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Transportable Optical Ground Station for QKD using Adaptive Optics with a Plenoptic Wavefront Sensor

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ABSTRACT

The Institute of Astrophysics of the Canary Islands, IAC, and specifically its technology transfer division IACTEC, has a long history of participation in free-space optical communications projects (FSOC). These activities are nowadays being pushed forward to achieve practical applications of quantum key distribution, leveraging its facilities and experience in the FSOC field and its "know-how" in Adaptive Optics.

A Free-Space Communications Laboratory has been installed at IACTEC clean rooms, intended to be used as a permanent facility where specific equipment for optical communications, quantum and classical, is available to our research and development group and its collaborators. Single photon detectors and sources, including both avalanche and superconducting nanowires(SNSPD), 16 GHz oscilloscope, FPGA-based time to digital converter, and many optical and electronic general-purpose building blocks are examples of the items existing at the facility, which should become a complement of the existing OGS telescope located at the Observatorio del Teide.

The main objective of the group is to make extensive use of the well-known adaptive optics techniques for the compensation of the aberrations introduced in the communications channel by the atmospheric turbulence. Specifically, a Transportable Optical Ground Station (TOGS) with adaptive optics will be presented, designed with the aim to provide efficient transmission of quantum keys between islands or from a LEO satellite.

The efficiency of coupling the received signal to a Single Mode Fibre is vital when using a SNSPD because they are commonly used as input to the cryostat, in order to minimize dark counts. When the communication optical link is expected to suffer atmospheric turbulence during its free-space path, being able to compensate them using adaptive optics could improve the coupling efficiency by a factor of 25 for a 1-meter telescope, as has been obtained in simulations carried out by our group.

Our group has also found in simulations that an adaptive optics system based on the plenoptic camera will behave especially well in the situation of high turbulence, as it can be expected for sea-level communications. An optical design based in the use of the plenoptic camera as wavefront sensor for the TOGS will be presented.

Keywords: Optical communications, Quantum Key Distribution, Transportable Optical Ground Station, Adaptive Optics, plenoptic camera, deformable mirror

1. INTRODUCTION

Day by day we can read in the newspapers, how companies of any sector suffer cyberattacks with data theft, locker, or spy. The encryption techniques used these years are based on a complex algorithm that is impossible to break with sufficient key length. But, since the development of the quantum computer, in the last year, this algorithm will be broken in minutes or seconds. In this way, the Quantum Key Distribution, QKD, was born as the only solution to defend against cyberattacks in communications because the secrecy of the encryption key is guaranteed by the laws of quantum mechanics.[1]

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The use of QKD protocols through fiber optics networks is challenging, and it is limited to a distance of about 500Km,[2] because of the attenuation and birefringence of the medium. In order to avoid this, the free space optics communications with horizontal links or vertical links are the unique solution to implement QKD protocols ranging from hundreds to thousands of kilometers. Further, the increase in privatization of space activities has brought up a new generation of space companies, with launch cost a fraction of the cost of a traditional spacecraft. The so-called Cubesats have become very popular within centre researches or universities.

However, the main disadvantage of the free space communications is the negative effect of the atmosphere (clouds or turbulence). In this way, in emergency cases or natural disasters, for example, a Transportable Ground Station can be moved quickly to a place with better atmospheric conditions, Whereas a fixed optical ground station cannot.

Because of this, the optical ground station have been a similar deployment in the sector, searching for a low-cost solution and miniaturized. Until now, the Optical Ground Station used, have been fixed in astronomical observatories sites, but now, secret communications are required everywhere.

In this paper we present several designs of a Transportable Optical Ground Station that allow to share keys between two sites, with terrestrial or satellite LEO links.

