RECOMMENDATION ITU-R S.1590

Technical and operational characteristics of satellites operating in the range 20-375 THz

(Question ITU-R 264/4)

(2002)

The ITU Radiocommunication Assembly,

considering

a) that telecommunication links are being used and planned for use on some satellite systems for inter-satellite communications at frequencies within the range of 20-375 THz;

b) that the viability of fixed-satellite service telecommunication systems operating in the 20-375 THz range of the spectrum using Earth-to-space and space-to-Earth links is currently being investigated;

c) that astronomers are making observations in this part of the spectrum;

d) that this part of the spectrum is also being used for other science services;

e) that this part of the spectrum is also being used for scientific and industrial purposes other than communication;

f) that mechanisms of interference between satellites and passive systems such as astronomy operating above 20 THz may differ from those in the radio frequency part of the spectrum,

recognizing

a) that No. 78 of Article 12 of the ITU Constitution states that the functions of the Radiocommunication Sector include, "… carrying out studies without limit of frequency range and adopting recommendations …";

b) that, under Note 2 of 1005 in the Annex to the ITU Convention, Study Groups may consider "radiocommunication" to include electromagnetic spectrum above 3000 GHz propagated through space without artificial guide in the course of their studies and in the creation of draft new Recommendations;

c) that as of the end of 2001, use and sharing of this part of the spectrum has not been thoroughly studied within ITU-R,

recommends

1 that sharing studies of satellites operating in the frequency range 20-375 THz take into account the technical and operational parameters presented in Annex 1.

ANNEX 1

1 Introduction

The term “radio waves” is defined in the Radio Regulations as “Electromagnetic waves of frequencies arbitrarily lower than 3 000 GHz propagated in space without artificial guide”. With the increased pressure for use of the radio spectrum and the advancement of technology, more attention is being given to the use of frequencies above 3 000 GHz for free space telecommunications. Telecommunication links have become a reality in the frequency bands above 3 000 GHz as a result of many recent technological developments in optical communication devices such as optical fibre, solid state lasers (GaAs, InP)[1], modulators (electro-optic modulators) and detectors (photodiodes). Free space telecommunication at frequencies above 3 000 GHz has the ability to support data rates in the tens of Gbit/s as well as meet gain and directivity requirements of beams used for deep space applications.

For telecommunications, attention is being focused on frequencies in the band 20-375 THz (15-0.8 μm). Though some links have been demonstrated, much of the technology for these links is still in development but evolving rapidly. Such links can provide telecommunication signals on Earth-to-space, space-to-Earth, and space-to-space paths as well as on terrestrial links. They are being considered for satellites in geostationary orbit (GSO) as well as those in non-geostationary orbit (non-GSO) such as low Earth orbits.

Technical and operational characteristics are required for the free space telecommunication links operating in these spectral regions for use in future sharing studies. The specifications and operations of some systems in this region are described in the following sections. The purpose of this Recommendation is to identify system parameters required for conducting interference analyses for space applications.

2 Frequency considerations

Not all frequencies are equally suitable for free space telecommunications since the transparency of the atmosphere varies strongly with frequency. Earth-to-space and space-to-Earth links should operate in a region of low absorption while space-to-space links may want to choose a region of high absorption to achieve isolation from interference on the Earth and reduce the probability of causing interference to astronomical observations.

The use of near infrared lasers (0.850 μm) are more efficient in terms of signal-to-noise ratio. Medium infrared detectors near 15 μm need strong cooling in order to reduce thermal noise.

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[1] Lasers used in telecommunication are manufactured from III-V semiconductor compounds. The materials used are alloys of Gallium Arsenide (GaAs) and Indium Phosphide (InP). The wavelengths of such lasers are respectively 0.85 μm and 1.5 μm.

Figure 1 shows the frequency dependence of atmospheric absorption of an optical signal along a vertical path. This Figure assumes the path begins at sea level, and the line of sight continues into space through a standard atmosphere. Below about 15 THz (20 µm), the sky is effectively opaque. With increases in frequency toward the visible band, 400-750 THz (0.75-0.40 µm), there are numerous bands of various width and transparency that occur due to the presence of gaseous components in the atmosphere. These gases are not necessarily uniformly mixed and the proportions can vary as a function of altitude. The strength of the absorption lines is also generally dependent on pressure and temperature. At about 300 THz (1 µm), the envelope of the absorption starts to increase, due primarily to O_2 and O_3. The absorption increases up through the visible band, to about 1 000 THz (0.3 µm) where the atmosphere again becomes effectively opaque due to molecular absorption.

Currently, most of the interest in telecommunications links is focused around the frequencies 200, 283, 311 and 353 THz, whose corresponding wavelengths are approximately 1.5, 1.06, 0.965 and 0.850 µm. These frequencies are the same as those that are most widely used for communications in optical fibres.

