the latest technological advances to ground-based astronomical observations in the frequencies between 10 THz and 1 000 THz;

3 that studies of interference into astronomy systems operating at frequencies between 10 THz and 1 000 THz take into account the technical and operational parameters discussed in Annexes 1 and 2.

## **Annex 1**

### **1 Introduction**

A large variety of objects in the Universe can be observed by ground-based telescopes at frequencies below 275 GHz as well as in the spectrum between 10 THz and 1 000 THz (30  $\mu\text{m}$  to 0.3  $\mu\text{m}$ ). Measurements in different frequency domains usually provide information on the physical properties (like temperature, density and spatial distribution) of various states of the different components (like stars, gas and dust) that constitute the observed objects, as well as on local magnetic fields. In general, the larger the frequency range covered by the observations, the more detailed the information that can be derived about the local physical conditions. On the other hand, certain types of cosmic objects can exclusively, or more readily, be studied at frequencies below 275 GHz or in the spectrum between 10 and 1 000 THz (30  $\mu\text{m}$  to 0.3  $\mu\text{m}$ ).

The astronomical community has been observing in the band between frequencies of about 400 THz and 750 THz (0.75  $\mu\text{m}$  and 0.4  $\mu\text{m}$ ) with telescopes for about 400 years. In the last 30 years, the advent of detector technologies has widened the bands available for astronomical research to the spectrum from 10 THz to 1 000 THz (30  $\mu\text{m}$  to 0.3  $\mu\text{m}$ ). Astronomers generally refer to frequencies between 10 THz and 300 THz (30  $\mu\text{m}$  and 1  $\mu\text{m}$ ) as "infrared", while the spectrum between 300 THz and 1 000 THz (1  $\mu\text{m}$  and 0.3  $\mu\text{m}$ ) is generally referred to as "optical". The spectral range between 10 THz and 1 000 THz is optimal for studies of cosmic thermal emissions and for a large number of spectral lines from atoms and molecules. During the last 30 years, astronomers have seen technological advances that allow the sensing of certain signals once possible only from orbiting platforms. Amateur astronomers conduct observations in the spectrum between 400 THz and 750 THz (0.75  $\mu\text{m}$  and 0.4  $\mu\text{m}$ ).

Individual countries and international consortia are now investing heavily in building observatories with very large mirrors (antennas) of up to 10 m diameter or even larger, which in conjunction with modern detectors, will achieve unprecedented sensitivities. In the same manner, the advent of

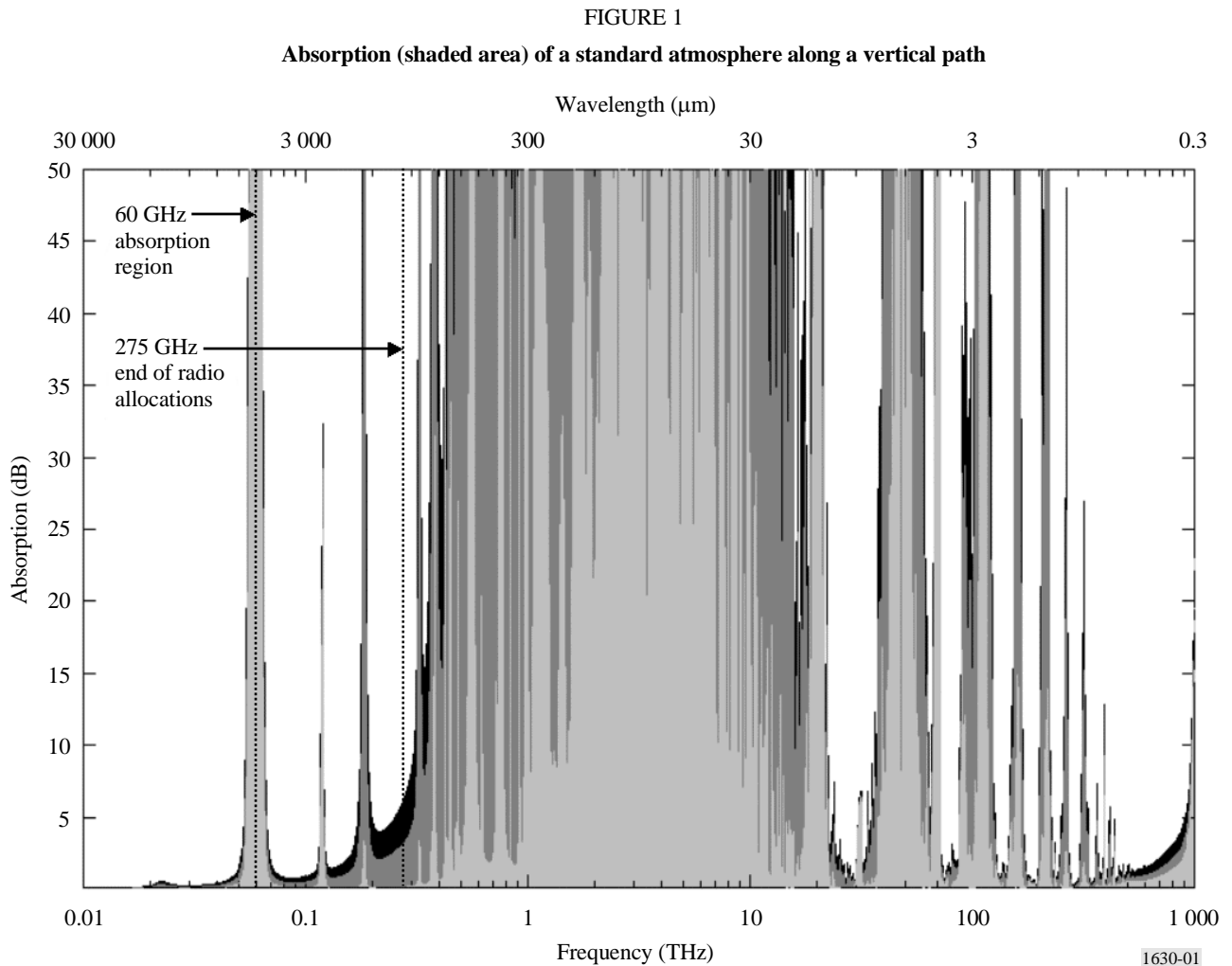
cheap, reliable lasers has led to a revolution in active applications. These include broadband, high-capacity space-to-space, Earth-to-space, space-to-Earth, and terrestrial data and communication links, radar and other range measuring devices.