2. QKD QUANTUM KEY DISTRIBUTION

In 1984, Bennet and Brassard proposed the first quantum cryptography protocol, known as BB84 protocol, referred to as Quantum Key Distribution QKD, in order to establish a common secret key between sender (named Alice) and receiver (named Bob) using polarized photons called qubits.[3] Since BB84, others protocols have been implemented: B92, ERP, SARG04, or COW protocol. A QKD generic scheme includes two parts:

a) Quantum channel. Alice code the bits of the key that want to share with Bob, in a sequence of quantum states and sends it. Bob measure these states and make the raw key.

b) Classic channel. Alice and Bob must distillate or compare the key, namely, exchange the bases between them, and erase those that do not match. This channel is also used for pointing, tracking and acquisition (PAT) and synchronization, so this channel is bi-directional classic link to post-processing.

QKD protocols can divide into discrete variables (DV) and continuous variables (CV), according to how send the information, and how detect it.

Table 1. Type of protocol according sending and detect information

Type of protocol QKD	How to send	How to Detect	Examples
DV Discrete Variable	Qubits, polarization of single photons	Counting single photons	BB84, SARG04
CV Continuous Variable	Spectrum modulation and quadrature of the ligth	Homodyne and hetero-dyne demodulation	Grosshans-Grangier, Noise Tolerant

From 1984 until today, many projects have been carried out, via fiber optics and free space channels, but currently, the maximum fiber optics distribution distance is 509 km, while satellite to ground with LEO satellite exceeds widely this amount.[4]

The benefit of fiber optics is that industry have alredy deployed large scale networks, and the cost of installing a new infrastructure is reduced, but the attenuation problem that affects the maximun achievable distance needs to be solved. Much greater distance could be reached in free space using satellite, i.e. LEO Low Earth Orbit.[5]

3. LINK BUDGET

When we use QKD to encode the photon polarization, the total number of photons collected (total optical power) is the limiting factor of the Secret Key Generation (SKR) rate. So we need to know the power we receive in the detector, in order to know the secret key rate we can obtain. In this way, it is important to have a good link budget with all components that affect it. The key rate of a QKD system is inversely proportional to the link losses.

Free space optics communications are unguided light beams transmitted through the atmosphere, and in this way, it can be scattered or absorbed under the effect of various atmospheric phenomena.

When we study a LEO-to-ground link, we consider certain losses in the optical beam when it propagates through the atmosphere:

– Absorption scattering losses

– Atmospheric turbulence

– Pointing losses

– Beam divergence losses

The optical power collected by the receiver is given by:[6]

$$Pr = P_t G_t G_r L_t L_s L_a L_r L_{sci}$$

Where P_t is the transmitted power, P_r is the receiver power, G_t is the transmission gain, G_r is the reception gain, L_t is the losses of the tr ansmitter, L_r at the receiver, L_a the atmospheric transmittance, L_p the pointing loss, L_s the free space losses and L_{sci} is the scintillation loss factor.

3.1 Absorption and scattering losses

The loss in the atmospheric channel is mainly due to the absorption and scattering process, and it´s described by Beer´s law:

$$T = \frac{I(z)}{I_0} = exp(-\gamma z)$$

Where T is the Transmittance, γ is the attenuation coefficient (absorption coefficient plus scattering coefficient), and z is the length of the transmission path.

So, the attenuation coefficient is determined by four individual processes: molecular absorption, molecular scattering, aerosol absorption, and aerosol scattering. Due to the transmittance being the contribution of this process, we can say that the total transmittance in the atmosphere could be calculated by the product of each transmittance of different elements available in the atmosphere.[?]

The atmospheric transmittance of the laser beam under clear sky conditions (absence of clouds, rain,. . .) is also dependent on the elevation angle and can be given by:[6]

$$L_A = L_{zen}^{\frac{1}{cos\phi}}$$

Where L_zen is the transmittance in the vertical path, calculated based on MODTRAN, and ϕ (rad) is the zenith angle of the link. At low angles, the attenuation will become larger due to the laser beam travelling through a longer distance.

