New trends in laser satellite communications: design and limitations

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ABSTRACT

Optical communications offer a capable alternative to radio frequency (RF) communications for applications where high data-rate is required. This technology is particularly promising and challenging in the field of future inter-satellite communications. The term laser satellite communications (LSC) stands for optical links between satellites and/or high altitude platforms (HAPs). However, optical links between an earth station and a satellite or HAPs can be also involved. This work gives an overview of nowadays laser satellite communications. Particularly, it is focused on the factors causing degradation of the optical beam in the atmosphere. If an optical link passes through the atmosphere, it suffers from various influences such as attenuation due to absorption and scattering, intensity fluctuations due to atmospheric turbulence and background radiation. Furthermore, platform vibrations cause mispointing and following tracking losses. Suitable devices and used pointing and tracking system for laser satellite communications are discussed. At the end, various scenarios of the optical links and calculations of their power link budgets and limitations are designed. Implemented software is used for calculation of optical links. This work proves that the Free Space Optics (FSO) systems on mobile platforms, like satellites and HAPs are a promising solution for future communication networks.

Keywords: laser satellite communications, high altitude platforms, optical inter-satellite links.

1. INTRODUCTION

The optical links in free space have inherent advantages over the RF links, such as wider bandwidth, a larger capacity, equipment that is more compact, lower power consumption, greater security against eavesdropping, immunity from interference, no regulatory restrictions for using frequencies and bandwidths, and the higher gain then comparable RF links. On the other hand, the drawbacks of the optical links are complexity of the tracking system due to narrower beam divergence angle and related propensity to mispointing. The design of optical communication systems in free space is very comprehensive task. It could be approached from various viewpoints. We have focused our work on calculations of a power link budget of different optical link scenarios. In the section 2, the procedure of determination of the link budget calculation and resulting budget diagram is given. The source [1] with some other contributions is mainly used. Designed software, which also utilizes equations referenced in section 2, is used for calculation of optical links in the sections 3 to 4. These links connects an earth station, HAP and satellites. In all cases, vertical (slant) paths are considered. On the other hand, a horizontal link between two HAPs is deeply examined in the section 4. The current limitations of the FSO systems are presented in section 5, and finally the conclusions.

2. LINK BUDGET

The link budget is a calculation of all of the gains and losses between the transmitter and the receiver in a telecommunication system. The geometrical loss of transmitted signal because of propagation, as well as the loss or gain because of the antenna and many others link parameters are taken into account. The main parameters for the optical link budget calculations are shown in Figure 1. The link budget contains relative parameters in (dB) and absolute parameters in (dBm). The parameters shown in Figure 1 can be divided into: 1) Parameters describing individual link components, where, P_L is the emitting power of the laser source (dBm), λ is the operating wavelength in (nm), α_{TXA} is the transmitter

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optics loss in (dB), α_{TW} is the transmitter cover glass loss in (dB), α_{RXA} is the receiver optics loss in (dB), α_{RW} is the receiver cover glass loss in (dB), α_{IF} is the interferential filter loss in (dB), and the *NEP* is the noise equivalent power in (dBm); and 2) Parameters related to system characteristic, where, α_{12} is the geometrical loss due to propagation in (dB), α_{att} is the atmospheric attenuation loss due to extinction in (dB), α_{turb} is the turbulence loss in (dB), α_{point} is the receiver pointing loss in (dB), α_{pol} is the polarization mismatch loss in (dB), α_L is the coupling loss in transmitter in (dB), α_{PD} is the coupling loss in receiver in (dB), γ_{RXA} is the transmitter optics gain in (dB), γ_{add} is the additional gain in (dB), L_{12} is the link distance in (m), θ is the beam divergence angle in (mrad), P_{rcvd} is the received optical power in (dBm), P_0 is the receiver sensitivity in (dBm), P_{sat} is the photodetector saturation level in (dBm), M is the link margin in (dBm), v_I is the bit rate in (bps), *BER* is the maximum allowed bit error rate, SNR_0 is the signal to noise ratio for particular BER, and Δ is the photodetector dynamic range in (dB).