Astronomical instrumentation operating in the spectrum between 10 THz to 1 000 THz (30  $\mu\text{m}$  to 0.3  $\mu\text{m}$ ) is highly vulnerable to interference or even burnout of detectors by strong signals. However, the high directivities of active systems such as telecommunication systems utilizing lasers operating at frequencies between 20 THz and 375 THz (15  $\mu\text{m}$  and 0.8  $\mu\text{m}$ ), together with the propagation properties of waves in this frequency range give rise to possibilities for hitherto unknown manifestations of interference, but also a wide range of options for interference avoidance and band sharing. Studies of interference avoidance and band sharing in this frequency range will require knowledge of the technical and operational characteristics of astronomical receivers and telescope systems.

## 2 Bands of interest

Due to atmospheric constraints, the majority of the ground-based astronomical observations above the current 1 THz upper limit of provision No. 5.565 of the Radio Regulations occurs in approximately the 100 THz to 1 000 THz spectral range. Figure 1 illustrates the frequency dependence of the transmittance of the atmosphere along three zenith paths. The area shaded in light grey represents a high-quality site with dry air located at 5 km above sea level. The darker grey area shows the additional atmospheric absorption that would occur for a site located 2 km above sea-level (e.g. Kitt Peak). The black regions show the further impact of the atmosphere for a site located at sea-level. All paths utilize the temperature and pressure profiles of Recommendation ITU-R P.835. Absorption below 1 THz is calculated using Recommendation ITU-R P.676. The figure clearly shows that the atmosphere, except at some chosen, high-altitude astronomical sites, is opaque to electromagnetic energy at almost all frequencies between about 1 THz and 10 THz. Above 10 THz, the transparency of the atmosphere becomes favourable to observations of cosmic energy from the surface of the Earth. Above about 1 000 THz the atmosphere again becomes opaque.

The transmittance of the spectral region between 10 THz and 1 000 THz is shown in detail in Fig. 2 for the same three zenith paths. It is characterized by a series of windows of visibility separated by narrow but strong regions of absorption. The individual windows of visibility are limited in their transparency by a fine structure of many weak absorption lines. Individual absorption lines occur due to the presence of gaseous components in the atmosphere including, but not limited to:  $\text{NH}_3$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{NO}_2$ ,  $\text{NO}$ ,  $\text{O}_2$ ,  $\text{O}_3$ ,  $\text{SO}_2$ ,  $\text{H}_2\text{O}$ , and various chlorofluorocarbons. Several of these gases, which are significant to astronomical observations between 10 THz and 1 000 THz, are not currently considered in existing ITU-R propagation Recommendations. The strength of the absorption lines is generally dependent on temperature and pressure. As the strength and width of these lines is variable, bands of interest to ground-based optical astronomers include all spectrum between about 10 THz and 1 000 THz.