MODTRAN approaches the atmosphere as a number of homogeneous layers, which can be modelled individually. The precision of MODTRAN has been confirmed through extensive validation with high spectral resolution model FASCODE.

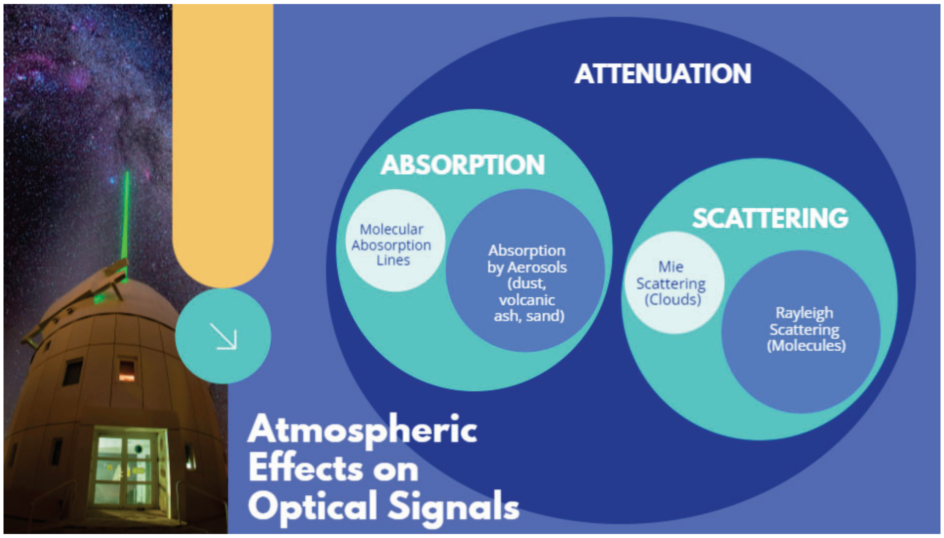

Figure 1. Atmospheric effects on optical signals

3.2 Free-space loss

The free-space loss of the optical signal is due to the optical wave propagation from the transmitter to the receiver and it is calculated as:

$$L_S = \left(\frac{\lambda}{4\pi R}\right)^2$$

Where $\lambda(m)$ is the wavelength of the signal and R is the distance between the satellite and the OGS, which depends on the elevation angle of the satellite.[7]

3.3 Scintillation loss

The atmospheric turbulence creates a random variation in the refractive index of the air, which is caused by pressure and temperature shift in the link way and induces eddies with changes in the index of refraction. From free space optical communications, the atmospheric turbulence has 3 main effects:

- Scintillation. Variation in the signal
- Fading in time
- Fading distribution. Statistics distribution in the intensity.

Scintillation can heavily affect an FSO communication link by causing intensity fluctuations at the receiver. These fluctuations are caused by thermal changes that lead to changes in the refractive index in small air cells, resulting in beam diffraction and beam wander. In the case of satellite downlink, the beam size is usually much larger than the size of these air cells; therefore, the effect of scintillation in the receiver is small but should be taken into consideration.

The intensity of scintillation could be weak, moderate ,or strong, depending of the value of the refractive index structure parameter $C_n^2(m^{\frac{2}{3}})$. In order to determinate the value of C_n^2, exist many statistics and numerical models, in which each one have different input values, or standard model with input values like altitude, pressure, wind speed, . . . , i.e Hufnagel- Valley 5/7, Cleari, and So.

