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A study of design trade-off of Skinakas Optical Ground Station upgrade

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ABSTRACT

Optical communications (OC) is an emerging transformative technology for scientific, commercial, and defense applications. Compared to radio-frequency (RF) communications, it can offer higher bandwidth, lower power consumption, and reduced size and mass of transceivers. Narrow, directed beams of light, OC can in principle increase link security and enable optical quantum communication, which provides absolute physical security. Free-space optical satellite networks will employ both satellite-satellite and satellite-Optical Ground Station (OGS) optical links. Optical Communication terminals (OCT) on-board a satellite have to comply to volume and energy limitations, restricting the available optical power and optical system parameters.

In this paper, we perform an optical link design trade-off between an OGS and a Low Earth Orbit (LEO) satellite. We study the feasibility of utilizing Skinakas Observatory in Greece as an OGS, for realistic OCT specifications and based on the criterion of link budget. We model an optical downlink and compute the results for various critical parameters of the OCT. Our results confirm the feasibility of such a link for optical communication purposes.

Keywords: Optical Communication, satellite optical communication, space technologies, Skinakas Observatory

1. INTRODUCTION

Satellites have become an integral part of our daily lives: They securely carry essential communication, even into distant places. They provide the raw data required to predict the weather, understand global warming, or current events. On the other hand, the bandwidth constrains imposed by conventional radio communications, make it difficult to efficiently handle this exponentially increasing data volume. Space-based laser communications (SLCom), an emerging transformative technology, can overcome constrains. Compared to radio frequency (RF) communications, SLCom can offer larger bandwidth allowing high data-rates, lower power consumption and reduced size and mass of the transceivers. By using narrow, directed beams it can, in principle, provide a better link security and avoid regulatory issues related to RF spectrum allocation. Likewise, as spacecrafts will continue to generate increasing amount of data, space-to-ground laser communications can provide high rate downlink capability to overcome a communication bottleneck.

From first demonstrations in the 1990s[1] optical communication links have significantly evolved from proof of concept experiments into the prime candidate for the next generation of high bandwidth and secure communication networks. In recent years, space to ground demonstrations of secure optical communication capabilities,[2] ultra-high data rates (> 5 Gbps) in bidirectional links with GEO satellites[2] and deep space links[3] have been

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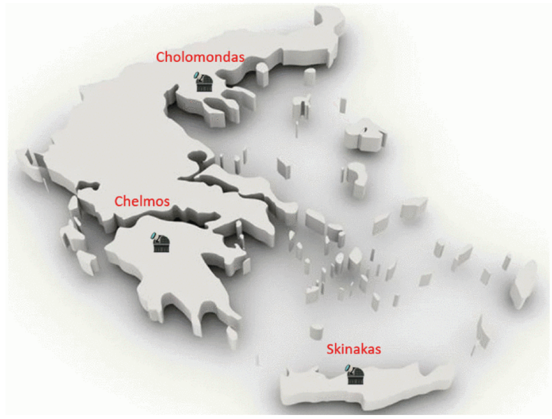


Figure 1: The location of the three observatories intended to participate in EuroQCI.[11]

performed. In the near future space terminals in LEO satellites promise high data-rate capabilities (OSIRISv2 and Optelµ at 1 Gbps, OSIRISv3 at 10 Gbps) demanding the development of suitable OGS technologies to fully exploit their potential.

Space optical communication's performance is still limited on the OGS by the adverse effects of the atmospheric channel. The severity of atmospheric effects can range from a reduction in data rate that can be addressed in the design of the receiver to complete link unavailability, for example in the case of total cloud cover. Propagation of optical waves in the atmosphere is also affected by absorption, scattering, turbulence,[4,5] by the tight photon budget related to limited onboard optical power, and by telecom detector sensitivity.[6,7] In the receiver chain, high data-rate links (at the hundreds of Gbps range) require very fast and thus small detectors (diameter of $20 - 50$ μm), making the focusing of the downlink signal on the chip a quite challenging process. Several approaches have been proposed to tackle these challenges using active optical elements such as tip/tilt mirrors[8] and adaptive optics.[9,10]

