Space Laser Communications:
Systems, Technologies, and Applications

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Abstract: Laser communication links in space are attractive alternatives to present-day microwave links. This tutorial describes the basic concept and the functions of an optical terminal on board a spacecraft. It points out the differences between free-space optical links on one hand and glass fiber systems and microwave directional links on the other hand. The requirements on data transmitters and receivers as well as on optical antennas and pointing, acquisition and tracking mechanisms are discussed. Typical application scenarios are outlined, experimental systems and their technologies are cited.

Key Words: laser communications, free space, intersatellite links, space communication, space networks

1. Introduction

Communication technology has experienced a continual development to higher and higher carrier frequencies, starting from a few hundred kilohertz at Marconi's time to several hundred terahertz since we employ lasers in fiber systems. The main driving force was that the usable bandwidth - and hence transmission capacity - increases proportional to the carrier frequency. Another asset comes into play in free-space point-to-point links. The minimum divergence obtainable with a freely propagating beam of electromagnetic waves scales proportional to the wavelength. The jump from microwaves to light waves therefore means a reduction in beamwidth by orders of magnitude, even if we use transmit antennas of much smaller diameter. The reduced beamwidth does not only imply increased intensity at the receiver site but also reduced cross talk between closely operating links and less chance for eavesdropping.

Space communication, as employed in satellite-to-satellite links, is traditionally performed using microwaves. For more than twenty five years, however, laser systems are being investigated as alternatives. [1-3] One hopes that mass, power consumption, and size of an optical transceiver module will be smaller than that of a microwave transceiver. Also, fuel consumption for satellite attitude control when quickly re-directing antennas should be less for optical antennas. On the other hand, a new set of problems had to be addressed in connection with the extreme requirements for pointing, acquiring, and tracking the narrow-width laser beams.

In this tutorial we will first discuss the basics of an optical free space link (Sect. 2) and then point out the differences to terrestrial fiber systems and to microwave links in Sect. 3. Section 4 presents the requirements for and the available technologies to implement transmitters, receivers, optical antennas, as well as the PAT system (PAT...pointing, acquisition, and tracking). Next we sketch application scenarios, and we conclude with both a glimpse onto past and future system technologies.

2. System Layout

A scenario typical for the transmission system in question asks for point-to-point data transfer between two spacecraft (see Fig. 1). The distances to be bridged may extend anywhere from a few hundred kilometers to 70 000 km (e.g. in near-earth applications) up to millions of kilometers in case of signals transmitted by a space probe.[4] Today the data rates in mind range from several hundred kbit/s to some 10 Gbit/s.

Terminals for optical communication in space are mostly designed for bi-directional links, at least concerning the optical tracking function. They comprise both a transmitter and a receiver that generally share the optical antenna. Another peculiarity is the necessity of beam steering (or pointing) capability with sub-microradian angular resolution and possibly with an angular coverage exceeding a hemisphere.

These requirements lead to a transceiver block diagram as shown in Fig. 2. The light source S is a laser, preferably operating in a single transverse mode in order to achieve the highest possible antenna gain. If the laser operates continuously or in a pulsed mode producing a periodic pulse train, an external modulator (M) is utilized to impress the data signal onto the beam. Alternatively, internal modulation may be employed with some lasers. The modulated beam passes an optical duplexer (DUP) and a fine pointing assembly (FPA) before it enters a telescope acting as

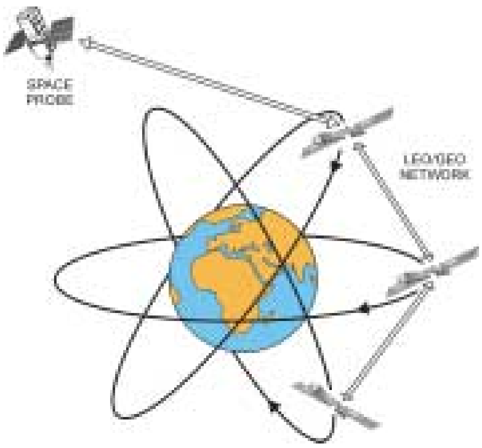

Fig. 1 A scenario of laser communication links in space.