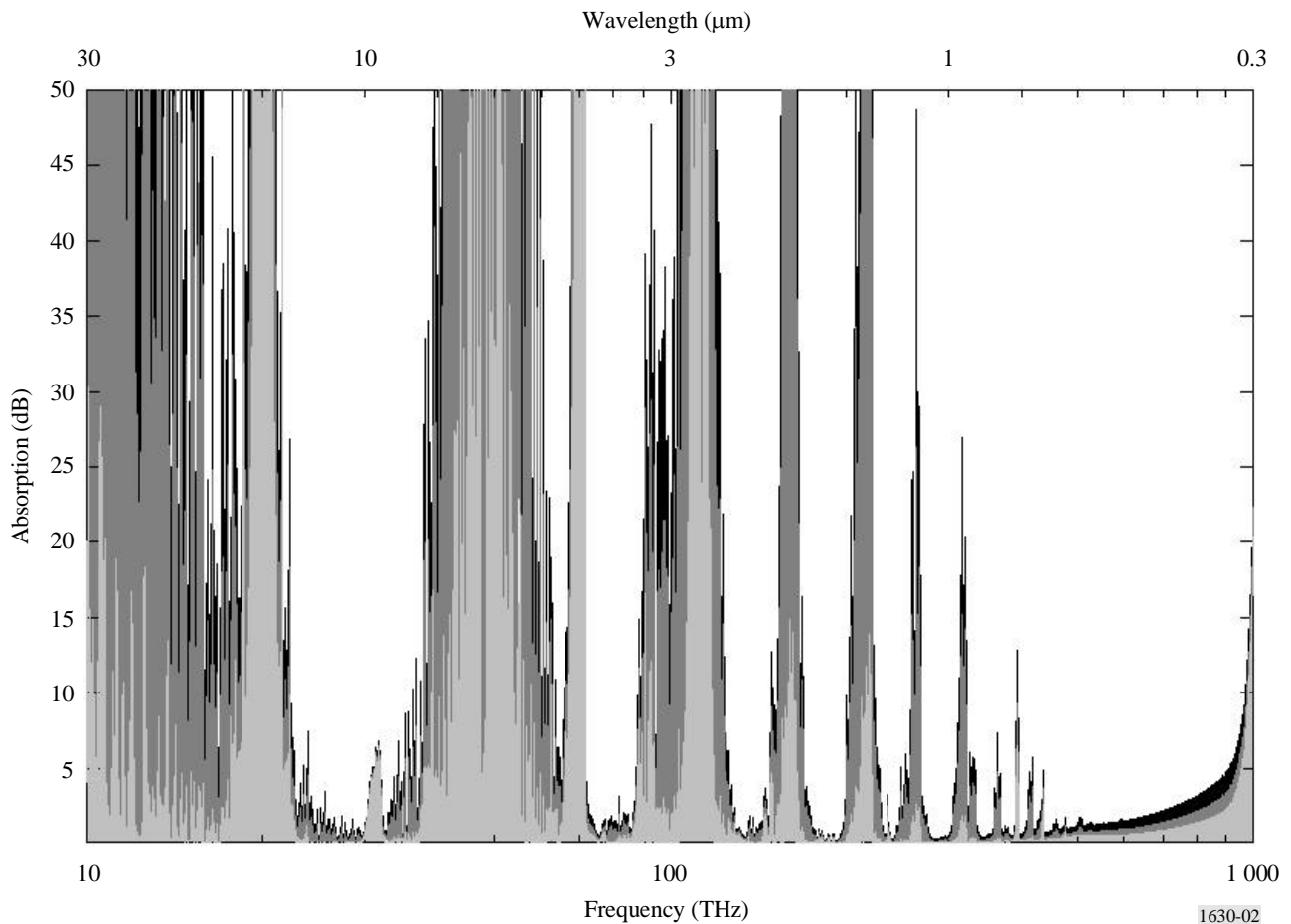
Access to more spectrum is available through the use of airborne observatories, such as balloons and aircraft, dedicated to astronomical observations. In order to have broader access to this astronomically important range, space-borne observatories such as the Hubble Space Telescope are used.

### 3 Types of observations

Some of the observations made in the spectral range between 10 THz and 1 000 THz frequency range are similar to those made in bands currently allocated to the radio astronomy service, namely measurements of continuum spectral power flux-density (spfd), spectral line properties (line spfd, Doppler shift and shape). One of the notable differences between astronomical observations made at frequencies below 275 GHz and in the frequency range between 10 THz and 1 000 THz is the much greater ease with which direct imaging may be carried out in the latter range, both in continuum and spectral line modes. The availability and sensitivity of detector arrays with several million pixels each, and photographic cameras, make this a widely used technique. Also, generally much wider bandwidths are used.

FIGURE 2

Absorption (shaded area) above 10 THz of a standard atmosphere along a vertical path



Astronomy data in the frequency range between 10 THz and 1 000 THz is collected using several measurement techniques. Each technique provides unique information about the object(s) being measured. Typical values used of parameters such as bandwidth, receiver sensitivity, observed field size and angular resolution are, in practice, dependent on the type of measurement performed.