Greece actively seeks to enhance its capabilities in satellite technologies and applications including satellite exchange data, for example, by contributing to the European Union's (EU) Govsatcom program for secure communication among with the European Quantum Communication Infrastructure. Towards that direction, the Ministry of Digital Governance in Greece announced the general guidelines for the implementation of the the Greek National Satellite Space Project.Through this project, Greece is interested in manufacturing and operating small satellites hosting multipurpose payloads serving the needs for national and European secure communication. Further to that, the potential of telecommunications in the context of quantum communications, border surveillance and forest monitoring are also considered. Optical communications promise to have a significant contribution to Greece long term vision and for this reason all the national assets, including the OGS at Chelmos, Skinakas and Chomolondas are planned to be utilized. These OGS are intended to become nodes in the proposed EuroQCI of the EU[11] as shown in Fig. (1).

In this paper, we study the feasibility of an optical downlink between a LEO satellite and the 1.3m telescope at the Skinakas observatory in Greece. The effect on the link budget of various parameters of the space OCT is discussed. A realistic preliminary analysis of the effect of atmospheric turbulence on the signal reception in the downlink is performed. We find that there is a broad region where a reliable optical link could be achieved.

2. SKINAKAS OBSERVATORY

The Skinakas Observatory operates as a part of a scientific collaboration between the University of Crete in Greece and the Foundation for Research and Technology-Hellas (FORTH). The site of the Observatory, which has clear and dark skies for much of the year, is the Skinakas summit of Mount Ida (Psiloritis) at an altidute of 1760 m and a distance of 60 km from Heraklion (Crete, Greece).

The Skinakas summit has proven to be an excellent site for astronomical observations. Using a two-aperture Differential Image Motion Monitor (DIMM) the seeing over Skinakas was measured during observations in 2000 and 2001. For a total of 45 nights, the median seeing was found to be less than 0.7 arcsec. Night sky BVR brightness observations were conducted in August 2008 and revealed that Skinakas Observatory is a dark site, with the exception of the direction towards the city of Heraklion (North East). The average night sky surface brightness towards zenith was found to be $B = 22.36 \pm 0.16$, $V = 21.60 \pm 0.14$, $R = 21.07 \pm 0.14$ in absolute magnitudes per square arcsecond.

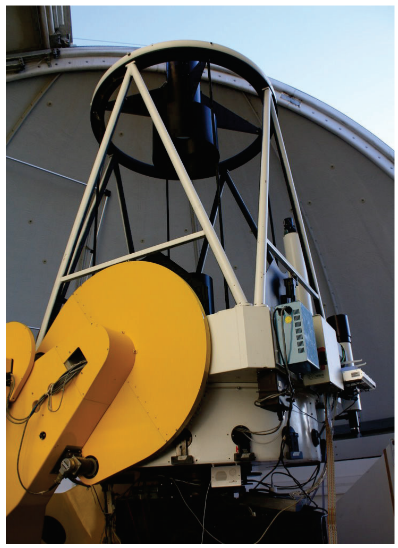


Figure 2: The 1.3 m. telescope of Skinakas Observatory.

The optical system was manufactured by Karl Zeiss, and the mechanical parts by DFM Engineering, Germany. It has an $f/8$ focal ratio giving a scale of 0.02 arcsec/μm in direct mode, while with the use of the focal reducer, the scale is multiplied by 1.87. The telescope works together with an off-axis guiding unit, which provides tracking with accuracy of 0.2 arcsec.