FIGURE 1

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

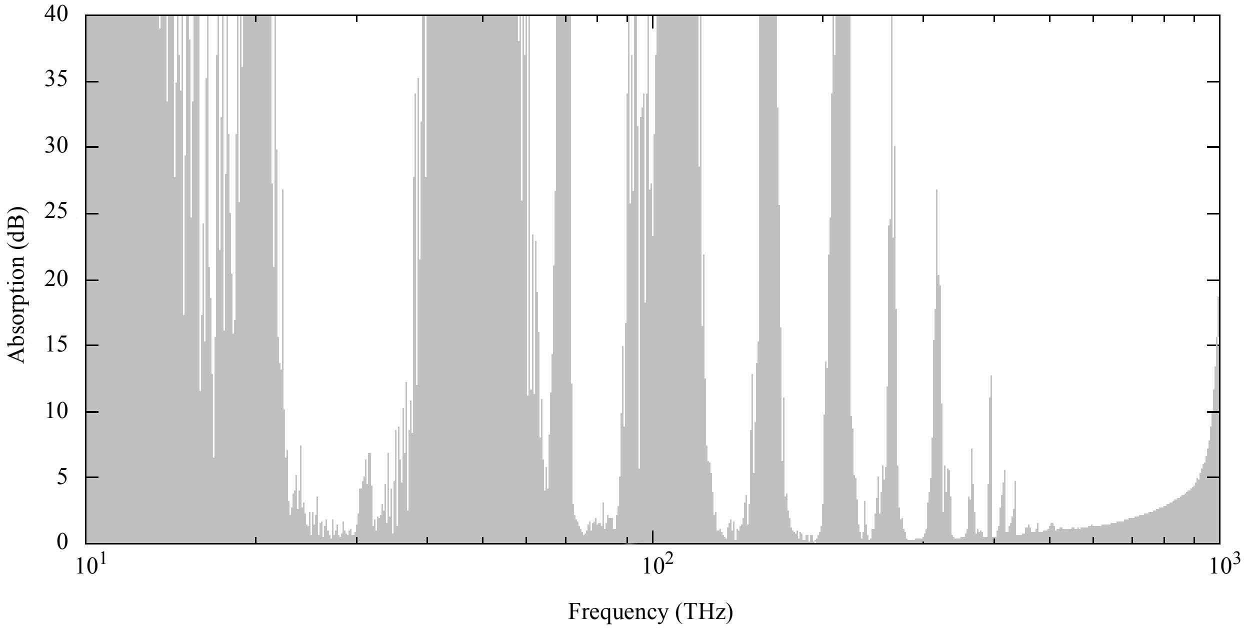

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Table 1 shows some characteristics for typical lasers used in terrestrial optical communications.

TABLE 1

Typical characteristics of solid-state lasers in the range of 0.75 µm to 1.6 µm

Laser medium	**Transition wavelength**	**Typical maximum output power (W)**	**Continuous-wave (CW) or pulsed**	**Single mode (S) Multimode (M)**	**Transition linewidth**
$In_{1-x}Ga_{1-y}P_y$(1) Semiconductors	1.1 µm to 1.6 µm	1	CW	S/M	A few GHz up to 10 THz
Nd^{3+}:YAG(2) Glass	1.064 µm	10	CW	S/M	120 GHz
In_xGa_xAs Semiconductors	0.965 µm	1	CW	S/M	A few GHz up to 10 THz
AL_xGa_xAs Semiconductors	0.75 to 0.87 µm	10	CW	S/M	A few GHz up to 10 THz

(1) $0 < y < 1$ and $0 < x < 1$

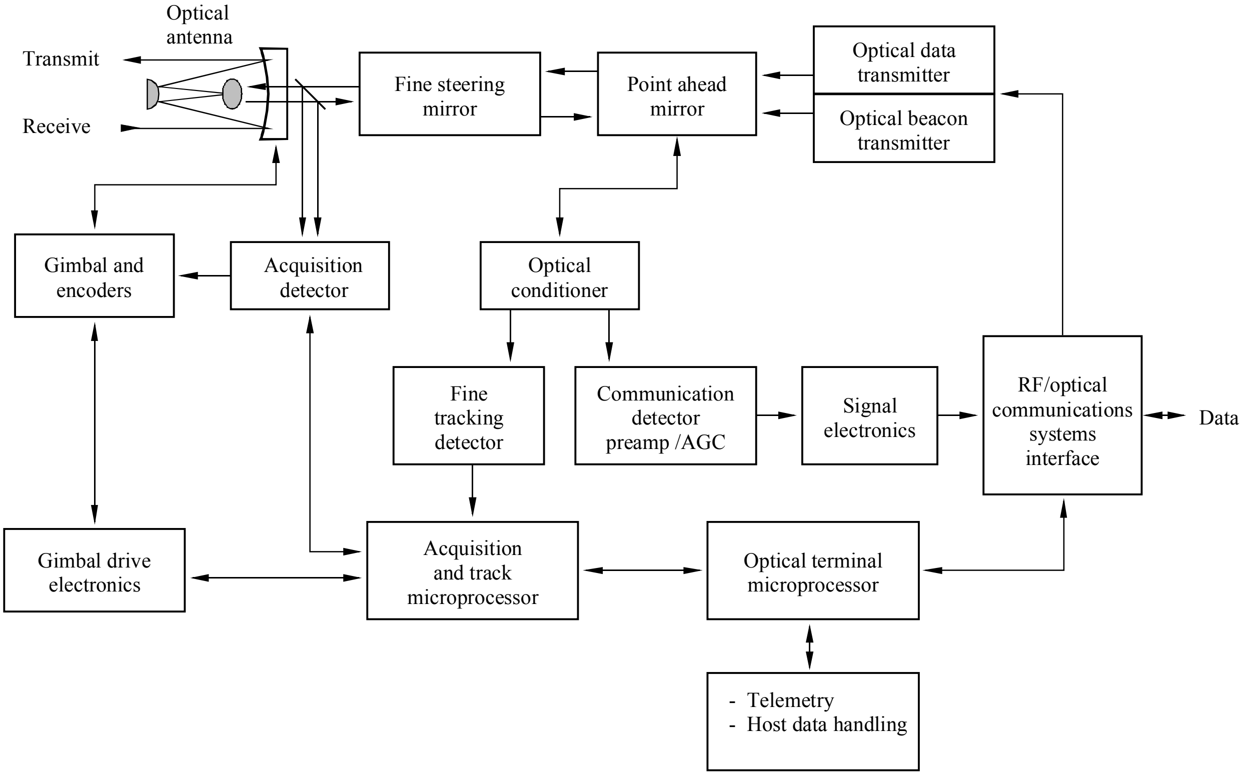
(2) YAG: yttrium aluminium garnet.

3 Generic block diagram

A generic block diagram of a typical optical telecommunications system is provided in Fig. 2.