Integration times commonly used vary widely, ranging from as short as 0.001 s to many hours, depending upon the stability of the atmosphere, the type of detector used and the characteristics and intensity of the emission being observed. Multiple individual measurements made using short integration times are often recorded digitally, and then integrated later to produce the sensitivity benefits of a long integration time.

### 3.1 Photometry

Photometry is the high-frequency analogue of continuum observations made in the radio astronomy bands below 275 GHz of the spfd of cosmic sources.

Measurements of the spfd in the frequency range between 10 THz and 1 000 THz generally consider all types of galaxies, stars, objects in the solar system and dust between, or around stars in a large variety of objects found throughout the Universe.

Photometry is a technique used throughout the entire frequency range under consideration, using standard frequency bands defined by filters put in the light path of the detectors. A list of commonly used broadband filter bands in the frequency range between 10 THz and 1 000 THz is provided in Table 3. Examples of the different types of detectors used in different frequency ranges are provided in Table 2. These detectors include: bolometers and various photoconductive or photovoltaic detectors for the N and Q bands, InSb detectors for the J, H, K, L, and M bands and charge coupled device (CCDs) for the U, B, V, R and I bands. Narrow-band filters centred on spectral lines of particular interest are used as well.

Photometric observations are generally calibrated by comparison to well-characterized stars.

### 3.2 Spectroscopy

Spectroscopy is the high-frequency analogue of the measurement of spectral lines in the radio astronomy bands below 275 GHz. The wealth of spectral lines throughout the frequency range between 10 THz and 1 000 THz, the vast majority of which are from various states of elements and molecules which do not have lines at frequencies below 275 GHz, makes this an important branch of astronomy, and underlines the importance of having access to this frequency range.

Spectral line observations are made to derive, e.g. the composition, chemistry, physical properties and dynamics of a large variety of objects, such as interstellar clouds, individual galaxies, groups and clusters of galaxies, as well as the global expansion of the Universe and its local deviations, the composition and origins of stars, and cosmic magnetic fields.

The most widely used dispersive device for spectroscopy in the frequency range between 10 THz and 1 000 THz is the diffraction grating. A diffraction grating disperses incoming energy by its frequency. The dispersed energy is generally recorded by an electronic detector, such as a CCD array, to create a spectrogram.

At the lower end of this frequency range, analogue and, increasingly, digital spectrometers are used. However, such devices are not yet generally available, except in the case of heterodyne receivers that convert the received signals to a lower frequency.

The astronomical spectrum is then examined for the presence of lines that are characteristic of particular elements. If found, that element is known to be present in the cosmic body or, in some cases, in the space between the cosmic body and the receiving telescope. Spectroscopy also makes a major contribution to the study of the motions and dynamics of astronomical objects. By measuring the Doppler shift of the lines from stars and interstellar gas in, e.g. galaxies, radial motions along the line-of-sight can be determined for, among other things, studies of their velocities in space and of the internal dynamics of extended objects, like galaxies and interstellar gas clouds.

Spectroscopy can be performed at several levels of spectral resolution. The crudest resolution amounts to a form of photometry obtained using a spectrograph, where the spectrum is divided into a small number of frequency bands only to give an indication of the overall spectral energy distribution. With mid/high-resolution spectroscopy, the individual lines and molecular bands can be examined in increasing detail.

With the advances in detector array sensitivity and the construction of very large telescopes, spectroscopic studies can be made of increasingly faint objects and the spectra of brighter objects can be studied in unprecedented detail.

### 3.3 Imaging

When compared to the direct imaging devices available in the frequency range between 10 THz and 1 000 THz the presently available multi-element focal plane arrays of radio astronomy receivers used at frequencies below 275 GHz are rather limited in the number of elements and their spatial resolution.

In the frequency range between 10 THz and 1 000 THz, the possibility of many-element, focal plane arrays makes it more usual to obtain images more directly. These focal plane arrays may be CCDs which provide a digital map of brightness per pixel. This technique offers a number of dramatic advantages over the classical photographic process. Long integrations can be built up of accumulated short integrations. This makes it possible to remove pixels and frames degraded by interference and to apply various image enhancement and analysis algorithms. Currently readily available CCDs for astronomical applications consist of arrays of  $\sim 2\,000 \times 2\,000$  pixels, of which a number can be mounted in the focal plane of a telescope to create digital imaging devices with an even larger field of view.

Photographic techniques, introduced into astronomy soon after the invention of the photographic plate, are now largely restricted to observations requiring even larger number of pixels (larger angular field) than can be readily obtained using CCD cameras, as the largest currently used photographic plates have sizes still significantly in excess of those of the largest operational CCD cameras.