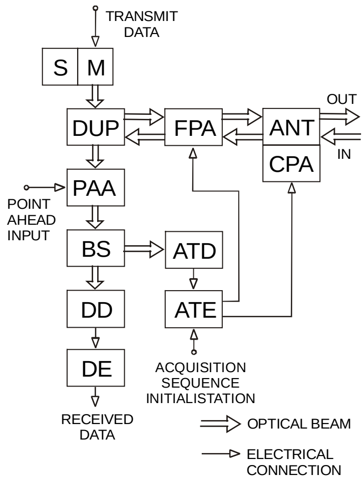

Fig. 2 Block diagram of optical transceiver for space-to-space links (S..laser source, M..modulator, DUP..optical duplexer, FPA..fine pointing assembly, ANT..antenna, CPA..coarse pointing assembly, PAA..point ahead assembly, BS..beam splitter, DD..data detector, DE..data electronics, ATD..acquisition and tracking detector, ATE..acquisition and tracking electronics).

transmit antenna (ANT). The telescope increases the beam diameter and thus reduces the beam divergence. A coarse pointing assembly (CPA) provides for steering the antenna.

The received radiation also passes the antenna and the fine pointing assembly, and is then directed to the receive part of the terminal with the aid of the duplexer. A beam splitter (BS) directs one part of the received beam to the data detector (DD) for demodulation and further signal processing in the data electronics unit (DE). Another part of the received power is used for controlling the fine and coarse pointing mechanisms in such a way that the acquisition and tracking detector (ATD) is always hit centrally. A point-ahead assembly (PAA) has to be inserted in either the transmit path or the receive path to allow electronic control of the internal angular alignment between transmission and reception (see Sect. 3.2).

It should be stressed that the block diagram of Fig. 2 shows only a basic outline and that it may be modified in several respects. Among such modifications are:

– the provision of separate laser sources to generate extra beams for acquisition and for tracking (beacon lasers),
– separate antennas for the outgoing and the incoming beam,
– means to deliberately increase the divergence of the beam used as beacon in order to illuminate the opposite terminal during the acquisition process,
– the provision of separate photodetectors for acquisition and for tracking, or the use of a single photodetector for data detection, acquisition, and tracking,
– the installation of an optical booster amplifier to increase the output power.

In any case, the task of engineering a laser terminal may be divided into three major complexes, namely

– one covering the data transmission aspects,
– one providing for pointing, acquiring and tracking (PAT) the very narrow laser beams,
– and one of designing space-qualifiable opto-mechanical structures and proper interfacing with the spacecraft platform.

While each of them requires a sophisticated concept, it should be stressed here that the problems associated with PAT are generally underestimated.

3. Peculiarities

Some of the readers may be more familiar with fiber-based optical transmission systems, others with conventional satellite links employing microwaves. The following two sections serve to point out basic differences of laser space communications with these systems.

3.1 Differences to fiber systems

While in fiber systems dispersion and non-linearity is a major concern, no such effects exist for the free space channel. Coupling the transmit signal into the channel - which is free space - requires an antenna, usually in the form of a telescope. Further, background radiation - e.g. caused by the Sun - may pose a problem, and, of course, no in-line amplifiers or regenerators can be implemented.

If a space link is to sustain data transmission in both directions simultaneously and if the terminal has only a single antenna, a duplexing element must separate the transmit and the receive beam in the transceiver (see Fig.2). The degree of isolation it has to provide for the transmit beam not to reach the own terminal's data receiver is quite large: For a transmit power of 500mW and a receive power of 5 nW, the degree of isolation should clearly exceed 90 dB to make cross talk negligible. Extremely low stray light levels of the duplexer are an essential prerequisite. Duplexers can be based on spectral discrimination (i.e. filtering), on polarization diversity, or on both. Hence a common suggestion is to use left hand and right hand circularly polarized light for the two directions, respectively. This also makes the transmission insensitive against rotation of the terminals along their antenna axes. Because polarization duplexing will provide only some 15 dB of isolation, wavelength duplexing must be designed into the system in any case.