3. PRELIMINARY STUDY OF OPTICAL COMMUNICATION LINK

3.1 Link budget and link margin

The link budget is a useful tool that can be used to predict the channel performance of optical communication systems, since it provides a key to system design and component selection.[12,13] The link budget represents the relationship between the transmitting power P_{Tx} and the optical power received at the input of the optical detector, P_{Rx} and can be estimated by using the link equation:

$$P_{Rx} = P_{Tx} \cdot \tau_{Tx} \cdot AG_{Tx} \cdot \tau_{mp} \cdot \tau_{Atm} \cdot FSL \cdot AG_{Rx} \cdot \tau_{Rx}\,, \tag{1}$$

where we assume circular T_x and R_x apertures.

$$AG_{Tx} = (\frac{\pi D_{Tx}}{\lambda})^2 \tag{2}$$

is the antenna gain T_x,

$$FSL = (\frac{\lambda}{4\pi z})^2 \tag{3}$$

is the free-space loss and

$$AG_{Rx} = (\frac{\pi D_{Rx}}{\lambda})^2 \tag{4}$$

is the antenna gain R_x, where D_{Tx} is the T_x telescope diameter, λ is the wavelength of the laser, z is the link distance and D_{Rx} is the R_x telescope diameter.

$$\tau_{mp} = e^{-2(\frac{\theta_{mp}}{\theta_w})^2} \tag{5}$$

is the T_x mispointing loss, where θ_{mp} is the T_x angular mispointing and θ_w is the T_x angular waist radius. τ_{Tx} is the T_x transmission loss with typical values between $0.7-1.0$, τ_{Atm} is the atmospheric loss with typical values between $0.6-0.9$ and τ_{Rx} is the R_x transmission loss with typical values of $0.2-0.7$.

The link margin (LM), which is calculated as the ratio of the received optical power P_{Rx} to the detector sensitivity DS for a specific data rate and BER, is defined as is defined as

$$LM = \frac{P_{Rx}}{DS}. \tag{6}$$

Typically, for a reliable link it should be LM > 2.[12] LM is a useful parameter to consider for the design of a suitable optical link between a LEO satellite and an OGS; additionally, both the Bit-Error Rate (BER) and the channel capacity should be analyzed to evaluate the optical channel quality in the presence of the atmospheric turbulence. In this paper, we analyze the performance of the optical link with respect to the LM.

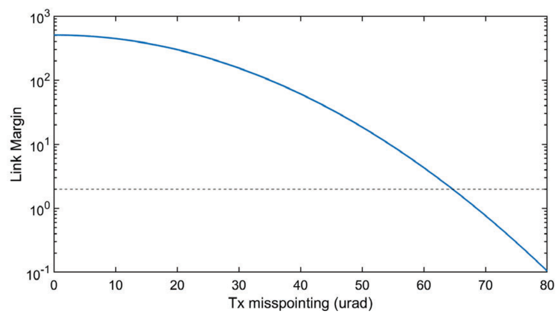
Table 1: Optical link model parameters

link distance, z	560 km
wavelength, λ	1550 nm
Transmit power, PT_x	0.1 W
T_x transmission loss, τT_x	0.9
T_x angular waist radius, θ_w	49.3 μrad
T_x pointing loss, τ_{mp}	0.01
Atmospheric loss, τ_{Atm}	0.8
R_x transmission including filter, τ_{Rx}	0.3
Lunar orbital velocity, Δv	7.5 Km/sec
Spectral radiance of the moon, SR_{moon}	7 mW/(m^2 nm sr)
Spectral radiance of blue sky, SR_{bsb}	13.01 mW/(m^2 nm sr)
detector diameter, d_p	200 μm
R_x focal length, f	9.85 m
R_x filter bandwidth, FB	10 nm
R_x detector sensitivity, DS	-44.2 dBm

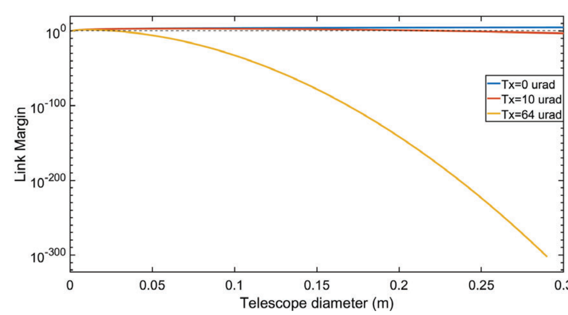
3.2 Numerical results and discussion

In the following we study the effect of various parameters in the link margin as described by Eq. (1). In more detail, we first investigate the impact of the T_x angle of misalignment θ_{mp} on the link margin and then study the relation between link margin and the diameter of the receiver telescope, the transmit power and the detector sensitivity for three different θ_{mp} angles.