FIGURE 2

Block diagram of a typical optical telecommunications system



AGC: automatic gain control

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It is noted that for nearly every optical link there is a return link to provide feedback for correcting the optical pointing. That is, the two links operate as a closed loop control network to maintain optical alignment.

It is desirable to examine the parameters the optical terminal designer has available. Obviously not all optical satellite terminals are the same. Rather their specific usage or applications drive their designs. In this section the basic components of optical terminals are described and details of the specific design characteristics that are unique to particular applications are discussed.

3.1 Transmitter

The data transmitter, a laser, is shown in the upper right corner of Fig. 2. The typical power of existing space qualified lasers is about 1 W. The use of higher power units is inhibited by lifetime and reliability concerns, but the technology is continually evolving. A requirement for data rates of tens of Gbit/s will require the designer to limit the selection to the tuneable class of lasers and most likely to use wavelength division multiplexing components. For the heterodyne and homodyne telecommunication systems, there is a need for lasers having narrow laser linewidths and minimal phase noise. In addition the lasers have to be frequency stable and highly tunable to address the problem of optical Doppler. In the case of a GSO to non-GSO link, Doppler considerations could require shifts that approach ±10 GHz.

3.2 Receiver

The receiver is comprised of the block in the middle of Fig. 2 labelled "Communication detector: preamp/AGC". Most current receivers are based on either the avalanche photodiode (APD) or a P*in* diode. For applications where the incident optical power on the detector is weak, such as in a direct detection receiver, the APD with its internal gain is preferred. For an APD, detection sensitivity on the order of 100 received photons per bit can be achieved. The APD can support link data rates up to 40 Gbit/s. Although the APD has reached a bandwidth limit, its sensitivity is being extended with the development of the optical fibre amplifier. P*in* diodes are simpler to operate and easier to fabricate than APDs but have a low gain. These diodes are typically used in heterodyne or homodyne detection systems.

3.3 Detection

Detection in optical systems works in much the same way as radio-frequency systems. The three techniques are: direct detection, heterodyne detection, and homodyne detection. Thus far, most systems have used direct detection, which is accomplished by converting the energy per photon (optical intensity) into charge carriers or electrical current. The signal is directly demodulated at the receiver back into the transmitted signal at baseband. The heterodyne receiver detects both amplitude and phase of the signal by first mixing the received optical signal with a strong local oscillator output, then detecting the combined optical signal. Homodyne detection is a special case of heterodyne detection where the local oscillator is matched with the incoming signal both in frequency and phase.

3.4 Acquisition

Acquisition is a complex process controlled by the "Acquisition and track microprocessor" block as well as blocks representing the gimbaling functions on the left of Fig. 2. To establish an optical link, the units go through an acquisition phase to align the optics and lock on any carriers. During this phase, a beacon is usually used for a signal and a charge coupled device (CCD) array is used to detect any misalignment. This technology has reached a high level of maturity. CCDs will probably remain the primary technology used to support this facet of optical communications.

3.5 Beacon transmitter

The beacon transmitter is shown with the data transmitter in the upper right corner of Fig. 2. During the acquisition phase each terminal emits a beacon with a beam significantly wider than the communications beam to assist in the initial alignment of the optics. The beacon laser technology is well in hand, with the terminal designer having various approaches available that are all supported by mature technology.

3.6 Tracking/servo

Tracking and servo are the precision pointing operations made by the "fine steering mirror" and "point ahead mirror" as shown in Fig. 2. These operations are taken together because the function they perform is integrally connected. It is extremely difficult to achieve optical crosslink pointing and tracking requirements while experiencing spacecraft jitter and motion. The penalty paid for failure to carry out this function is burst errors a condition that could cause a major loss of data.

3.7 Electronics

Although electronics is probably the most mature technology supporting optical telecommunication the terminal designer has to be aware that links supporting tens of Gbit/s digital telecommunications require slot widths of around 10 ps and rise and fall times of 2 ps or less. This performance requirement poses a technological challenge.

4 Satellite links

This section addresses the optical link parameters used in several typical applications and gives typical values for these parameters. These links represent both potential interferers and victims. The technical characteristics of the transmitters and receivers used with both Earth-space links and inter-satellite links operating at frequencies above 20 THz vary with data requirements and orbital parameters.

4.1 Inter-satellite links

GSO/GSO crosslinks are relatively stable as the two satellites are moving slowly with respect to each other in terms of range and azimuth angle. This is due to the basic fact that they remain relatively stationary over a location on the Earth's surface and have a small azimuth and elevation pointing range for communication. The acquisition and tracking requirements remain the same as the GSO/non-GSO crosslinks because the pointing uncertainty prior to acquisition is mainly driven by knowledge of the spacecraft's attitude in roll, pitch and yaw.

The GSO/non-GSO class of optical terminals is discussed here because of their similarity to the GSO/GSO terminals. Both classes of terminals are similar in the area of optical antenna size, which is the main element effecting optical terminal mass and both have similar link distances (≥ 40 000 km). The main difference between GSO/GSO and GSO/non-GSO links is the angular rate performance requirements of the antenna gimbal. Not only do GSO/non-GSO links have a higher angular range over which the gimbal is required to operate, there is an accompanying increase in the angular velocity and acceleration. Table 2 provides an example of the parameters for typical GSO/GSO and GSO/non-GSO systems. The GSO/non-GSO system is based on the SPOT4 spacecraft to ARTEMIS link.