For the general case that both terminals experience a relative velocity along the line-of-sight, v_D, the Doppler effect will yield a frequency shift Δf in the received signal. As long as $v_D \ll c$ (c ... velocity of light), one has $\Delta f = v_D/\lambda$ where λ is the carrier wavelength. In a LEO-GEO* link, v_D may amount up to some $\pm 8 \cdot 10^3$ m/s. Because of the small wavelength, the resulting Doppler shift is large and amounts up to $\pm$ 7.5 GHz at $\lambda = 1.06$ µm for the example cited. Such a large frequency shift might be negligible in a direct detection receiver (as long as no extremely narrow optical filtering is applied). In a heterodyne receiver,** however, the frequency shift has to be compensated by either tuning the local laser oscillator, by tuning the electrical oscillator in a second intermediate frequency stage, or by both.

In space applications - even more than in undersea fiber systems - reliability and lifetime is of special importance. As examples, the laser source itself or a (cooled) detector may represent a weak point concerning reliability and thus require redundancy. Other subunits, like the telescope or the coarse pointing assembly may be too bulky and present such a high fraction of the mass budget that a single failure point is accepted in their case.

3.2 Differences to microwave systems

At a first glance, the equation governing the amount of power received in an optical directional link, P_R, is the same as one knows from microwave links, namely

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi R} \right)^2 L_T \, L_R \, L_P \, . \qquad (1)$$

Here P_T is the optical output power generated at the transmitter, G_T and G_R are the gain values of the transmit and receive antenna, λ is the carrier wavelength, R the distance between the terminals and the factors L_T and L_R cover the loss within the transmit and receive terminal. However, the last factor, L_P, which accounts for loss caused by non-ideal pointing, may correspond to several dB in a free-space laser link: Because of the extremely small beamwidths involved in optical links, transmit and receive antenna will, in general, not yield their maximum gain. Despite the implementation of an active tracking control loop to align the antenna axes, some mispointing will persist and the receive intensity will vary statistically.

To a first approximation, the antenna gains G_T, G_R are related to the diameters of the (circular) transmit and receive antenna, D_T, D_R as

$$G_{T,R} = \left(\frac{\pi D_{T,R}}{\lambda} \right)^2 \, . \qquad (2)$$

Substituting (2) into (1) reveals the $1/\lambda^2$-dependence of receive power P_R which makes the optical regime so attractive compared to microwaves. Equation (2) is applicable in case of diffraction limited antenna operation. The full beam divergence then obtained is on the order of

$$\theta \approx \frac{\lambda}{D_T} \, . \qquad (3)$$

The very small beamwidths θ at optical frequencies (some 5 µrad for typical values of λ and D_T) are, of course, the reason for the high antenna gain achievable (some 115 dB). However, this advantage is not gained for free: Establishing and maintaining contact with extremely narrow beams is a tough task, especially if transmitter and receiver change their relative position (see Sect. 4.4).

One critical aspect of intersatellite laser communications with narrow beams results from the need to introduce a point ahead angle. Because of the finite velocity of light (c) and the relative angular velocity of two communication terminals moving in space, the transmit beam must be directed towards the receiver's position it will have at some later time. This point ahead angle is given by [5)]

$$\beta = \frac{2 \, v_R}{c} \, , \qquad (4)$$

where v_R is the relative velocity component of transmitter and receiver, orthogonal to the line-of-sight, as illustrated in Fig. 3. Point ahead is generally required in both dimensions. It amounts up to 40 µrad for a GEO-GEO link and up to 70 µrad for a LEO-GEO link and may thus be appreciably larger than the beamwidth. The point ahead angle can be introduced in either the receive or the transmit path of each transceiver and must be adjustable if v_R varies with time. It is difficult to design a control loop for automatic adjustment of point ahead. Therefore today's concepts rely on the calculation of point ahead angles from known ephemeris data and on open loop implementation.

