Design of a Two Wavelength Optical Downlink for LEO Spacecrafts

GABRIEL DE FREITAS FERNANDES[1]

[1] *Federal University of Pernambuco, Department of Electronics and Systems*
[*] *gabriel.freitasf@ufpe.br*

Compiled July 23, 2020

Optical fiber brought high data transmission for terrestrial communication systems, consequently the community had the ambition of establishing similar data rates for free-space optical links. This work presents a system architecture and a design method for optical downlink for spacecrafts in Low-Earth orbit - LEO - and aims to achieve easy integration as well as simplicity for assembly. A statistical model for laser propagation in atmosphere is employed in order to obtain a theoretical model for description of the system. © 2020 Optical Society of America

http://dx.doi.org/10.1364/ao.XX.XXXXXX

1. INTRODUCTION

The advent of fiber-based optical communications has benefited terrestrial data transmission with higher data rates compared to RF communication. This ambition is also present in the scope of aerospace communications. First experimental results were obtained by Galileo mission, operated by NASA in 1992. In 2001 the first laser data connection in space was achieved by the satellite Artemis, developed by the European Space Agency. Most recently, NASA's OPALS experiment achieved a 400Mbit/s optical link in 2014.

This work presents a proposal for an optical communication downlink with two channels based in On-Off Keying - OOK - and it's designed to attend dimensional specifications for cubesats. The system also strives for simplicity and aims to be possible to build with commercial devices in a laboratory environment. The downlink is designed to operate in LEO, as Earth observation and communication satellites are in this orbit, including the International Space Station. Here are described the OOK modulator circuit, telescope design, system architecture and theoretical model for atmospheric laser propagation.

2. ATMOSPHERIC LOSS AND LINK BUDGET EQUATION

Equating the optical link requires a model for atmospheric losses in beam propagation. Rytov's theory is used for propagation in turbulent media and therefore a statistical model based on the power received in the photodetector is developed. As previously derived by Giggenbach et al[1] and Rytov[2] , we have:

$$\sigma_R^2 = 2.25 \cdot k^{7/6} \int_0^L C_n^2 \cdot (L-z)^{5/6} dz \quad (1)$$

$$= 1.23 C_n^2 k^{7/6} L^{11/6}, k = \frac{2\pi}{\lambda} \quad (2)$$

With C_n^2 being the Rytov constant,

$$\sigma_{P,sph}^2(D_{Rx}) = exp\{\frac{0.2\sigma_R^2}{[1+0.18d^2+0.2(\sigma_R^2)^{6/5}]^{7/6}} + \frac{0.21\sigma_R^2[1+0.24(\sigma_R^2)^{6/5}]^{-5/6}}{1+0.9d^2+0.21d^2(\sigma_R^2)^{6/5}}\} - 1 \quad (3)$$

for $d = D(\pi/2\lambda L)^{1/2}$.

$$\frac{P_{min}(p_{thr})}{P_o} = \frac{exp\{erf^{-1}(2p_{thr}-1)\cdot[2Ln(\sigma_P^2+1)]^{1/2}}{(\sigma_P^2+1)^{1/2}} \quad (4)$$

Equations (1) and (2) bring the Rytov variance, equation (3) shows the relation between the Rytov variance and power scintillation variance. Equation (3) brings the power scintillation variance. Both equations (2) and (3) culminates in the dimensionless term found in (4). This term needs to be included in the optical link analysis for representing the atmospheric loss, and has p_{thr} as an experimental parameter, which is the probability of receiving a signal below of the minimum power for detection.

Considering the atmospheric, as well as the free path loss, we can obtain the total loss that needs to be overcome in order to establish an optical communication link. This is the first important information to obtain in the design so it's possible to be aware of the gain needed and the system architecture can be proposed.

At this point the first decision about the design is made. The wavelengths of choice are 1310nm and 1550nm. These wavelengths are widely used in fiber communications systems and optical devices are easier and cheaper to find in this spectrum.

The loss for both wavelengths can now be calculated, as Figure 1 and 2 shows for 1310nm and 1550nm respectively.