### 3.4 Interferometry

At frequencies below 275 GHz, radio images are generally produced by measurement of individual Fourier components of the brightness distribution, which are then processed to form a final image. In general, various imaging imperfections are associated with the synthesized aperture, falling short of the desired, perfect representation. Due to the complexities introduced by rapidly varying atmospheric influences in the frequency range between 10 THz and 1 000 THz interferometry is a quite new technique in this spectral range. Generally, the angular resolution of a single ground-based telescope in the frequency range between 10 THz and 1 000 THz, even that of the 10 m diameter mirrors currently in operation is restricted in practice by atmospheric turbulence, in particular in the frequency range between 100 THz and 1 000 THz.

The need for higher angular resolutions for the studies of certain objects in the frequency range between 10 THz and 1 000 THz, like stars and active galaxies, has led to the increasing use of interferometry. This technique is quite new, but considerable effort is going into technical developments and it is possible that interferometry will become as important at these frequencies as it is in bands currently allocated to the radio astronomy service. Interferometric observing modes are presently being implemented at most of the largest telescopes operating in the frequency range in question.

By coherently combining the signals of two or more telescopes placed at a distance from each other, the angular resolution can be increased substantially and the effects of atmospheric turbulence reduced significantly. Optical interferometers can be used to directly measure the diameter of a cosmic body. Many widely separated telescopes can perform interferometry over large baselines to provide measurements with a precision of as little as  $2.8 \times 10^{-8}$  degrees.

Some interferometer measurements occurring around 30 THz (10  $\mu\text{m}$ ) are performed using heterodyne detection. The use of coherent techniques allows much narrower bandwidth that may result in improved sensitivities under special circumstances. The division of measured energy between multiple telescopes does not reduce the  $S/N$  of the heterodyne system as it would in a direct detection system. Heterodyne interferometers tend to measure across bands several GHz wide. This bandwidth is much narrower than those observed during other types of measurements.

#### 4 Technical characteristics of some astronomical detectors

Detectors used for astronomical observations in the frequency range between 10 THz and 1 000 THz are often specified in units and measures differing from those of radio astronomy receivers operated below 275 GHz. These differences occur for practical reasons and because unique technologies are utilized for detection of energy in the radio and optical bands. Practical considerations such as desirable characteristics of site locations and calibration sources may also vary between the two above-mentioned spectral ranges. These differences often lead to some difficulty in applying standard radio astronomy terminology to astronomy in the frequency range between 10 THz and 1 000 THz. Further, typical units used to describe similar physical parameters may differ between the two frequency ranges. A comparison of units typically used in radio and optical astronomy is provided in Table 1.

TABLE 1

##### A comparison of typical units used to describe radio and optical astronomy parameters

Parameter	Units used in radio astronomy below 275 GHz	Units used in astronomy between 10 THz and 1 000 THz	Conversion
Frequency	kHz, MHz, GHz, THz	$\text{cm}^{-1}$	1/cm $\sim$ 30 GHz
Wavelength	mm, cm, m	$\mu\text{m}$ , nm, $\text{\AA}$	1 m = $10^6$ $\mu\text{m}$ = $10^9$ nm = $10^{10}$ $\text{\AA}$
spfd	$\text{W}/(\text{m}^2 \cdot \text{Hz})$ , $\text{dB}(\text{W}/(\text{m}^2 \cdot \text{Hz}))$ , Jy	Jy, magnitudes	1 Jy = $10^{-26}$ $\text{W}/(\text{m}^2 \cdot \text{Hz})$



#### 4.1 Field of view and angular resolution

The size of the field of view is related to the physical size of the detector and the focal length of the telescope. It may be determined by the equation:

$$\theta = \frac{180d}{\pi F} \quad (1)$$

where:

- $\theta$ : field of view (degrees)
- $d$ : diameter of the detector (m)
- $F$ : focal length of the telescope (m).

In practice, the field of view of a telescope may be reduced with the use of a diaphragm, for various reasons (e.g. imperfect imaging quality in the outermost parts of the field of view).

Improvements in detector technology are progressing in the direction of allowing astronomers to observe increasingly large portions of the sky, while improving the angular resolution of their observations. These improvements are generally effectuated through the use of arrays of detectors with larger effective areas and smaller pixel sizes. The field of view of detector arrays may frequently be as large as  $0.2^\circ \times 0.2^\circ$  but depending on the instrumentation and the telescope, can be as little as a  $10^{-4}$  degrees in diameter. The largest currently available fields of view are on the order of several square degrees. Multiple detectors may be used with a single telescope to observe energy from a single source. Furthermore, detectors may be interchanged within periods as short as a few minutes. Therefore the definition of a single field of view for any particular telescope is not appropriate.

Another useful figure for astronomers is angular resolution. The angular resolution of a telescope is a measure of its ability to identify distinct objects that are closely spaced within its field of view. The maximum theoretically attainable angular resolution for a given aperture, assuming perfectly operating instruments, and without the detrimental effects of the Earth's atmosphere, is:

$$\Delta\theta = \frac{\lambda}{3.974D} = \frac{75.49}{fD} \quad (2)$$

where:

- $\Delta\theta$ : angular resolution (arcs)
- $f$ : frequency (THz)
- $\lambda$ : wavelength ( $\mu\text{m}$ )
- $D$ : diameter of the primary aperture (m).