TABLE 2

GSO/GSO and GSO/non-GSO crosslinks

<table>
<tr><th colspan="2">Parameters</th><th>GSO/GSO</th><th>GSO/non-GSO</th></tr>
<tr><td colspan="2">Range (km)</td><td colspan="2">40 000-80 000</td></tr>
<tr><td colspan="2">Frequency (THz)</td><td colspan="2">200, 283, 311, 353</td></tr>
<tr><td colspan="2">Wavelength (μm)</td><td colspan="2">{1.50, 1.060, 0.965, 0.850}</td></tr>
<tr><td rowspan="7">Terminal No. 1</td><td>Power (mW)</td><td colspan="2">500-1 500</td></tr>
<tr><td>Aperture (cm)</td><td colspan="2">20-30</td></tr>
<tr><td>Gimbal range(1) (degrees)</td><td>±2 azimuth;
0 to –60 elevation</td><td>±20 azimuth;
±20 elevation</td></tr>
<tr><td>Angular velocity(2) (μrad/s)</td><td>Not applicable</td><td>200 azimuth;
200 elevation</td></tr>
<tr><td>Field of regard(3) (mrad)</td><td colspan="2">8.0 × 8.0</td></tr>
<tr><td>Divergence – Acquisition (μrad)</td><td colspan="2">130</td></tr>
<tr><td>Divergence – Communication (μrad)</td><td colspan="2">10</td></tr>
<tr><td rowspan="5">Terminal No. 2</td><td>Aperture (cm)</td><td>20-30</td><td>10-15</td></tr>
<tr><td>Gimbal range (degrees)</td><td>±2 azimuth;
0 to –60 elevation</td><td>±175 azimuth;
±140 elevation</td></tr>
<tr><td>Field of regard (mrad)</td><td colspan="2">8.0 × 8.0</td></tr>
<tr><td>Divergence – Acquisition (μrad)</td><td colspan="2">130</td></tr>
<tr><td>Divergence – Communication (μrad)</td><td colspan="2">10</td></tr>
</table>

(1) Gimbal range: The angle through which the optical antenna can be moved.

(2) Angular velocity: The maximum rate of change of the optical antenna pointing.

(3) Field of regard: The angular region of uncertainty of the opposite node at the initiation of acquisition.

Several terminals are commercially available for GSO/GSO and GSO/non-GSO crosslinks. To date the terminals have been built in support of existing space-based optical telecommunication technology demonstrations.

Table 3 lists generic values for a classic non-GSO/non-GSO optical telecommunications link between two satellites in adjacent circular orbits.

TABLE 3

Non-GSO/non-GSO crosslinks

Parameters		Non-GSO/non-GSO
Range (km)		1 000-7 000
Frequency (THz)		200, 283, 311, 353
Wavelength (μm)		{1.50, 1.060, 0.965, 0.850}
Terminal No. 1	Power (mW)	1 000
	Aperture (cm)	4-15
	Gimbal range (degrees)	±90 azimuth; ±5 elevation
	Field of regard (mrad)	5.5 × 5.5
	Divergence – Acquisition (μrad)	160
	Divergence – Communication (μrad)	16
Terminal No. 2	Aperture (cm)	4-15
	Gimbal range (degrees)	±90 azimuth; ±5 elevation
	Field of regard (mrad)	5.5 × 5.5
	Divergence – Acquisition (μrad)	700
	Divergence – Communication (μrad)	16

4.2 Earth-space links

GSO/ground links are relatively stable as the satellite and the earth station are moving slowly with respect to each other in terms of range and azimuth angle. The satellite will remain relatively stationary over a location on the Earth's surface and for any given link have a small azimuth and elevation pointing range. The acquisition and tracking requirements for the satellite remain the same as the GSO/GSO crosslinks because the pointing uncertainty prior to acquisition is mainly driven by knowledge of the spacecraft's attitude in roll, pitch and yaw.

There is little interest in using optical links for non-GSO/ground communications with current space system configurations. It is difficult to maintain an optical communications link with an earth station operating with an elevation angle below 40° E due to the atmospheric effects at lower angles. Thus the orbital arc and time over which the satellite is visible from an earth station is severely limited.

TABLE 4

GSO/ground links

Parameters		**GSO/ground**
Range (km)		35 000-40 000
Frequency (THz)		200, 283, 311, 353
Wavelength (μm)		{1.50, 1.060, 0.965, 0.850}
Terminal No. 1	Power (mW)	500-1 500
	Aperture (cm)	20-30
	Earth station gimbal range (degrees)	±90 azimuth; 40 to 90 elevation
	Satellite station gimbal range (degrees)	±180 azimuth; –80 to –90 elevation
	Field of regard (mrad)	8 × 8
	Divergence – Acquisition (μrad)	130
	Divergence – Communication (μrad)	10

5 Signal-to-Noise Ratio (SNR)

Like most telecommunications links, the performance of optical links is highly dependent on achieving a high SNR at the receiver. In general:

$$SNR = \frac{P_r}{N_t} \tag{1}$$

where:

P_r: receiver power (W)

N_t: noise power from all sources (W).

The basic equations describing the performance of a laser optical crosslink or a link through the atmosphere can be simplified by the following basic assumptions:

- Optical transmitting and receiving antennas have no central obstructions.
- Transmitted waveforms are Gaussian and are truncated at the $1/e^2$ points.
- Received waves are plane waves.
- Airy disks are truncated at the first null of the Airy disk pattern.

5.1 Signal

The received signal power is related to the power output of the laser transmitter as well as other link parameters via the following range equation that is quite similar to the conventional microwave equation.

$$P_S = P_t \, G_t \, G_r \, T_t \, T_r \, T_a \, L_S \tag{2}$$

where:

P_S: receiver signal power (W)

P_t: average laser output power (typical value is 1 W)

G_t: transmitter antenna gain (typical value is 10^{11})

G_r: receiving antenna gain (typical value is 10^{11})

T_t: transmitter losses (typical value is 0.5) that include the effects of absorption, scattering, or reflection losses in the optical trains of the transmitter

T_r: receiver losses (typical value is 0.5) that include the effects of absorption, scattering, or reflection losses in the optical trains of the receiver

T_a: atmospheric losses (typical value is up to 0.03) in a space-to-ground or ground-to-space link. For a space-to-space link T_a is assumed to be 0 dB. Calculation of T_a is discussed further in § 8

L_S: free space loss.