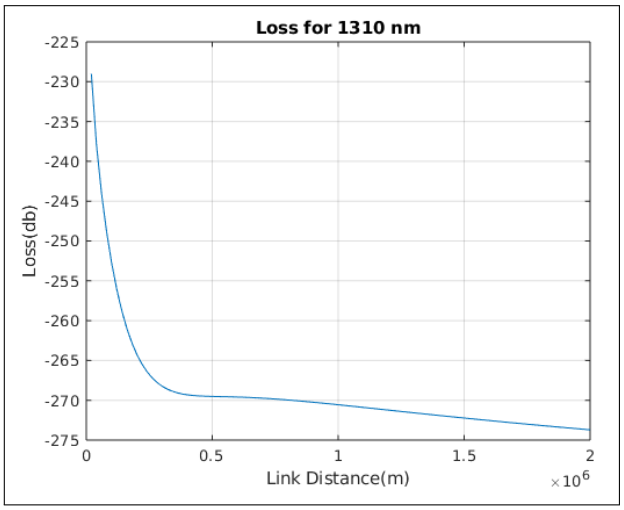

Fig. 1. Atmospheric and Path Loss for 1310nm.

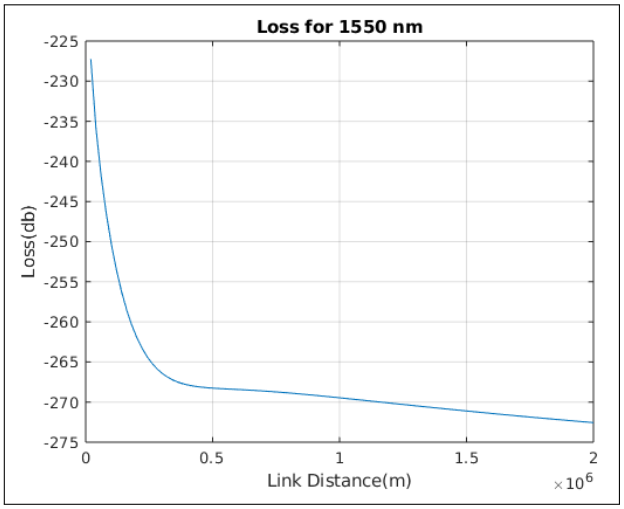

Fig. 2. Atmospheric and Path Loss for 1550nm.

It is observable that the farther in the infrared spectrum the lower is the atmospheric loss.

With the loss calculated it is important to know the minimum optical power able to be detected by the optoelectronic system of the receiver. With this information it's possible to obtain the necessary gain to be applied in order to the signal to be detectable. Considering a generic optoelectronic reception system that is able to detect signals in the order of μW, it will be need approximately 215db gain. This must be achieved by optical amplifiers and the receiving and emitting telescopes.

With the results offered by the analysis of atmospheric propagation, we can equate the optical link. As developed in chapter 3 of the reference [3] and with the introduction of the equation (4), we can obtain one single equation to calculate gain and losses in the optical link, the so called Link Budget equation, which is shown as (5).

$$P_r = P_t \cdot \frac{4\pi A}{\lambda^2} \cdot e^{-8(\theta/\theta_d)} \cdot (\frac{\lambda}{4\pi L})^2 \cdot \frac{exp(erf^{-1}(2p_{thr}-1)\cdot\sqrt{2Ln(\sigma_P^2+1)})}{\sqrt{\sigma_P^2+1}} \cdot (\frac{\pi D}{\lambda})^2 \quad (5)$$

With $A = \pi a^2/4$, θ_d being the divergence angle of the laser device, θ the misalignment angle between the spacecraft and the reception point on the ground and D the receiving telescope aperture.

To observe its behaviour in dB, the link budget equation can be rewritten as (6).

$$P_r(dB) = P_t(dB) + 10[log_{10}(\frac{4\pi A}{\lambda}\cdot(\frac{\pi D}{\lambda})^2) - log_{10}(e^{-8(\theta/\theta_d)}\cdot (\frac{\lambda}{4\pi L})^2 \cdot \frac{exp(erf^{-1}(2p_{thr}-1)\cdot\sqrt{2Ln(\sigma_P^2+1)})}{\sqrt{\sigma_P^2+1}})] \quad (6)$$

3. SYSTEM ARCHITECTURE

Based in the losses obtained for both wavelengths and considering the minimum power possible to be detected, the system architecture can be proposed. This must contain the telescope, optical amplification devices, laser beam combiner as well as the modulator circuit. The proposed architecture is shown in Figure 3.

