RECOMMENDATION ITU-R SA.1805

Technical and operational characteristics of space-to-space telecommunication systems operating around 354 THz* and 366 THz**

(Question ITU-R 235/7)

(2007)

Scope

This Recommendation specifies technical parameters (frequencies, link direction, signal and data characteristics, antenna parameters, etc.) and operational characteristics of telecommunication systems operating in the space-to-space direction around 354 THz and 366 THz, which could be used in sharing studies.

The ITU Radiocommunication Assembly,

considering

a) that telecommunication links are planned for use on some satellite systems for inter-orbit telecommunication at frequencies in the region of 354 THz and 366 THz;

b) that using recent technological developments, astronomers are making a concerted effort to build telescopes and make observation in this segment of the spectrum;

c) that this segment of the spectrum is also being used for other terrestrial and space services;

d) that this segment of the spectrum is also being used for scientific and industrial purposes other than telecommunication,

recommends

1 that sharing studies considering space research satellites operating in the space-to-space direction around 354 THz and 366 THz should take into account the technical and operational parameters presented in Annex 1.

Annex 1

1 Introduction

Due to increased pressure for use of the electromagnetic spectrum and the advancement of technology, there is more attention being given to the use of frequencies above 3 000 GHz for free-space telecommunications. Free-space telecommunication at frequencies above 3 000 GHz has the ability to support higher data rates with less mass than traditional RF systems as well as meet gain and directivity requirements of beams used for space-to-space applications.

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* 1 THz = 1 000 GHz.

** This Recommendation should be brought to the attention of Radiocommunication Study Group 1.

1.1 Frequency considerations

Currently, most of the interest in free-space telecommunications links above 3 000 GHz 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 most widely used for telecommunications in optical fibres. For inter-orbit telecommunication, attention is being focused on the use of high power semiconductor lasers operating around 0.850 μm or the use of a semiconductor laser beam amplified by an Erbium-doped (Er) fibre-optical amplifier (EDFA) at the wavelength of 1.5 μm. The system with semiconductor lasers operating around 0.85 μm is superior to that with EDFA in reliability and power consumption for relatively low data-rate applications which do not require high transmitter power.

1.2 Generic mission parameters

Technical parameters suitable for interference analyses should be based on generic inter-orbit telecommunication links near the Earth. Therefore, link distances will be between a few to several hundred thousand km. A summary of the fundamental technical parameters around 354 THz and 366 THz near-Earth inter-orbit telecommunication link is provided in Table 1.

TABLE 1

Technical parameters of a reference inter-orbit telecommunication system operating around 354 THz and 366 THz in the space-to-space direction

Parameter	Forward link	Return link
Transmitter power (mW)	10	40
Transmitter aperture (cm)	25	26
Transmitter frequency (wavelength) (THz)	Comm: 366 (0.819 μm) Beacon: 374 (0.801 μm)	354 (0.847 μm)
Modulation	2PPM	NRZ
Pointing accuracy (μrad)	± 2.6 (3σ)	
Range in free space (km)	up to 40 000	
Data rate (Mbit/s)	2.048	49.3724
Receiver aperture (cm)	26	25
Detector type	APD detector	APD detector

APD: avalanche plid-o-diode

NRZ: non-return to zero

PPM: parts per million

2 Link considerations

Inter-orbit links are established between a goesynchronous Earth orbit (GEO) satellite and a low-Earth orbit (LEO) satellite in the space-to-space direction, operating around 366 THz for the forward link and 354 THz for the return link. A beacon signal at 374 THz is emitted to assist with telescope pointing and tracking.

2.1 Link performance

Like a space-to-space system operating in the traditional RF spectrum, performance of a link operating around 354 THz and 366 THz is measured in terms of data rate andBER. Performance is calculated as a function of power, telescope quality, propagation considerations, noise and receiver sensitivity. Each of these parameters is a function of additional variables.

2.1.1 BER

Frames of data must have a BER of less than 10^{-6} after error correction in order to be retained. A link must retain 99% of data frames.

2.1.2 Margin requirement

The typical margin requirement of an inter-satellite link operating around 354 THz and 366 THz is on the order of 1 to 3 dB.

2.2 Modulation

The return link operating around 354 THz utilizes NRZ. The forward link operating around 366 THz utilizes 2PPM. This modulation technique allows for direct detection by the receiver rather than implementing coherent receivers.