Theoretical angular resolutions of  $10^{-5}$  degrees are common for a single aperture.

In practice, however, the angular resolution of a single telescope is generally limited by atmospheric turbulence. In practice, at the very best ground based observing sites, angular resolutions of about 0.6 arcs are commonly achieved without the use of adaptive or active optics (see § 4.4) to stabilize the image, while the theoretically attainable angular resolution for the largest, 10 m diameter telescopes operating at optical wavelengths (at a frequency of 600 THz) is only  $10^{-2}$  arcs. Measurements using a technique called interferometry (see § 3.4) are capable of producing measurements down to the order of  $10^{-5}$  arcs of angular resolution.

## 4.2 Sensitivity

The gain of the main beam of an astronomical antenna operating in the frequency range between 10 THz and 1 000 THz is calculable using the same equations as those operating up to the GHz region. Baffling in astronomical telescopes reduces side lobes and backlobe gains to negligible levels.

There are several technologies available to astronomers for detecting energy in the frequency range between 10 THz and 1 000 THz. Table 2 provides a list of frequently used gains and quantum efficiencies for many common optical detector and array technologies.

TABLE 2

Parameters of some of the arrays and detectors utilized in the optical bands

Device	Frequency range (THz)	Typical dimension ( $10^{-3}$ m)	Type $\eta$	Type G	Material
Semiconductor photodiode	10 to 2 000	0.1-250	0.7-1	1	Si, Ge, InSb, HgCdTe
Avalanche photodiode	300 to 2 000	0.1 (typical)-250	0.7-1	$10^6$	Si
Blocked-impurity-band detector	1 to 10	5-15	0.1-0.7	1	Si:As, Si:Sb, Si:Ga, Ge:Ga
Photomultiplier tube	300 to 1 000	5-25	0.1-0.5	$10^6$ - $10^8$	Na <sub>2</sub> KSb:Cs, GaAs:Cs-O, Cs <sub>3</sub> Sb
Extrinsic photoconductor	1 to 10	10-50	0.05-0.4	0.1-10	Si:As, Ge:Be, Ge:Ga, Ge:Sb
Heterodyne detector	0 to 50	Electronic amplification and detection			
CCD	60 to 2 000	5-8	0.8-0.9	1	Si, InSb

Each of these types of detectors has a unique frequency dependent sensitivity and efficiency for detecting energy. They function by translating received energy into an electrical current, as given by:

$$I_R = \frac{\eta G e P_R}{h \nu} \quad (3)$$

where:

$I_R$ : current induced in the detector (A)

$\eta$ : quantum efficiency

$G$ : gain

$e$ : electron charge ( $1.602 \times 10^{-19}$  C)

$P_R$ : received power at the detector (W)

$h$ : Plank's constant (J-s)

$\nu$ : frequency (Hz).

The noise level, or dark current, in a detector covers a wide range of values but is usually less than 10 electrons/s. This value could be orders of magnitude larger for some systems but 10 electrons/s is representative of quality instruments and measurements. The amount of unwanted current in the detector is given by:

$$I_{dark} = 1.6 \times 10^{-19} r \quad (4)$$

where:

$I_{dark}$ : dark current (A)

$r$ : rate of dark current electrons passing through the detector (electrons/s).

### 4.3 Telescope location

Astronomical telescopes operating between 10 THz and 1 000 THz are located throughout the world. The site with the largest and most sensitive telescopes are chosen largely for their atmospheric stability, low water vapour content, and isolation from unwanted energy in the bands of interest (as defined in § 2). Optimal locations are typically at high altitudes, often at least 2 km above sea level, away from urban areas with arid local climatic conditions. The high altitudes are essential for mitigating the effects of turbulence associated with the atmospheric “boundary layer”. The minimization of the thickness of the atmospheric layers between the telescopes and the cosmic bodies to be studied maximizes the spectral bands effectively available (see Figs. 1 and 2). The number of highest quality sites located throughout the world is small, so up to 20 telescopes may be co-located at a single site. Preferred site criteria for radio astronomical observations in the frequency range between about 275 and 1 000 GHz and for observations in the frequency range between 10 THz and 1 000 THz are quite similar, and therefore an increasing number of top quality observing sites are accommodating both radio and optical telescopes (such as the Mauna Kea site on Hawaii and the La Silla site in Chile). Some advanced astronomical telescopes that are currently under development, or are operating, are either located on aircraft or in space. Amateur astronomers, while preferring the same high-altitude locations, may perform their observations anywhere on land with a clear line of sight to the sky.