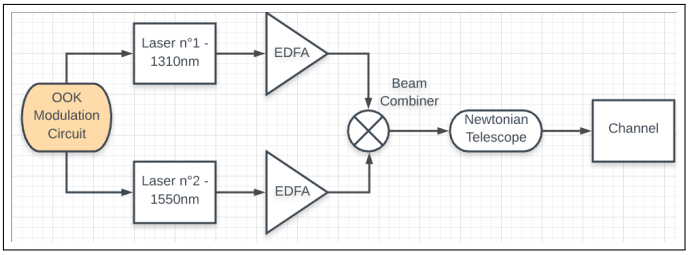

Fig. 3. Proposed system architecture.

The system architecture is based in an On-Off Keying (OOK) modulator, two laser devices in 1310 and 1550 nm, as previously stated, two EDFA (Erbium Doped Fiber Amplifier) optical amplifiers, a laser beam combiner and a Newtonian telescope for collimation.

To reduce chromatic distortion, and therefore wave front error, two possibilities for telescope configuration emerge. Based on the absence of dispersive elements the Cassegrain and Newtonian configurations are the options considered. The Newtonian is shown in the Figure 3 mainly because of the simplicity of its fabrication.

The communication system is simulated based on the power emitted by the laser devices, the gain provided by the telescopes and the atmospheric losses. The simulation is executed considering laser diode devices emitting a 80W signal and 30dB gain provided by the EDFA. The emitting Newtonian telescope has a 3cm aperture, which is achievable in small spacecrafts, and the simulated receiving telescope aperture is 80cm. Considering $p_{thr} = 10^{-6}$, and an index-of-refraction structure constant $C_n^2 = 10^{-17} m^{-2/3}$, as can be observed in higher altitudes (more than 2km above ground), the link budget equation is evaluated separately for each channel. These values must result in a design able to provide sufficient gain to the signal to be detectable in the ground.

4. RESULTS AND DISCUSSION

Based in equation (6), it's possible to investigate the received power behaviour for both channels. Observing equation (6), it's useful to present the misalignment in terms of the divergence angle, which is a parameter of the commercial laser device being employed. The goal is to calculate the maximum possible deviation of the angle between the spacecraft and the receiving telescope through the effect it has on the received power. This analysis is useful for obtaining the maximum tolerated misalignment angle for the required SNR, and it can be a parameter for spacecraft control system design. Figure 4 shows a schematic representation of the misalignment angle. Figure 5 shows the received power behaviour for channel 1, while Figure 6 shows curves for channel 2.

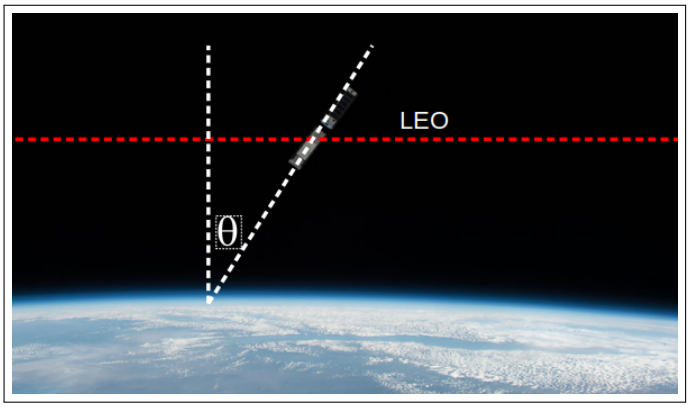

Fig. 4. Representation of the misalignment angle θ. Red dashed line represents the Low Earth Orbit.

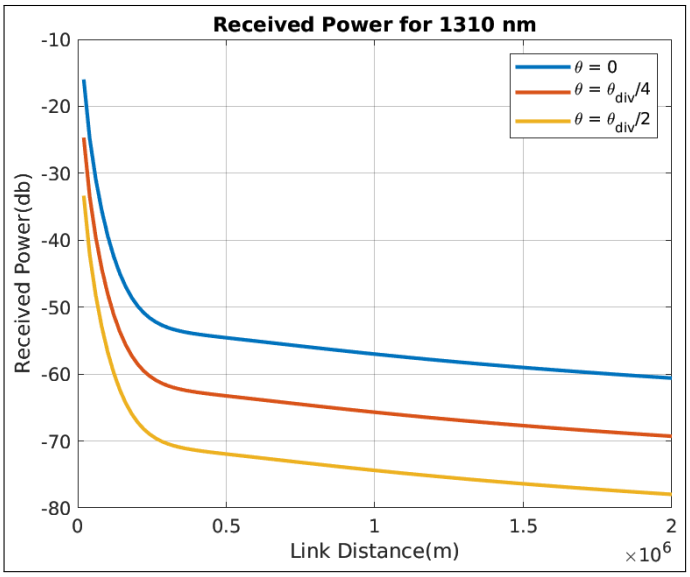

Fig. 5. Received power for 1310nm link.