2.3 Received signal

The general method for calculating the signal level around 354 THz and 366 THz received by the space-to-space station is the same as that used with traditional RF systems.

$$P_S = P_t + G_t + G_r + L_t + L_r + L_p + L_S \qquad \text{dBW} \qquad (1)$$

where:

P_S: received signal power (dBW)

P_t: average laser output power (dBW)

G_t: transmitter antenna gain (dBi)

G_r: receiving antenna gain (dBi)

L_t: transmitter losses (dB)

L_r: receiver losses (dB)

L_p: pointing losses (dB)

L_s: free-space loss (dB).

2.4 Link losses

– L_t includes the effects of absorption, scattering and reflection losses in the optical system of the transmitter;

– L_r includes the effects of absorption, scattering, and reflection losses in the optical train of the receiver;

– L_p includes the effects of antenna or satellite jitter and mispointing of the transmitting antenna;

– L_s is due to the physical separation between the transmitter and receiver.

Values of each source of loss vary with hardware design, hardware age, mission requirements and the phase of the mission. Suggested values of losses to be used in generic interference analyses are provided in Table 2.

TABLE 2

Link losses of a reference inter-orbit telecommunication system operating around 354 THz and 366 THz in the space-to-space direction

Mechanism of loss	Typical value
Transmitter losses, L_t	0.63 (= –2 dB)
Receiver losses, L_r	0.5 (= –3 dB)
Pointing losses, L_p	0.5 (= –3 dB)

Free-space loss, L_s, is calculated around 354 THz and 366 THz in the same manner as with traditional radio-frequency systems.

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

where:

R: distance between the transmitter and receiver (m)

λ: wavelength (m)

f: optical frequency (Hz)

c: speed of light (m/s).

2.5 Transmit/receive telescope parameters

Telecommunication links operating around 354 THz and 366 THz utilize telescopes as transmitting and receiving antennas. The transmitter and receiver antenna patterns are also different since the transmitter optics are usually fed by a Gaussian distributed beam while the receiver optics use a planar detector. For an envelope of the antenna gain patterns of transmitting and receiving antennae operating around 354 THz and 366 THz see Annex 2 of Recommendation ITU-R SA.1742. A reference antenna gain pattern for space-to-Earth optical systems operating at 283 THz is provided in Recommendation ITU-R SA.1742. This pattern is also applicable for space-to-space systems operating around 354 THz and 366 THz.

2.5.1 Diameter

For the purposes of interference analyses, the diameter of the optical antenna should be assumed to be 26/25 cm. The aperture will either be unobstructed or have a 5 cm obscuration.

2.5.2 Transmitting gain pattern

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 per cent of the beam power is wasted. Two points of reference are the angles 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.

The full-angle beamwidth at the 1/e^2 point is approximated by:

$$\theta_{1/e^2} = \frac{4\lambda}{\pi D} \quad \text{rad} \tag{3}$$

where:

θ_{1/e^2}: angular width of the beam at the 1/e^2 point (rad)

D: diameter of the aperture (m).

In the case of a 354 THz Gaussian beam transmitted from a 26 cm aperture, the beamwidth at the 1/e^2 point is approximately 4.1×10^{-6} rad.

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. Use of these equations makes the following basic assumptions:

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

– the antenna gain patterns are measured in the far field; and

– the aperture is circular.

The gain pattern of a transmitting 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 (4) below. 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.

$$G_t(\alpha, \gamma, X) = G_0 g_t(\alpha, \gamma, X) \tag{4}$$

where:

$$G_0 = \frac{4\pi A}{\lambda^2} = \left(\frac{2\pi a}{\lambda}\right)^2 \tag{5}$$

$$g_t(\alpha, \gamma, X) = 2\alpha^2 \left| \int_{\gamma^2}^{1} J_0\left(X\sqrt{u}\right) e^{-\alpha^2 u} \, \mathrm{d}u \right|^2 \tag{6}$$

$$\gamma = \frac{b}{a} \tag{7}$$

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

a: radius of the telescope mirror (m)

b: radius of the secondary mirror (m)

g_t: gain efficiency

J_0: Bessel function of the first kind of order zero

α: the ratio, a/ω

γ: obscuration ratio

u: the variable of integration

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

θ: angle of the optical axis (rad).