### 4.4 Atmospheric compensation

The angular resolution of single aperture telescopes greater than 1 m in diameter with fixed mirrors or lenses is limited in practice by atmospheric turbulence, even at the best high-altitude observing sites. The angular resolution of telescopes may, however, be improved using adaptive or active optics. Under certain circumstances the improvement may allow the performance of the telescope to approach the theoretical diffraction limit (see equation (2)).

#### 4.4.1 Active optics

Gravitational deflections and thermal gradients across a mirror’s surface can lead to imperfect measurements. Active optics is a technique intended to compensate for these slow-moving, time-varying distortions and is regularly incorporated into astronomical telescopes at least 4 m in diameter.

#### 4.4.2 Adaptive optics

Adaptive optics is a technique intended to compensate for rapid, time-varying fluctuations in the atmosphere that distort astronomical observations. Fluctuations addressed by an adaptive optics system typically occur at rates as fast as 100 Hz. Phase errors in the incoming wavefront ranging from about  $10^{-8}$  to  $10^{-6}$  m may be corrected.

A laser guide star (LGS) is a frequently used method of applying adaptive optics to correct for atmospheric aberrations. A LGS is created by propagating a laser from the ground along a path within the field of view of the telescope and measuring returned energy. Measured fluctuations in the laser guide star due to the atmosphere may then be used to compensate for atmospheric distortions on targets elsewhere in the telescope's field of view. These fluctuations are typically only useful for correcting atmospheric distortions with a small angular separation from the LGS. Therefore, multiple lasers are sometimes used to correct over a wider field of view.

The most widely used form of LGS focuses on the sodium layer in the high mesosphere at approximately 90 km above the surface of the Earth. These lasers are tuned to a frequency of 509.3 THz ( $0.589 \mu\text{m}$ ) and cause the sodium atoms to fluoresce. Lasers used to generate sodium guide stars typically transmit average powers of 10 to 25 W but powers of as much as 1 kW are technologically feasible. Adaptive optics based on sodium guide stars is typically associated with astronomical observations made at frequencies below 400 THz (wavelengths longer than  $0.75 \mu\text{m}$ ). Another form of adaptive optics, called atmospheric tomography, uses lasers over the 833.3 THz to 857.1 THz ( $0.35 \mu\text{m}$  to  $0.36 \mu\text{m}$ ) range. Atmospheric tomography is based on Rayleigh scatter and measures across a wider range of altitudes that are typically below the sodium layer. Typical power requirements are around 50 to 250 W.

### 5 Technical characteristics of observational facilities

The technical and operational characteristics for astronomical facilities operating in the frequency range between 10 THz and 1 000 THz are not necessarily the same as those for radio astronomy facilities operating below 275 GHz. However, certain similarities do exist.

#### 5.1 Typical hours of operation

The times at which ground-based astronomical observations can be made in the frequency range between 10 THz and 1 000 THz are greatly limited by atmospheric conditions and the position of the Sun. For most astronomical observations in this frequency range, favourable atmospheric conditions (in general, clear skies) are required, as well as the absence of the Sun from the visible sky, as its presence dramatically increases the sky brightness, thus rendering fainter sources undetectable. The rising and setting of the Sun causes changes in temperature through the layers of the atmosphere, thereby inducing unfavourable, turbulent atmospheric conditions for astronomical observations. The amount of atmospheric instability is largely dependent on season and microclimate effects making it a site-dependent variable.

Therefore, most, but not all, astronomy observations in the frequency range under consideration take place after the end of local twilight and before the onset of local dawn. During twilight and dawn conditions, routine calibration observations are made towards positions on the sky. Examples

of astronomical observations that are routinely performed during daylight conditions are observations of the Sun in the entire frequency range under consideration and observations of relatively bright sources, other than the Sun, in the frequency range between 10 THz and 30 THz. Some calibration observations may also be performed on the sky during the daytime.

## 5.2 Telescope slew rates

The angular velocity of an astronomical telescope that is tracking a celestial object through the sky is generally the Earth's rotational speed of approximately 0.25 degrees/min ( $\approx 4.167 \times 10^{-3}$  degrees/s), or values generally close to it for observations of objects within the solar system (the fastest moving objects tracked being asteroids in the vicinity of the Earth). Telescopes can often move at much higher speeds when repositioning to observe another object. However, when repositioning, pointing accuracy is usually diminished to the point that no useful data can be obtained.

## Annex 2

For the purposes of calculating the severity of interference into a ground-based optical astronomy receiver, the parameters presented in Tables 1, 2 and 4 should be considered representative of existing systems. The astronomical telescope parameters and detector parameters, including usable frequency bands, are listed in separate tables because astronomical telescopes are independent of the detectors attached to them.

Names associated with spectral filters have been adopted by the astronomical community and are in common use. The central frequencies of each filter are roughly correlated with the windows of atmospheric visibility and are presented in Table 3.