The Hufnagel-Valley 5/7 model has been used to determine the C_n^2 statistics, with a 5cm Fried parameter, the C_n^2 has been calculated as it follows:

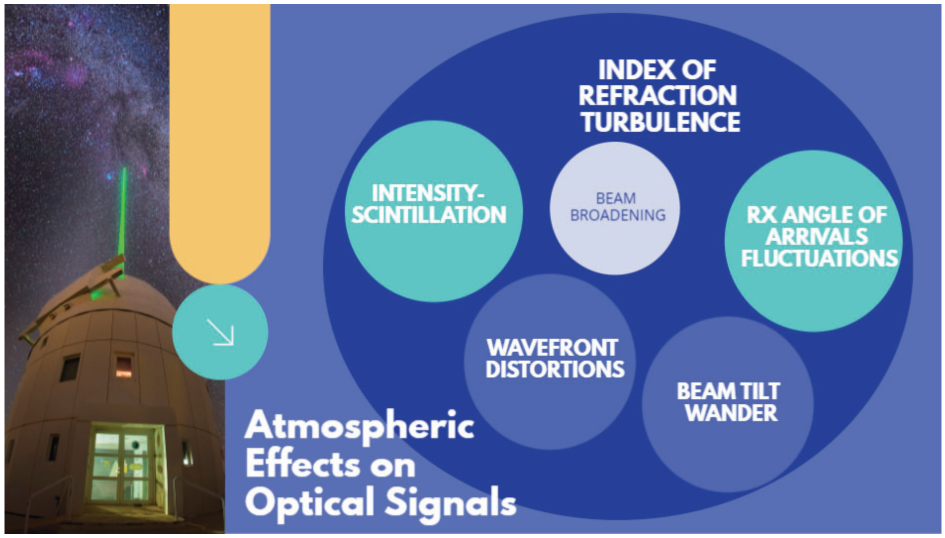

Figure 2. Atmospheric effects on optical signals

$$C_n^2 = A_0 exp\left(\frac{-H_{OGS}}{700}\right) exp\left(\frac{(H_{OGS}-h)}{100}\right) + 5,94\times 10^{(-53)}\left(\frac{V_{rms}}{27}\right)^2 h^{10} exp\left(\frac{-h}{1000}\right) + 2,7\times 10^{-16} exp\left(\frac{-h}{1500}\right)$$

Where $A_0(m^{(\frac{2}{3})})$ is the refractive index structure parameter at ground level, $V_{rms}\,(fracms)$ is the average wind speed along the path, $H_{OGS}(m)$ is the OGS altitude height and $h(m)$ is the height above the ground station altitude.

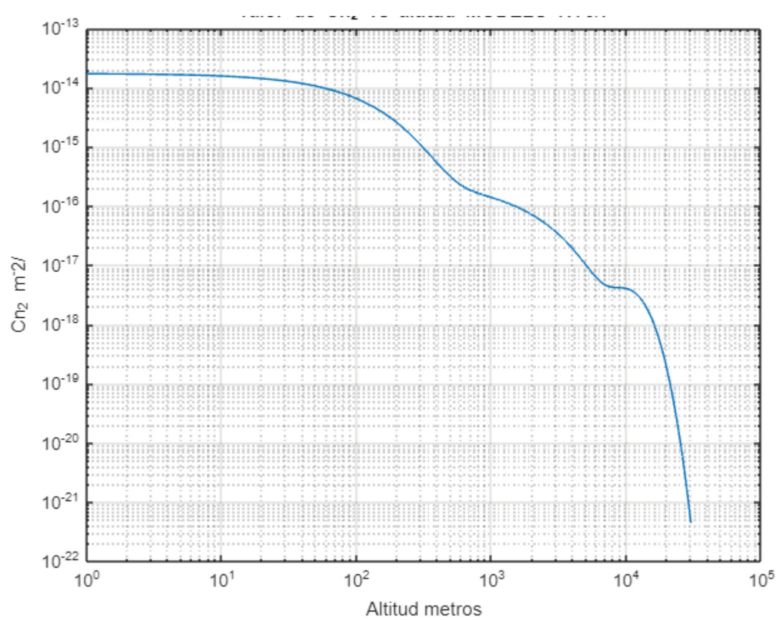

Figure 3. Variations of atmospheric structure constant with altutude for the H/V 5/7 model