As the graph shows, the mathematical model is able to predict the power received on the ground and the influence of misalignment between the satellite and the receiving telescope. For the 1310 nm wavelength, in this system architecture, it would be possible to obtain a signal of circa -60dB with ideal alignment. Increasing the angle of misalignment causes a drop in signal

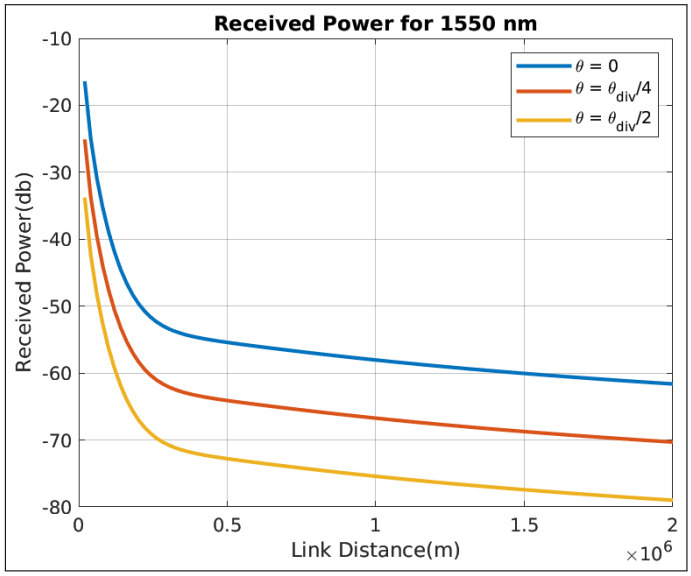

Fig. 6. Received power for 1550nm link.

power, which is expected, even if intuitively. For $\theta = \theta_d/2$, a theoretical value of about -69 dB is obtained for the signal received on the ground.

For the 1550 nm wavelength, we have a curve with similar behavior but with slightly lower received power values. This might be unexpected since the farther in the infrared spectrum, smaller the power scintillation due to the effects of atmospheric turbulence. But the gain provided by the telescopes play a more significant role in the behavior of the received power, and it is higher for lower wavelengths. For ideal alignment, a -61.78dB signal is obtained, while for misalignment angle equal to half the divergence angle, a -79dB signal is obtained. By this technique one can calculate the maximum misalignment angle for a specific reception system.

The signal received on the ground could be read with the use of a dichroic mirror and two different photodetectors, one for each wavelength.

It is necessary to note that this system is susceptible to synchronization problems. So when a considerable amount of information packages is lost, it must be detected and the sending must be restarted. This situation could occur when the laser beam passes through a thick cloud, for example. The ground detection of lost packages should be made as fast as possible, once the passing of time increases the misalignment between spacecraft and ground telescope. Such communication system should be implemented with the help of an artificial star, a strong laser beam fired from ground to disperse clouds, to avoid losses of information packages.

5. CONCLUSIONS

Considering the main objective of the work, which is developing a design philosophy for a two wavelength optical downlink for LEO spacecrafts, the process is started at defining the wavelengths to be used in the system. Subsequently, atmospheric losses are calculated and the amplifiers and telescope are chosen, culminating in the final system architecture. To obtain design parameters of the downlink, statistical models are applied for turbulent media wave propagation, transmission and reception are included in the link budget equation, which is also used

to observe the received power behaviour on the ground. This paper presents a simple design philosophy which offer easy integration, while the mathematical formalism can be used to model similar systems varying in number of channels, employing different telescope configurations or alternative wavelengths, as well as different laser devices.

The problems that this design should face are also discussed and possible solutions are cited.

ACKNOWLEDGMENTS

The author acknowledges Asa Branca team from the Federal University of Pernambuco. This work was done in context of the Cobruf Association competition.

6. REFERENCES

1. GIGGENBACH, D.et al. (2008). Fading-loss assessment in free-space optical communication links with on-off keying. Optical Engineering.
2. RYTOV, S.M. et al. (1989). Principles of Statistical Radiophysics 4. Springer.
3. LAMBERT, S.G. et al. (1995). Laser Communications in Space. Artech House.