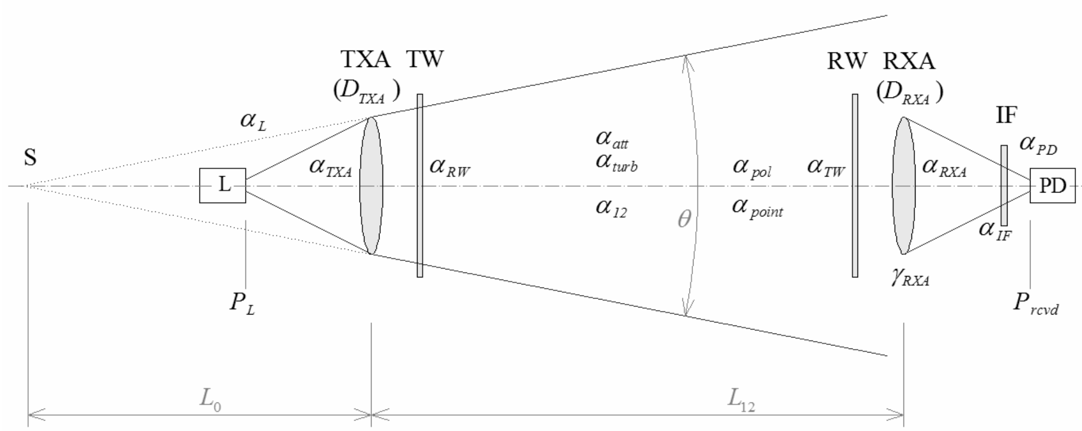

Fig. 1. Design parameters considered in an optical link budget (TXA – transmitter optics, TW – transmitter cover glass, RXA – receiver optics, RW – receiver cover glass, L – laser, PD – photodetector).

In the next section, we present the software that we have developed for solving optical links between earth, HAPs and satellites in vertical or slant paths. This software is based on the equations for the design of LSC presented in the references [1-3].

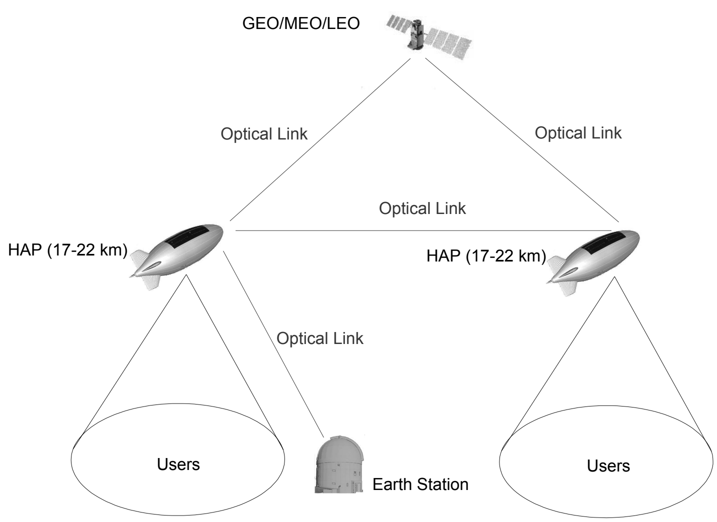

Fig. 2. Architecture of platforms and satellites in the atmosphere.

3. DESCRIPTION OF THE LB SOFTWARE

The software called "LB" and developed in the programming language of MATLAB® 6.5 is used for calculation of the optical links between an earth station, HAPs and satellites in vertical or slant paths, see Figure 2. In Figure 3, the screen of LB is shown. The LB consists of two files named LB.m (Matlab M-file) and LB.fig (Matlab figure file), which is the file of graphical user interface (GUI) that has been used for development. The program can be run by typing "LB" to the Command Window of Matlab.

In the upper part of the window, shown in Figure 3, are two popup menus. First named "Link" has two options: Earth – HAP (Satellite) - the link between Earth station and HAP (or satellite) and HAP - Satellite - the link between HAP and Satellite. This division is made due to different structure of the atmosphere at the ground level and in the upper levels. The second popup menu named "Channel" has two options as well: Uplink and Downlink. The division into uplink and downlink communication channel is important due to a different treatment of scintillation index in these cases. To describe properly the varying strength of optical turbulence as a function of altitude, the Hufnagel-Valley (H-V) theoretical model is involved in the design [2].