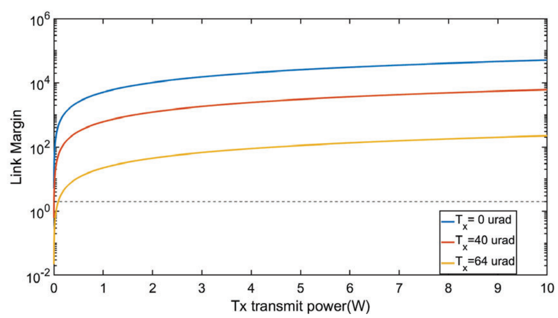
In our study, we numerically analyze the performance of the optical communication link between an OGS with a LEO satellite ($\sim$ 560 km, orbital velocity of 7.5 km/sec). In our simulations, we consider a T_x telescope diameter of 1 inch while for the R_x OGS downlink we use the typical values of the Skinakas Observatory, which is equipped with an optical telescope of 1.3 m diameter and is located at an altitude of 1760 m. A detailed list of the optical link model parametersused in our numerical simulations are shown in Table 1.



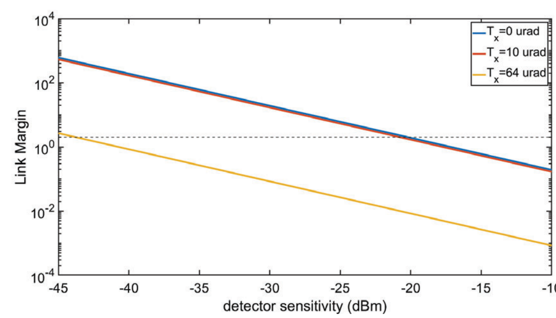
(a) Link margin as a function of the T_x misalignment angle θ_{mp} (estimation for a 1 inch T_x telescope diameter).



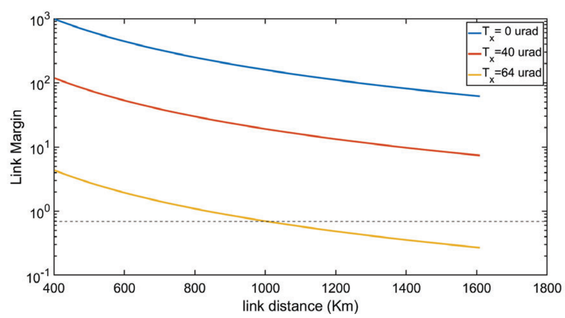
(b) Link margin as a function of the T_x telescope diameter for three different T_x misalignment θ_{mp}.



(c) Link margin as a function of the T_x transmit power for three different T_x misalignment θ_{mp} (estimation for a 1 inch T_x telescope).



(d) Link margin as a function of the detector's sensitivity in dBm for three different T_x misalignment θ_{mp} (estimation for an 1 inch T_x telescope).



(e) Link margin as a function of the link distance for three different T_x misalignment θ_{mp} (estimation for an 1 inch T_x telescope and for LEO).

Figure 3: Numerical results on the effect of various parameters in the link margin.

Fig.(3) shows the numerical results on the effect of various parameters in the LM. Despite the fact that, with respect to the RF case, we can achieve higher data rate with lower size and mass, space links face several challenges, such as pointing errors.Compared to RF, and in order to maximize the received power, optical beams are extremely narrow, posing tight requirements in terms of pointing accuracy. As a consequence, the mispointing between the transmit and the receiver antennas cannot be neglected. The link margin as a function of the transmitter T_x misspointing angle θ_{mp} is shown in Fig. (3a). The calculations are performed assuming an 1 inch R_x telescope diameter, while the black dashed line depicts the lower limit where the optical link is reliable. As we can clearly observe, we can have a reliable optical link for a T_x misspointing up to 65 μrad.