4. Requirements and technology

4.1 Data transmitter

The main parameters characterizing the optical source are wavelength, output power, transverse mode,

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* LEO..low earth orbiting (satellite), GEO..geostationary (satellite), see also Sect. 5

** see Sect. 4.2

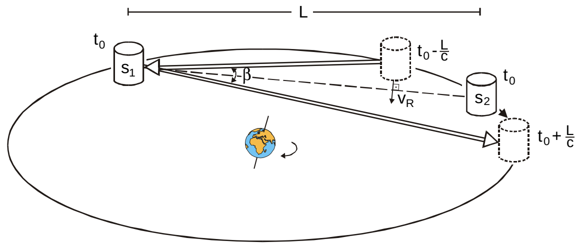

Fig. 3 Point ahead angle β for space craft S1 and S2 that have a relative velocity component vR orthogonal to the line of sight. Shown with dotted lines: position of S2 at time instants indicated (L..distance, c..velocity of light).

polarization, linewidth, and modulation capability. A smaller wavelength requires increased surface quality of optical elements which in turn asks for bulkier devices if diffraction limited operation is essential. Thus the mass of the antenna (and hence the load for the coarse pointing assembly) is strongly influenced by the choice of λ. Also, the wavelength dependence of the sensitivity of available optical receivers must be considered. The output power will have to be in the range of 100 mW and 1 W, depending on the link distance and data rate. It should be available in a single transverse mode to achieve maximum on-axis antenna gain, and in a single longitudinal mode to obtain optimum spectral efficiency. For coherent reception, phase noise is detrimental and thus a narrow linewidth of both the transmitter laser and the local laser oscillator in the receiver is required. The usually linear state of polarization emitted by the laser source is to be converted into circular polarization before the beam leaves the terminal (see Sect. 3.1). Modulation may be achieved directly (e.g. in case of diode lasers and moderate data rates) or with an external modulator. Especially in connection with a subsequent optical booster amplifier, the insertion loss introduced by an electro-optic or acousto-optic modulator may be tolerable. As with fiber systems, binary modulation formats are envisaged for space links. In connection with a coherent receiver, phase shift keying (and possibly frequency shift keying) is an attractive alternative to on-off keying, as it makes better use of the carrier power.

4.2 Data receiver

For space applications, good receiver sensitivity is an extremely valuable asset, not at least because no in-line amplification is possible. It is often characterized by the minimum number of input photons per bit to achieve a bit error probability of 10^{-6}. If other sources of noise than that due to the quantum nature of radiation are negligible, a direct detection receiver needs $n = 6.6$ photons/bit. As an example for a coherent receiver, a homodyne receiver with PSK modulation would require $n = 5.6$ photons/bit.[***] To what extent this quantum limit is reached in practice depends on the engineer's ability to make negligible the effect of other noise contributions, as there is

– excess noise in avalanche photodiodes (APDs),
– optical preamplifier noise (amplified spontaneous emission),
– transistor noise and circuit noise in the receiver electronics,
– laser phase noise,
– transmit-receive cross coupling,
– background radiation.

Today direct receivers employing APDs can be used up to 2.5 Gbit/s. Their sensitivity is determined by electronic and by multiplication noise and may be less than 100 photons/bit at low data rates.[6)] With optical preamplification by an Erbium-doped fiber amplifier, direct receivers have shown sensitivities of 40 photons/bit at 10 Gbit/s.[7)]

With coherent reception, the received optical field is transposed into the electrical regime (intermediate frequency, IF) by mixing it with the field of a local laser oscillator.[8)] A photodetector serves as mixer element. Information is preserved not only about amplitude but also about frequency and phase of the received field, hence frequency and phase modulated optical signals can be detected, too.[†] As optical mixers have sensitive areas with dimensions large compared to the wavelength, in the optical regime the spatial modes of received and local field have to be matched to obtain maximum IF signal. Matching requires identical polarization and asks for equal amplitude and phase distribution, the latter two optimized with respect to the mixer element.