The section "Input parameters" serves for input data entry, against that the section "Output parameters" is determined for results. All the losses are entered as positive values. The results in graphical form are displayed in the window named "Link Budget Diagram". If results are required to be in a separate window (e.g. due to printing), the radio button named "Separate diagram" has to be tick.

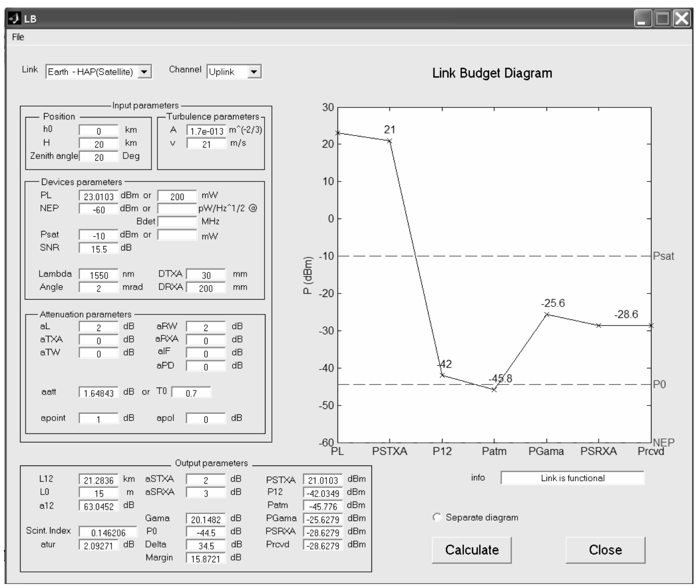

Fig. 3. Window of the LB software.

After setting all input parameters, press the button "Calculate" to solve link budget. If you want to close the program, press the button "Close". All the data can be save or load as well. For saving data, select File → Save. For loading data, select File → Open. The field "info" is designed for supplemental information.

In this work this software has been applied to design several examples of LSC links. The first scenario is focused on the optical link between the earth station and the HAP (uplink channel) at an altitude of 20 km. The second scenario presents the optical link between LEO satellite and the earth station (downlink channel). Third scenario deals with the optical link between HAP and GEO satellite (uplink channel). The operating wavelength of 1550 nm was chosen due to its correspondence to fiber optics, less attenuation in the atmosphere and as well and better eye safety than the shorter optical wavelengths. It This wavelength is used in all designed scenarios and it can be recommended for optical communication within the atmosphere. The transmit power was 200mW or 400mW. For these scenarios, the beam divergence angles are in sequence 2 mrad, 0.2 mrad and 0.017 mrad. These angles were chosen based on the link distance and presence of the atmosphere. For calculation of the turbulence loss, the structure parameter at near ground level is 1.7e-13 $m^{-2/3}$ and high-altitude wind speed 21 m/s or 35 m/s. Than, the overall link margin is within the range from approximately 5 dB to 15 dB. The next scenario examines possibilities of the horizontal optical link between two HAPs.

4. DESIGN OF HAP TO HAP OPTICAL LINK

This section examines the methodology in the design of optical horizontal links between HAPs in the above described LB software, the most particular of the optical links designed. The HAPs serve in the same way as the GEO satellites because of their stationary position over a particular area. However, the HAPs altitude is much lower and a round trip delay is much shorter in comparison with the GEO satellites, see Figure 2. Since the atmosphere at the typical HAPs altitudes of approximately 20 km is very thin and the refractive index structure parameter is much smaller than at the ground level, this scenario is well suited for the optical cross-links. In this section, the main effects that may have an influence on the performance of the optical cross-links between HAPs will be introduced. More comprehensive point of view is involved on the link budget calculations when compared to the previous sections related to the vertical and slant paths. Some of this data has been previously presented in [4]. Link budget calculations for the optical cross-links between HAPs have to consider various effects. At the beginning, the communications link equation must be discussed [4]. Consequently, a description of TXA and RXA telescopes must be presented [4-5]. The receiver characteristics must also be considered [4]. Platform vibrations, atmospheric attenuation and scintillation, and background light are also very important factors in case of the inter-HAP links and following sections will be devoted to them [4]. In the previous scenarios, the link budget calculations contain also inner quantities of the optical heads as the coupling loss or transmitter/receiver optics loss. However, for comparison purposes, this design considers only power calculations between TXA and RXA planes. All the design presented in our software will be related to two HAPs at an altitude of 20km each and separate by 300km and 600km. Furthermore, the intensity modulation with the direct detection (IM/DD), which is the most common optical transmission scheme, will be used.