TABLE 3

Most frequently used broadband filters in the 10 THz to 1 000 THz range

Filter	Q	N	M	L'	L	K	H
Centre frequency (THz)	15	30	63	79	86	136	180
Wavelength ( $\mu\text{m}$ )	20.25	10.1	4.80	3.80	3.50	2.20	1.65
Bandwidth (THz)	15.2	18.2	15.9	14.7	17.3	30.1	33.3
( $\mu\text{m}$ )	6.50	5.70	1.20	0.70	0.70	0.48	0.30
Filter	J	I <sub>r</sub>	I <sub>s</sub>	R	V	B	U
Centre frequency (THz)	240	330	370	430	560	700	830
Wavelength ( $\mu\text{m}$ )	1.25	0.90	0.80	0.70	0.54	0.43	0.36
Bandwidth (THz)	74.7	90.5	115.1	138.1	93.2	164.5	163.6
( $\mu\text{m}$ )	0.38	0.24	0.24	0.22	0.09	0.10	0.07

Astronomical telescopes assume a wide variety of sizes and focal lengths. A list of the relevant parameters to assess interference into astronomical telescopes is provided in Table 4.

TABLE 4

## Parameters of some of the major ground-based astronomy systems operating in the 10 THz to 1 000 THz range

Aperture diameter (m)	Telescope	Location	Focal length (m)	Latitude (°N)	Longitude (°W)	Altitude (m)
10	Keck I	Mauna Kea, HI, United States of America	17.5 (f/1.75)	19.83	155.47	4 123
	Keck II					
9.2	Hobby-Eberly Telescope (HET)	Mt. Fowlkes, TX, United States of America	13.08 (f/1.4)	30.67	104.02	2 072
8.3	Subaru	Mauna Kea, HI, United States of America	15 (f/1.8)	19.83	155.47	4 100
8.2 × 4	Very Large Telescope	Cerro Paranal, Chile	14.8 (f/1.8)	-24.63	70.40	2 635
8.0	Gemini North	Mauna Kea, HI, United States of America	129.6 (f/16.2)	19.83	155.47	4 100
	Gemini South	Cerro Pachon, Chile	129.6 (f/16.2)	-30.33	70.98	2 737
6.5	Multi-Mirror Telescope (MMT)	Mt. Hopkins, AZ, United States of America	8.1 (f/1.25)	31.68	110.88	2 600
	Magellan I	La Serena, Chile	8.1 (f/1.25)	-29.00	70.71	2 282
6.0	Bolshoi Azimuthal Telescope (BTA)	Zelenschuskaya, Russian Federation	24 (f/4.0)	43.39	41.26	2 070
5.0	Hale	Palomar Mt, CA, United States of America	16.5 (f/3.3)	33.35	116.87	1 900
4.2	William Herschel Telescope (WHT)	Roque de los Muchachos, Spain of America	10.5 (f/2.5)	28.45	17.52	2 350
4.0	Victor M. Blanco	Cerro Tololo, Chile	11.5 (f/2.9)	-30.17	70.82	2 200
4.0	Mayall	Kitt Peak, AZ, United States of America	10.3 (f/2.7)	31.95	111.62	2 100
3.9	Anglo-Australian Telescope (AAT)	Siding Springs, Australia	12.7 (f/3.3)	-31.28	210.93	1 164

TABLE 4 (end)

Aperture diameter (m)	Telescope	Location	Focal length (m)	Latitude (°N)	Longitude (°W)	Altitude (m)
3.8	United Kingdom Infrared Telescope (UKIRT)	Mauna Kea, HI, United States of America	9.5 (f/2.5)	19.49	155.28	4 194
3.6	ESO 3.6 m	La Silla, Chile	8.1 (f/2.2)	-29 15	70.44	2 400
	Canada-France-Hawaii (CFHT)	Mauna Kea, HI, United States of America	15.1 (f/4.2)	19.83	155.47	4 200
	Telescopio Nazionale Galileo (TNG)	Roque de los Muchachos, Spain	38.5 (f/11.0)	28.45	17.52	2 350
3.5	WIYN	Kitt Peak, AZ, United States of America	22 (f/6.3)	31.95	111.62	2 100
	ARC	Apache Point, NM, United States of America	6.1 (f/1.75)	32.78	105.82	2 788
	Calar Alto 3.5 m	Calar Alto, Spain	12.2 (f/3.5)	37.22	2.55	2 168
3.0	Shane	Mt. Hamilton, CA, United States of America	15 (f/5)	37.35	121.63	1 300
	NASA IRTF	Mauna Kea, HI, United States of America	7.6 (f/2.3)	19.83	155.47	4 160
	NODO	Cloudcroft, NM, United States of America	4.5 (f/1.5)	32.98	105.73	2 758

NOTE 1 – The observable spectral range of most measurements is limited by the detector. Most, but not all telescopes are capable of observing with varying degrees of performance across all atmospheric windows of visibility.