Coherent receivers perfectly reject radiation from other than the nominal input direction. Equally well they discriminate against unwanted spectral components by their IF filter. Therefore they are *a priori* less sensitive against background radiation and cross talk.[††] An experimental heterodyne receiver with phase shift keying at 565 Mbit/s has demonstrated a sensitivity of 22 photons/bit.[9)]

4.3 Antennas

The transmit antenna is essentially a telescope which magnifies the diameter of the beam emitted by the laser (or by a booster amplifier). This beam is generally well modeled by a Gaussian intensity distribution. The antenna will not only introduce truncation via its finite diameter D_T but may also cause some central obscuration, depending on the telescope's construction. These two effects reduce the ideal on-axis antenna gain given by equ. (2) by typically 1.5

[***] In both cases binary signaling and equally probable marks and zeros are assumed.

[†] For high-data rate frequency-shifted and differential-phase-shifted signals, optical demodulation in combination with a direct receiver is feasible, too.

[††] The same degree of spatial and spectral filtering is obtained with a direct receiver equipped with a singlemode spatial filter (e.g. a fiber preamplifier) and an optical filter matched to the data spectrum.

dB.[10] The antenna pattern resembles that of an Airy pattern. Alignment tolerances of the optical elements constituting the telescope are usually very tight, as the output beam has to be perfectly collimated for maximum gain.

The main specifications of the optical antenna are: diameter of primary mirror (or lens), magnification, aberrations, wavelength dependence of throughput, sensitivity to temperature changes and gradients, and stray light level. Usually, refractive telescopes are envisaged in case of small diameters while reflective systems are preferred for diameters exceeding several centimeters. With increasing antenna aperture it becomes more and more difficult (and expensive) to meet specifications. Large antennas will also increase the mass and size of an optical transceiver considerably, as the telescope and the coarse pointing assembly do contribute appreciably to these characteristics. Presently it is felt that the diameter of diffraction limited antennas should not exceed some 25 cm for free-space laser links. Coarse pointing may be accomplished via gimbal mounting the antenna or by a separate unit consisting of two orthogonally mounted steering mirrors or one gimbaled reflector.

4.4 Pointing, acquisition, and tracking.

To establish an optical link in space, a sophisticated spatial pointing and acquisition procedure must be initiated. Information on the position of the two space terminals has to be available. Still, because of position uncertainty and incomplete knowledge of the spacecraft's orientation (attitude uncertainty), one terminal's beam width has to be widened deliberately as to illuminate the second terminal despite the uncertainty in position. A spatial search operation by the (narrow beam) receive path of the second, and subsequently, of the first terminal have to follow before acquisition is completed and switching to the tracking mode can occur. Wide-field-of-view acquisition detectors in the form CCDs are most helpful.

During data transmission, the angle between the line-of-sight and the transmit beam axis must be kept to within a fraction of the transmit beamwidth θ which may be as small as a few µrad. To maintain sufficient alignment of the transmit and receive antennas despite platform vibrations, both terminals have to be equipped with a tracking servo loop. Optical beacons have to be provided in both directions to render input information for the control loops. The data carrying beams themselves may serve as beacon, or separate optical beams may be implemented, e.g. in a one-way link. Tracking should ensure a mispointing of typically less than 1 µrad. Whenever the tracking loop signals optimum receive position, the transmitted beam (or beacon) will be correctly directed to the opposite terminal. This would require a perfect coaxial alignment for the optical transmit and receive path within each transceiver. However, some bias, or point ahead angle, has in general to be introduced into the alignment, as was discussed in Sect. 3.2. To ensure short acquisition time and adequate tracking accuracy, sufficient optical power for the acquisition and the tracking process must be received.

5. Application scenarios

One of the first scenarios considered was a bi-directional, symmetric link between two geostationary satellites (GEOs). The orbital distance between the GEO satellites may lie anywhere between a few degrees and some 120°, corresponding to distances between a few thousand kilometers and 75 000 km (see Fig. 4a). Such a link has the attractive features of a single (or very seldom) acquisition process, of a nominally zero Doppler shift, and of low angular tracking velocities. Connections to ground stations could be performed with microwaves.