The classic forms of the transmitter antenna and receiver antenna gain equations are:

$$G = \left(\frac{\pi D}{\lambda} \right)^2 = \left(\frac{\pi D f}{c} \right)^2 \tag{3}$$

where:

D: unobstructed diameter of the primary aperture of the antenna (m)

λ: wavelength (m)

f: frequency (Hz)

c: speed of light (m/s).

The free space loss or channel loss, L_S, is given by:

$$L_S = \left(\frac{\lambda}{4\pi R} \right)^2 = \left(\frac{c}{4\pi f R} \right)^2 \tag{4}$$

where:

R: distance between terminals (m).

In Tables 5 and 6, three different links are presented and representative values for the link parameters are given. The Tables were generated using the simplified link equation previously described in this Annex.

TABLE 5

Typical non-GSO/non-GSO and GSO/GSO link budget parameters

Link parameters	**Non-GSO/non-GSO**		**GSO/GSO**	
P_t	1.0 W average 2.29 W peak	33.6 dBm	1.0 W average 2.29 W peak	33.6 dBm
G_t	10 cm (diameter)	110 dB	30 cm (diameter)	119.5 dB
G_r	10 cm (diameter)	110 dB	30 cm (diameter)	119.5 dB
T_t	0.5	–3.0 dB	0.5	–3.0 dB
T_r	0.5	–3.0 dB	0.5	–3.0 dB
T_a	Not applicable	0.0 dB	Not applicable	0.0 dB
L_s	7 000 km	–278 dB	40 000 km	–294 dB
P_s	0.912 μW 4.6×10^{12} P/s	–30.4 dBm	1.81 μW 9.1×10^{12} P/s	–27.4 dBm

Frequency = 283 THz

(Wavelength = 1.06 μm)

P/s: Photons per second

TABLE 6

Typical GSO/ground and GSO/non-GSO link budget parameters

Link parameters	**GSO/ground**		**GSO/non-GSO**	
P_t	1.0 W average 2.29 W peak	33.6 dBm	1.0 W average 2.29 W peak	33.6 dBm
G_t	10 cm (diameter)	110 dB	30 cm (diameter)	119.5 dB
G_r	100 cm (diameter)	130 dB	30 cm (diameter)	119.5 dB
T_t	0.5	–3.0 dB	0.5	–3.0 dB
T_r	0.5	–3.0 dB	0.5	–3.0 dB
T_a	0.03 (worst case)	–15 dB	Not applicable	0.0 dB
L_s	36 300 km	–293 dB	40 000 km	–294 dB
P_s	0.091 μW 4.6×10^{11} P/s	–40.4 dBm	1.81 μW 9.1×10^{12} P/s	–27.4 dBm

Frequency = 283 THz

(Wavelength = 1.06 μm)

With the tremendous advances in laser artificial guide stars and adaptive optics technology, a safe assumption that the atmospheric losses in the space-to-ground example outline in Table 6 could be improved by at least 10 dB.

5.2 Noise

The performance of optical telecommunication links depends directly on achieving a high SNR at the receiver. The higher the SNR, the lower the bit error rate. The primary detectors of choice for optical communications are solid-state devices such as APDs and P*in* diodes. Most current applications use a direct detection receiver with an APD, which has internal gain. Some of the newer applications use P*in* diodes, which are simpler to operate and easier to fabricate than APDs, but have a low gain. These diodes are typically used in heterodyne or homodyne detection systems.

The SNR for the commonly used APD in direct detection is developed below. This is for the case where there is sufficient signal that it is photon-noise limited and other noise sources such as amplifier noise and background illuminations can be ignored. For a detector followed by a lowpass filter of bandwidth B, the total current at the detector output is given by:

$$i = i_S + i_N \tag{5}$$

The signal current, i_S, is defined by:

$$i_S = \frac{\eta \, e \, P_S}{h \, f} \tag{6}$$

and the shot noise current, i_N, with zero mean and mean-square value is given by:

$$\sigma_N^2 = < i_N^2 > = 2e \, B \, i_S = \frac{2\eta \, e^2 \; B \, P_S}{h \, f} \tag{7}$$

where:

η: detector quantum efficiency (0.7 to 1 typical)

e: electron charge (1.602×10^{-19} C)

h: Planck’s constant (6.63×10^{-34} J/s)

f: optical frequency (Hz)

P_S: received signal power (W)

B: filter bandwidth (Hz).

Note that the noise power varies directly with the signal power, P_S.

Then, in the absence of atmospheric effects, the output SNR is:

$$SNR = \frac{i_S}{\sigma_N} = \sqrt{\frac{\eta \, P_S}{2h \, f \, B}} \tag{8a}$$

or in a power form:

$$SNR = \frac{\eta \, P_S}{2h \, f \, B} \tag{8b}$$

6 Antenna considerations

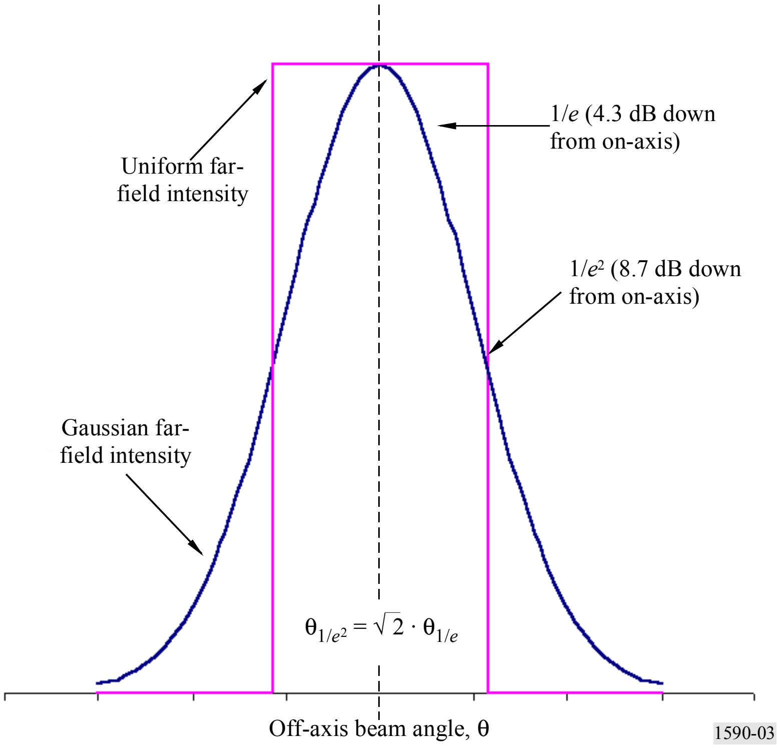
Free space laser telecommunication systems use conventional telescopes as transmitting and receiving antennas. Normally these telescopes are of the classic Cassegrain design, but with the advent of modern telescope manufacturing technology and the dramatic increase in optical power available, the current designs utilize primarily refractive elements or off-axis telescope designs to eliminate obscurations and the resultant reduction in on-axis gain. The transmitter and receiver antenna patterns are different since the transmitter optics are usually fed by a laser with a Gaussian beam while the receiver optics have a planar detector.

6.1 Transmitter antennas

The transmitter utilizes a telescope that is fed by a laser. Such lasers normally operate only in the lowest cavity mode, TEM_{00}, which results in a beam that has a Gaussian distribution of energy with a maximum intensity along its axis of transmission. The beam pattern is tailored such that as the intensity of the beam falls off in amplitude with angular separation from the axis of transmission, no more than a few percent of the beam power is wasted. Two points of reference are the points at which the beam amplitude falls off to either 37% or 13% of the amplitude on axis. These points are called the $1/e$ and $1/e^2$ points respectively and are referred to frequently in the characterization of emitted laser energy patterns. An example of this beam pattern is provided in Fig. 3.

FIGURE 3

Gaussian amplitude curve



The beamwidth at the $1/e^2$ point is given by:

$$\theta\,1/e^2 = \frac{2.44\,\lambda}{D} \tag{9}$$

where:

$\theta\,1/e^2$: beamwidth (rad).

Typical beamwidths are on the order of 1×10^{-5} rad or 5.7×10^{-4} degrees.

For the transmitting terminal, the following equations can be used to calculate the far field radiation pattern of a laser with a Gaussian amplitude plane wave feeding a telescope under the following basic assumptions:

– the laser source is characterized as single mode Gaussian emission; and

– the antenna gain patterns are measured in the far field.

The gain of a telescope of radius "*a*" fed with a Gaussian amplitude plane wave having a waist radius of "ω", where "ω" is the distance from the central axis of the optical system to the $1/e^2$ intensity point, and having a central obscuration of radius "*b*" is given by equation (10). The term, G_0, is the upper limit on antenna gain which is obtained for a uniformly illuminated unobscured circular aperture. The second term, $g_t(\alpha, \gamma, X)$, is a gain efficiency term which accounts for obscuration, truncation, off-axis intensity, and defocusing effects.

$$g_t(\alpha, \gamma, X) = G_0 \cdot g_t(\alpha, \gamma, X) \tag{10}$$

where:

$$G_0 = \frac{4\pi\,A}{\lambda^2} = \left(\frac{2\pi\,a}{\lambda}\right)^2 \tag{11}$$

$$g_t(\alpha, \gamma, X) = 2\,\alpha^2 \left| \int_{\gamma^2}^{1} \mathrm{J}_0\left(X\sqrt{u}\right)\, \mathrm{e}^{-\alpha^2 u}\,\mathrm{d}u \right|^2 \tag{12}$$

A: area of the telescope aperture (m^2)

a: radius of the telescope aperture (m)

λ: wavelength (m)

J_0: Bessel function of the first kind of order zero

α: the ratio, a/ω, of the radius of the transmitter aperture, a, to the radius of the Gaussian feed beam waist, ω, at the $1/e^2$ point

γ: the ratio, b/a, of the radius of the central obscuration, b, to the radius of the transmitter aperture, a

u: the variable of integration

$X = \left(\frac{2\pi}{\lambda}\right) \cdot a \cdot \sin(\theta)$

θ: angle off the optical axis (rad).

For the on-axis, $X = 0$ and the gain efficiency term in equation (12) becomes:

$$g_t(\alpha, \gamma, 0) = \left[\frac{2}{\alpha^2} \left[e^{-\alpha^2} - e^{-\gamma^2 \alpha^2} \right]^2 \right] \tag{13}$$

Then the on-axis maximum main beam gain in equation (10) becomes:

$$G_t(\alpha, \gamma, 0) = \frac{4\pi A}{\lambda^2} \cdot \left[\frac{2}{\alpha^2} \left[e^{-\alpha^2} - e^{-\gamma^2 \alpha^2} \right]^2 \right] \tag{14}$$

Any obscurations will reduce the main beam gain, fill in the nulls, broaden the beamwidth and increase the side lobes.