Another fundamental design parameter of the optical link is the diameter of the transmitter's telescope. In Fig.(3b) we show the effect of the T_x telescope diameter on the link margin for three different T_x misalignment angles θ_{mp}.While for no misalignment, $\theta_{mp} = 0$, we can have a reliable link for a T_x telescope diameter of more than 0.5 m, a small misalignment of $\theta_{mp} = 10$ μrad drops this value to $\sim$ 20 cm. Furthermore, for a larger misalignment, $\theta_{mp} = 64$ μrad, we can have a reliable link for a T_x telescope diameter not larger than 2 cm. In Fig.(3c) we can see the link margin in terms of the T_x transmit power in Watt again for three different mispointing angles θ_{mp}. For no misalignment we can have a trustful link for transmit power of less than 1 mW, while for an angle of 64 urad the transmit power must be larger than 90 mW.

Likewise, in Fig.(3d) we show the relation between the link margin with respect to the detector's sensitivity in dBm, again for three different mispointing angles θ_{mp}. For up to $\theta_{mp} = 10$ μrad the detector's sensitivity could be up to -23 dBm, while for $\theta_{mp} = 64$ μrad could be maximum around -40 dBm.

In Fig.(3e) we show the effect of the link distance to the link margin, considering the case of a LEO satellite (i.e. $402 - 1609$ km). As we expect, for no misalignment, i.e. $\theta_{mp} = 0$, we can have a reliable link between the LEO satellite and the OGS in the whole range of the Leo Earth Orbit. What is noticeable is that as the misalignment angle gets larger the link distance where we can have a reliable optical link gets smaller. More specifically, for $\theta_{mp} = 64$ urad we cannot have a reliable link for a distance greater than 577 km.

3.3 Effect of the turbulent atmosphere

In order to simulate the propagation of the T_x beam through a turbulent atmosphere we preformed $2 + 1D$ numerical simulations using a slit step technique involving the propagation of the angular spectrum.[14] The effect of atmospheric turbulence was approximated by a sequence equally spaced of thin random phase screens placed along the propagation[4,15] using the modified von-Karman power spectral density of the refractive index fluctuations $\Phi_n(\kappa)$ described by the equation:[4,16,17]

$$\Phi_n(\kappa) = 0.033 \cdot C_n^2 f_n(\frac{\kappa_s}{\kappa_l}) \cdot \frac{e^{-\frac{\kappa_s}{\kappa_l}^2}}{(\kappa + \kappa_0^2)^{11/6}} \tag{7}$$

where $\kappa_l = 0.33/l_0,\ \kappa_0 = \frac{2\pi}{L_0}, \kappa = \vec{\kappa}$, C_n^2 is the refractive index structure constant indicating the strength of turbulence, and $l_0,\ L_0$ refer to the inner and outer scale of the turbulence respectively. Likewise, the function f_n is defined as:

$$f_n(x) = 1 + 1.802 \cdot x - 0.254 \cdot x^{\frac{7}{6}}. \tag{8}$$

In our simulations the values of the refractive index structure constant C_n^2, as well as, the values of the inner and outer scales ($l_0,\ L_0$) were a function of the altitude.[5] Assuming that turbulence is important bellow an altitude of 3 km and using typical reference values for the inner and outer scales[5] we have simulated turbulence effect on the R_x receiver.

In Fig.(4) we depict typical results of the effect of turbulence both on the plane of the R_x telescope primary mirror and on the R_x receiver (focal plane of the telescope) for moderate turbulence. In our simulations, the values of the refractive index structure constant C_n^2 depend on altitude[5] and vary between $4 \cdot 10^{-15}$ at R_x altitude and $2 \cdot 10^{-17}$ at 3 km.