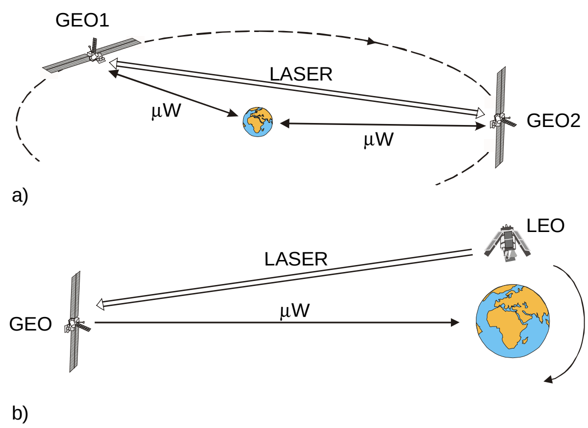

Fig. 4 Two geostationary satellites (GEO1, GEO2) are connected by a laser duplex link (a). A low-earth orbiting satellite (LEO) transmits data via a laser link to a GEO acting as data relay (b). In both cases the downlink is via microwaves (µW).

Large data streams generated on a low-earth-orbiting satellite (a LEO, with a distance to ground of less than 1000 km) may advantageously be transmitted to a GEO acting as a relay before being directed to the earth via microwaves (see Fig. 4b). Distances for this asymmetric link may be as large as 45 000 km. The concept allows continual data transfer to a single earth station for at least half a LEO orbit.

Another use of a laser data link was already included in the upper part of Fig. 1. Characterized by very large distances (e.g. millions of kilometers) and by relatively low data rates (e.g. some 100 kbit/s), such a link would serve to transfer data from interplanetary and deep space probes to relay satellites orbiting the earth. This relay could be equipped with a large receive telescope. Further transport to ground stations would use microwaves. As an alternative, an optical ground station would receive the probe's data after passage through the atmosphere.

For satellite networks now being planned or established to serve mobile data transfer, interconnectivity at very high data rates could be achieved by optical links (see Fig. 1). Frequency allocation problems - as they persist increasingly for radio links - are practically non-existent, with the merit of negligible mutual interference. Another advantage is the expected smaller mass and volume of optical terminals.

6. System technologies

The almost three decades of efforts towards intersatellite laser links have seen various technologies,[1-3] starting from those based on lamp-pumped, mode-locked Nd:YAG lasers,[11] on CO_2 lasers [5] operating at λ = 10 µm, on GaAlAs diodes (0.85 µm), up to those employing diode-pumped Nd:YAG lasers (λ = 1.06 µm) [12] and InGaAsP semiconductors operating at λ = 1.5 µm.

Only a few experimental systems have been launched so far. The European space agency, ESA, has put a terminal on SPOT IV, a LEO earth observation satellite.[13] It employs a diode laser at λ = 0.85 µm and shall transmit data at 50 Mbit/s. The counter terminal still awaits its launch on board of the GEO satellite ARTEMIS. The development of this system, dubbed SILEX (semiconductor laser intersatellite link experiment), started as early as 1985. Japan will participate in this experiment by launching, in 2001, a dedicated satellite named OICETS. This LEO satellite is equipped with an optical terminal to communicate with ARTEMIS. - Between 1994 and 1996 a laser link was tested between a terminal placed on the Japanese test satellite ETS-VI and ground stations in Tokyo and in California, although the satellite did not reach the intended GEO orbit but a highly elliptical one.[14] The down link operated with a diode laser, the up link with an Argon laser.

For future applications, systems based on Nd:YAG lasers [12] and on diode lasers at 1.5 µm in connection with Erbium-doped fiber amplifiers [7] are investigated presently. With the specific properties inherent to these laser sources, they lend themselves especially to coherent detection and to optically pre-amplified direct detection, respectively.

In the future one should take into consideration not only recent technological developments like optical demodulation of phase modulated signals, the use of low-duty-cycle return-to-zero coding, or a combination of both. One should also give serious thoughts to use the large, mature, and reliable technology base commercially available in the 1.5 µm band. Only then one can hope to achieve economy in medium-scale applications like intersatellite networks.

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