6.1.1 Example

For example, performance of an optical antenna with an aperture diameter of 15 cm, operating at a frequency of 282.8 THz (a wavelength of 1.06 μm) and no central obscuration is as follows:

$\lambda = 1.06\ \mu\text{m}$

$a = 0.075$ m

$b = 0$

then:

$$\gamma = \frac{b}{a} = 0$$

The gain efficiency term for the on-axis case then becomes:

$$g_t(\alpha,0,0) = \left[\frac{2}{\alpha^2} \left[e^{-\alpha^2} - 1 \right]^2 \right] \tag{15}$$

It has been shown that for optimum performance when there is an obscuration, the relationship between feed beam, α, and γ should follow the relationship in equation (16), which is accurate to within ±1% for $\gamma \leq 0.4$:

$$\alpha = 1.12 - 1.30\,\gamma^2 + 2.12\gamma^4 \tag{16}$$

For the present case with no obscuration, $\gamma = 0$, the equation reduces to $\alpha = 1.12$. The gain efficiency term then becomes:

$$g_t(1.12, 0, 0) = 0.8145 \tag{17}$$

The upper limit of the on-axis gain for this uniformly illuminated unobscured circular aperture of radius 15 cm is then:

$$G_0 = \frac{4\pi A}{\lambda^2} = \left(\frac{2\pi a}{\lambda} \right)^2 = 1.976 \times 10^{11} \tag{18}$$

The maximum on-axis gain is, using equation (10):

$$G_t(1.12, 0, 0) = 1.61 \times 10^{11} \tag{19}$$

The off-axis radiation pattern (dB) for this case becomes, using equation (10):

$$G_t(1.12, 0, X) = 10 \log\left[G_0 \cdot g_t(1.12, 0, X)\right] \tag{20}$$

where:

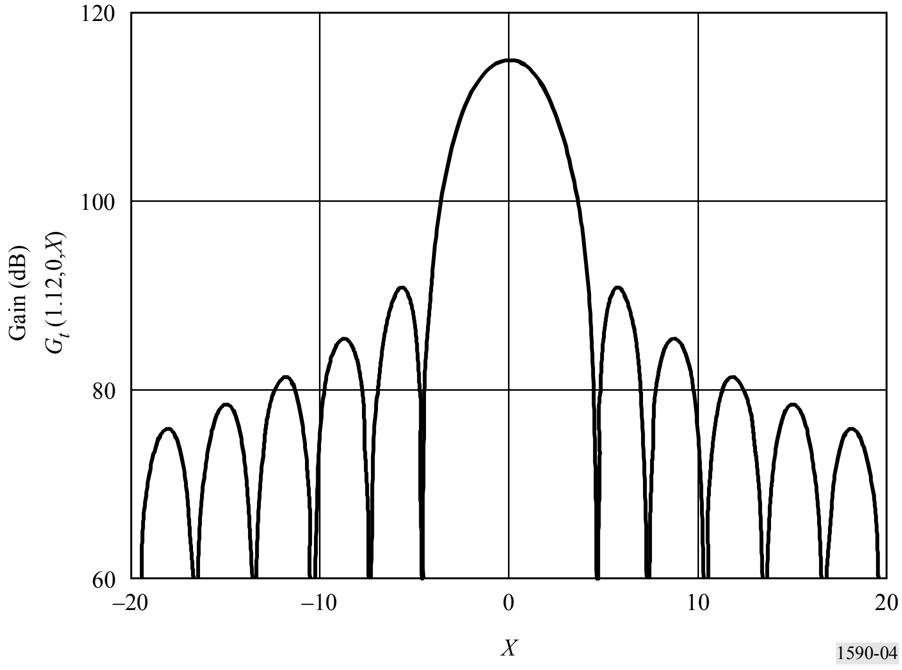
$$g_t(1.12, 0, X) = 2\alpha^2 \cdot \left| \int_0^1 \mathrm{J}_0\left(X\sqrt{u}\right) \cdot \mathrm{e}^{-\alpha^2 u} \mathrm{d}u \right|^2 \tag{21}$$

with:

$$X = \left(\frac{2\pi}{\lambda}\right) \cdot a \cdot \sin(\theta) \tag{22}$$

FIGURE 4

Gain (dB) for a 15 cm diameter antenna



For the above case, the first null occurs at about $X = 4.7$ where $\theta = 10.6$ µrad or 0.0006°. The first side lobe occurs at about $X = 5.6$ where $\theta = 12.6$ µrad or 0.0007° and is down about 27 dB below the main beam gain.

6.2 Receiver antenna

Assuming the receiving aperture is in the far-field of the transmitting antenna, the received energy is normally treated as a plane wave. The receiving system may use a common or separate aperture from the transmitting system. The beamwidth of the receiving aperture is also typically measured in terms of its $1/e^2$ point.

The maximum, on-axis, gain of a receiving antenna, G_R, is given by:

$$G_R = 10 \log \left(\frac{4\pi\, A}{\lambda^2} \right) + 10 \log (1 - \gamma^2) + \delta \tag{24}$$

where:

A: area of the primary mirror (m^2)

λ: wavelength of the incoming signal (m)

and

$$\gamma = \frac{b}{a} \tag{25}$$

where:

a: radius of the primary mirror (m)

b: radius of the secondary mirror (m).

The gain calculated in equation (24) represents the quantity of energy incident on the detector. The term G_R assumes that the receiving antenna is located in the far-field of the transmitter, and the aperture and the detector are round. The first term of equation (24) is the classic antenna gain realized by an ideal unobscured antenna of area A. The second term accounts for losses due to the obscuration introduced by the secondary mirror of a Cassegrain system. In the case of systems without secondary mirrors, the value of b in equation (25) becomes zero and the second term of equation (24) may be neglected. The third term, δ, of equation (24) accounts for losses (dB) due to spillover of the signal energy beyond the edge of the detector.

For direct detection systems, δ reduces as the ratio of the detector size to focal length of the telescope increases. For most practical values, δ will be no more than –0.5 dB. For heterodyne and homodyne systems, δ becomes a function of the distribution of the local oscillator energy across the detector. The detector may receive Gaussian or uniform illumination. For Gaussian and uniform illumination, δ may be closely approximated by equations (26a) and (26b) respectively.