Likewise, in order to simulate the effect of temporal variations we have repeated the simulations, using different phase screens in every iteration. As we can observe in the lower row of Fig.(4) this moderate turbulence has an observable effect to the R_x telescope focus. The focal spot is blurred and turbulence results to beam wonder, equivalent to a 4.7 urad misalignment, a value very close to the measured median seeing $\sim$ 3.4 urad of the Skinakas Observatory. This temporal variation of the signal intensity and phase as collected by the R_x telescope results in scintillation (i.e. temporal signal variation) of the R_x detector signal. The scintillation is measured by means of the scintillation index σ_I defined as:

$$\sigma_I^2 = \frac{< I^2 >}{< I >^2} - 1 \tag{9}$$

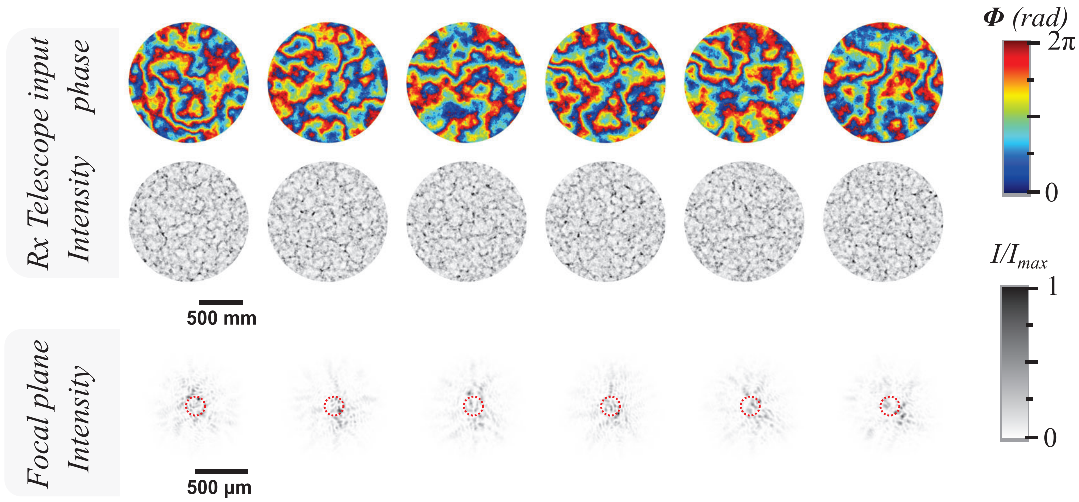


Figure 4: Numerical simulation results on the effect of atmospheric turbulence on R_x signal detection. Columns indicate different time instances. The two first rows indicate the phase Φ and intensity I in the input plane of the R_x telescope mirror (obscurations from secondary mirror and it's mounting are not taken into account). Lower row: Intensity distribution on the R_x telescope focal plane. (The R_x detector is denoted by a dotted red circle).

In our study, in order to simulate the effect of temporal variation, we have repeated the simulations using every time a new set of random screens. By repeating the process for a large number of iterations we were able to numerical estimate the expected value of the scintillation index $\sigma_I \sim 0.16$ for a 200 um detector in the focal plane. We have to note here that for a more complete analysis of the scintillation effect, the temporal spectrum of the R_x signal intensity variations should be taken into account.

4. SUMMARY AND OUTLOOK

We have performed a preliminary feasibility study for the Skinakas Observatory in Greece as an OGS for the case of an optical link with a Low Earth Orbit (LEO) satellite. Based on the criterion of link budget and using typical values for the LEO sattelite T_x parameters we have modeled the optical downlink and we have studied the effect of various critical parameters of the Optical Communication Terminals (OCT), such as the angle of misalignment θ_{mp}, the telescope diameter, the transmit power etc., for three different values of misalignment angle. Furthermore, we have preformed numerical simulations on the effect of atmospheric turbulence on R_x signal detection for a realistic scenario of moderate turbulence that depends on altitude. Our results confirm the feasibility using Skinakas Observatory as a OGS of such a link for optical communication purposes. Our future goal is to further develop our analysis to include also the uplink, with a focus on for specific LEO satellites, and also expand to a wider range of turbulence conditions.

5. ACKNOWLEDGEMENTS

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