4.1 Atmospheric Effects

Atmospheric effects with relevance to optical inter-platform links will be can be divided into two groups: extinction and refractive index fluctuations (optical turbulence). The extinction causes reduction of the optical intensity at the receiver. The refractive index fluctuations in addition cause a number of disturbances. The most important disturbances in case of the optical inter-platform links are beam spreading and scintillations, both caused by the refractive index fluctuations. In typical scenarios with distance up to 600 km, the losses associated with the beam spreading are below 0.25 dB and have almost no influence on the link budget. Angle-of-arrival fluctuations can be also presented, however they can be neglected since the residual pointing and tracking errors are much more significant [4]. Refractive index fluctuations can be estimated based on the refractive index structure parameter C_n^2. This parameter depends on the altitude h and the most used theoretical model for variation in altitude is the Hufnagel-Valley (H-V) model. However, the H-V model sometimes does not correspond exactly to various measurements [4]. That is why much simpler models derived from measurements will be introduced here. These models stand for worst and best turbulence scenario cases and are given by [4]

$$C_{n,BC}^2 = 10^{-15.7-\frac{h}{7350\text{m}}}, \qquad \text{h} \geq 13 \text{ km} \tag{1}$$

$$C_{n,WC}^2 = 10^{-14.5-\frac{h}{7630\text{m}}}, \qquad \text{h} \geq 13 \text{ km} \tag{2}$$

The RXA integrates the intensity over its aperture area, therefore optical received power fluctuations are correlated to the intensity fluctuations. Nevertheless, the observed variations are reduced by aperture averaging. The scintillations time constant is much larger than one-bit period; accordingly, the mean bit error probability is expressed as [4]

$$\langle p_B \rangle = \int_0^\infty Q\left(\frac{\langle P_{rcvd} \rangle / P_{char} \cdot y}{1+\sqrt{1+\xi \cdot \langle P_{rcvd} \rangle / P_{char} \cdot y}} \right) \cdot f_y(y)\, dy \ , \tag{3}$$

$$Q(x) = 0.5 \cdot \text{erfc}\left(\frac{x}{\sqrt{2}} \right) \tag{4}$$

where $\langle P_{rcvd} \rangle$ denotes mean received power and $f_y(y)$ is the probability density function of the optical received power normalized to $\langle P_{rcvd} \rangle$ and erfc stands for the complimentary error function. The scintillation index of the partially coherent partially polarized beam propagating in weak and strong atmospheric turbulence can be reduced up to the factor of two compared with a linearly polarized partially coherent beam having the same on-axis intensity in the source plane [6-7]. Attenuation in the atmosphere is caused by absorption and scattering. In the stratosphere, the volcanic activity in addition has to be taken into account as a source of the absorption and scattering. In our software the best and worst case are considered. Attenuation loss for the scenarios ranges from 0.1 dB up to approximately 5 dB for 1550 nm and up to 15 dB for 800 nm at the link distance of 600 km. The wavelength 1550 nm seems to be better solution for the design of HAP to HAP optical links due to difference of 10 dB compared to 800nm.