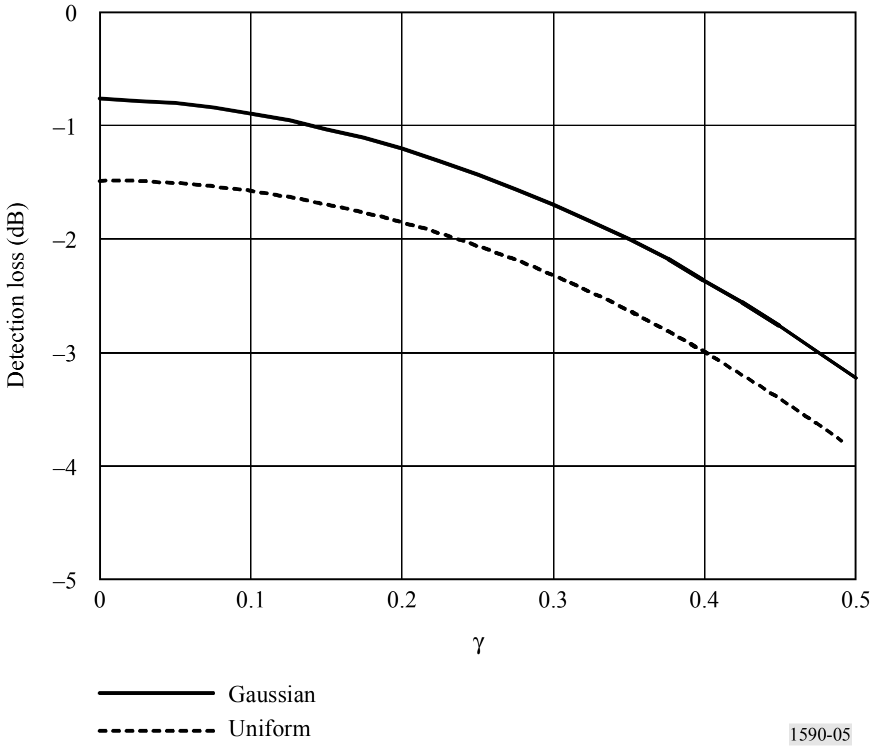
$$\delta = -8.9114\gamma^2 - 0.452\gamma - 0.7621 \tag{26a}$$

$$\delta = -9.5836\gamma^2 + 0.1113\gamma - 1.4937 \tag{26b}$$

Gaussian illumination results in slightly smaller detector losses. For the case of uniform illumination, δ is typically ~0.6-0.7 dB more severe. The effects of detection loss, as given by equations (26a) and (26b) are plotted in Fig. 5.

FIGURE 5

Heterodyne or homodyne detection loss as a function of obscuration ratio, γ



6.2.1 Field of view

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:

$$\varphi = \frac{d}{F} \tag{27}$$

where:

φ: field of view (rad)

d: diameter of the detector (m)

F: focal length of the telescope (m).

The value of φ given in equation (27) relates to the angular width of the $1/e$ point.

6.2.2 Off axis considerations

The pattern of a receiving antenna is typically matched to the detector. The detector is isolated from unwanted energy with the use of field stops and exposed only to the portion of the main beam within φ radians of the axis of the main beam. Therefore, unwanted energy received in the side lobes of the receiving antenna pattern does not arrive at the detector and may be neglected in the course of interference analyses.

6.2.3 Examples

Assume an earth station operating with a uniformly illuminated heterodyne detector and the following physical characteristics:

$f = 353$ THz

$\lambda = 0.85$ μm

$a = 0.50$ m

$b = 0.15$ m

then:

$$A = \pi(0.5^2) = 0.7854 \qquad \text{m}^2$$

$$\gamma = \frac{0.15}{0.50} = 0.3$$

$$\delta = -9.5836(0.3^2) + 0.1113(0.3) - 1.4937 = -2.3$$

$$G_R = 10 \log\left(4\pi \frac{0.7854}{(0.85 \times 10^{-6})^2}\right) + 10 \log(1 - 0.3^2) + (-2.3) = 131.4 - 0.4 - 2.3 = 128.7 \qquad \text{dB}$$

For a spaceborne receiving antenna used with a direct detection system with the following physical characteristics:

a: 0.075 m, and

b: 0.0 m (no secondary mirror)

then:

$A = 0.018$ m^2

$\gamma = 0$, and

$\delta = -0.5$ dB

for

f: 200, 283, 311, and 353 THz

G_R = 109.5, 112.5, 113.4, and 114.5 dB respectively.

7 Reflectivity

Each satellite using an optical link for telecommunications will be illuminated by a laser beam and reflect some of the incident energy. For nearly every optical link there is a return link to provide feedback for correcting the optical pointing. That is, the two links operate as a closed loop control network to maintain optical alignment. Thus, every optical transmitter is illuminated with a return beam that may result in strong reflections. Large solar panels are known to be very reflective and may cause strong reflections in the rare and brief periods when there is proper alignment with an observer. In addition, many of the satellites are covered with a reflective, thermal blanket. These coverings are usually wrinkled and have many small facets with significant reflectivity. This can cause reflections that are strong but concentrated in a very narrow beam.

Typical values for the reflectivity of some of the materials currently used for thermal blankets are given below. These values depend on frequency, especially for semiconductors and metal.

Black Kapton	6% (−12 dB)
Aluminized Mylar	86% (−0.7 dB)
Germanium	50% (−3 dB)
“Gold” Kapton	62% (−2.1 dB)

8 Propagation

Atmospheric propagation in this region of the spectrum is being addressed in Radiocommunication Study Group 3 through Question 228/3 – Propagation data required for the planning of space radiocommunication systems and space science service systems operating above 275 GHz.

9 Earth station location

The performance of earth stations operating at frequencies above 30 THz is strongly influenced by the atmosphere, both by its attenuation and its turbulence. Optimal locations for an earth station are typically at high altitudes, usually at least 2 km above sea level. The high altitude is essential to get above much of the turbulence associated with the atmospheric boundary level. In addition, locations with low humidity are desirable since the humidity can cause significant atmospheric absorption and scatter.