For the on-axis, $X = 0$ and the gain efficiency term in equation (6) becomes:

$$g_t(\alpha, \gamma, 0) = \left[\frac{2}{\alpha^2} \left[e^{-\alpha^2} - e^{-\gamma^2 \alpha^2} \right]^2 \right] \quad (8)$$

Then the on-axis maximum main beam gain in equation (4) becomes:

$$G_t(\alpha, \gamma, 0) = \frac{4\pi A}{\lambda^2} \left[\frac{2}{\alpha^2} \left[e^{-\alpha^2} - e^{-\gamma^2 \alpha^2} \right]^2 \right] \quad (9)$$

Any obscuration (b) will reduce the main beam gain, fill in the nulls, and increase the side-lobes.

2.5.3 Receiving gain pattern

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:

$$\varphi = \frac{d}{F} \quad (10)$$

where:

φ: field of view of the detector (rad)

d: diameter of the detector (m) (typically 10^{-4} to 10^{-3} m)

F: focal length of the telescope (m).

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.

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:

$$G_R = 10 \log\left(\frac{4\pi A}{\lambda^2}\right) + 10 \log\left(1 - \gamma^2\right) + \delta \quad \text{dBi} \quad (11)$$

where:

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

λ: wavelength (m)

δ: losses due to energy spilling over the edge of the detector (dB) and:

$$\gamma = \frac{b}{a} \tag{12}$$

where:

a: radius of the telescope mirror (m)

b: radius of the secondary mirror (m).

The gain calculated in equation (11) 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 (11) 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 (12) becomes zero and the second term of equation (11) may be neglected.

The third term, δ, of equation (11) accounts for losses (dB), due to spill over of the signal energy beyond the edge of the detector. For direct detection systems such as PPM, 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.

2.6 Pointing and tracking

The narrow beamwidth and long range of a space-to-space link operating at around 354 THz and 366 THz impose strict pointing and tracking requirements on a system. Typical pointing requirements are determined by the divergence of the telecommunication beam. For the reference system outlined in Table 1, this equates to 2.6 µrad and a pointing loss of no more than 3 dB.

3 Signal-to-noise ratio (*S*/*N*)

The performance of space-to-space telecommunication links operating around 354 THz and 366 THz depends directly on achieving a high S/N at the receiver. The higher the S/N, the lower the BER.

In general:

$$S / R = \frac{P_s}{N_t} \tag{13}$$

where:

P_s: received signal power as given by equation (1)

N_t: noise power from all sources.

Noise comes from two independent sources, detector noise and the background signal. The background signal is due to extraneous energy of albedo and the light from the Sun, planets or stars reaching the detector. Detector noise, discussed in § 3.1, is due to the inherent noise within the detector.

The basic equations describing the performance of a laser optical crosslink 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.

3.1 Detector noise

A direct detection receiver with an APD is used for 354 THz and 366 THz telecommunication systems. APD detectors normally operate in one of two noise-limited detection regions. Detectors receiving high input power levels are generally limited by photon shot noise. However, detectors receiving low input power levels are detector noise limited. The *S*/*N* for the commonly used APD followed by a next-stage amplifier in a direct detection system is developed below.

Calculate the excess noise factor, N_E, by:

$$N_E = Gk + \left(2 - \frac{1}{G}\right)(1-k) \tag{14}$$

where:

N_E: excess noise factor
G: gain
k: electron/hole ionization rate.

The *S*/*N* may then be calculated by:

$$S/N = \frac{G^2 R_D^2 P_S^2}{2eG^2 B(N_E)(R_D P_S + i_B) + 2ei_S + 4N_A B_F \left(\frac{k_B T}{R_L}\right)} \tag{15}$$

where:

e: electron charge (1.6×10^{-19} coulomb)
P_S: received signal power (W)
R_D: APD responsivity
k_B: Boltzmann's constant (1.38×10^{-23} J/K)
T: temperature (K)
i_S: surface dark current in the detector (A)
i_B: bulk dark current in the detector (A)
R_L: resistance of the transimpedance amplifier (Ω)
N_A: noise figure of amplifier
B: filter bandwidth (μm)
B_F: filter bandwidth (Hz).