5. CURRENT LIMITATIONS

Generally in FSO systems, the main limitation is caused by the atmospheric channel. The atmospheric attenuation (from both scattering and absorption) and optical turbulence (scintillation) play the key role in beam degradation. Here, the current limitations and their leading causes in LSC will be pointed out:

5.1 Data rate and receiver sensitivity

Achievable data rate of the system is limited by two elements: the laser source and the photodetector. For use in FSO systems, directly modulated lasers operating up to 2.5 Gbps are commercially available. For higher speed such as 10 Gbps or more, external modulators can be used to modulate the output of the laser source. The modern APD photodetectors typically support data rates of 1.25 Gbps or more. However, at higher bit rates, which mean shorter bit duration, the number of photons that can be collected by the photodetector and converted to electrons is low and the receiver sensitivity becomes inverse proportional to the bit rate (higher bit rate → less sensitivity). The thermal (Johnson) noise affects the BER when the system reaches its sensitivity. Typical sensitivity values are -43dBm@155Mbps and -34dBm@622Mbps [8]. In systems with standards APD detectors, the receiver sensitivity is not generally better then 500 photons per bit because of the receiver thermal noise and other negative electronic effects. In STROPEX system, the receiver sensitivity was measured at 168 photons per bit at a data transmission rate of 1.25 Gbps and BER of $3e10^{-7}$ [9].

5.2 Beam divergence angle

The beam divergence plays important role in design of LSC system. Too wide beam divergence angle does not have any negative effect on the pointing and tracking, however it can caused insufficient power level on the detector and vice versa. Narrower beam divergence angle means higher power level on the detector but the right compromise must be chosen. Beam divergence angle for precise LSC systems can be less than 20 μrad [10]. At the optical communication experiment between ARTEMIS and SPOT 4 in 2001, the divergence angle of the communication beam was only 8 μrad [11]. In communications between HAPs, the divergence angle is supposed to be wider due to shorter link distance and the presence of the atmosphere.

5.3 Pointing and tracking accuracies

The accurate Acquisition, Pointing and Tracking (APT) system is required to successfully maintain the optical link between two platforms. Typical pointing accuracies for LSC systems vary from 1 to 200 μrad, however most typical, systems have a pointing accuracy within the range of 10 to 50 μrad. In the tracking phase, the current values of accuracies typically reach 1 to 3 μrad [10,12].

5.4 Transmit power

Further, a suitable transmit power depends on many factors. There is no point in increasing the transmit power over approximately 800mW because of inadequate response in dB scale. In additional, higher transmit power means higher power consumption from the battery. Therefore, the right compromise must be chosen. In case of mobile platforms, typical values of the transmit power of laser transmitter(s) range from 50 mW to 200 mW. However, the link distance, type of the link and other factors must be considered. For example, during the STROPEX experiment, the optical transmit power for the communication beam was 100 mW [9].

6. CONCLUSION

This work gives an overview of the current laser satellite communications. The atmosphere affects negatively any optical link that even partially passes through it. The attenuation, composed from scattering and absorption, is inherently present in all optical communications through the atmospheric channel. Generally, the FSO communications is nearly impossible in fog conditions. The optical turbulence is responsible for random fluctuations in the laser beam intensity (irradiance) termed scintillations. In case of the slant path, the scintillation and related beam spreading of the uplink channel are more significant than the scintillation of the downlink channel. Current LSC mainly uses the intensity modulation with the direct detection (IM/DD). This robust schema is proved to be suitable and compatible with the other present technologies and devices. The coherent detection has demonstrable advantages over the direct detection, however for its complexity and significant demand on accuracy is not employed yet. As the photodetectors, modern Inter-satellite Links systems mostly use the APD diodes, which have the internal gain. However, particular design is very dependent on the transmitter technology and the method of communication. In this work has been to design several examples of LSC links. For their simulations, software called "LB" has been developed using the programming language of Matlab 6.5. The scenario examines possibilities of the horizontal optical link between two HAPs. In this case, more comprehensive point of view is involved in the link budget calculations. Two links between HAPs at an altitude of 20km each and separate by 300km and 600km are considered. In this scenario, the overall link margin is approximately 2.6 dB and the mean bit error probability is 2.64e-8 for distance of 300 km and 3.76e-8 for distance of 600 km. These simulations have shown the possibility to use optical links between particular platforms. However, additional research must be performed.

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