For plane wave and Kolmogorov models, the scintillation index for weak, mean ,and strong turbulences can be given by the following expression:

$$\sigma^2_{(I,point)} = exp\left(\frac{0,49\sigma_R^2}{(1+1,11\sigma_R^{\frac{12}{5}})^{\frac{7}{6}}} + \frac{0,51^2_R}{(1+0,69\sigma_R^{\frac{12}{5}})^{\frac{5}{6}}}\right) - 1$$

Where σ_R^2 is the Rytov index, which when taking into account the OGS´s height can be calculated as:

$$\sigma_R^2 = 2,25k^{\frac{7}{6}} sec\zeta^{(}\frac{11}{6}) \int_{H_{OGS}}^{H_turb} C_n^2(h)(h - H_{OGS})^{\frac{5}{6}} dh$$

Where $k(rad/m)$ is the wavenumber, $\zeta(rad)$ is the zenith angle, and H_turb is the turbulence altitude, which is considered negligible for altitudes higher than 20Km.

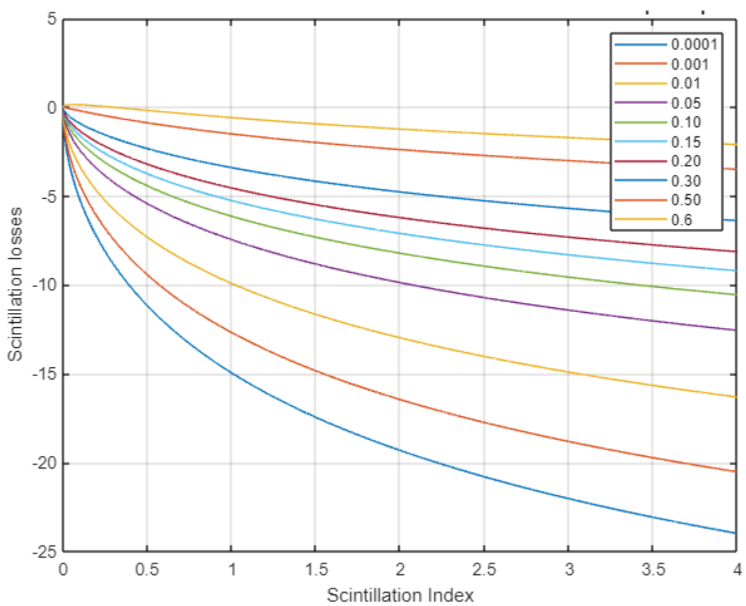

Figure 4. Scintillation index versus losses scintillation

To continue, we also must consider the aperture–averaging effect to take the receiver´s aperture diameter into account.[8] This factor is expressed as:

$$A(D_r) = \frac{\sigma_I^2}{\sigma_{I,point}^2}$$

Where σ_I^2 is the scintillation index for the receiving telescope, so the aperture-averaging factor is calculated according to the following expression:

$$A(D_r) = \left(1 + 1,062\left(\frac{D_r}{(2\Phi_I)}\right)^2\right)^{\frac{7}{6}}$$

Where ϕ_I is the intensity structure size parameter, and it is defined by:

$$\Phi_I = 1,5\sqrt{(\frac{\lambda}{2\pi}H_d\left(\frac{\frac{\theta}{90}}{(\frac{\theta}{90})^2 + (\frac{10}{90})^2}\right)}$$

Where H_d is 12,000 m and $\theta(grade)$ is the elevation angle of the link.

Finally, for modelling the signal fluctuation due to the scintillation effect, we used the log-normal distribution that suits weak-and moderate turbulence regimes, so with the probability of availability of the link, we can calculate the scintillation losses in dB:[9]

$$L_{sci}(dB) = 4.343\left(erf^{-1}(2\rho_0 - 1)2ln(\sigma_I^2+1)\right)^{\frac{1}{2}} - \frac{1}{2}ln(\sigma_I^2+1)$$

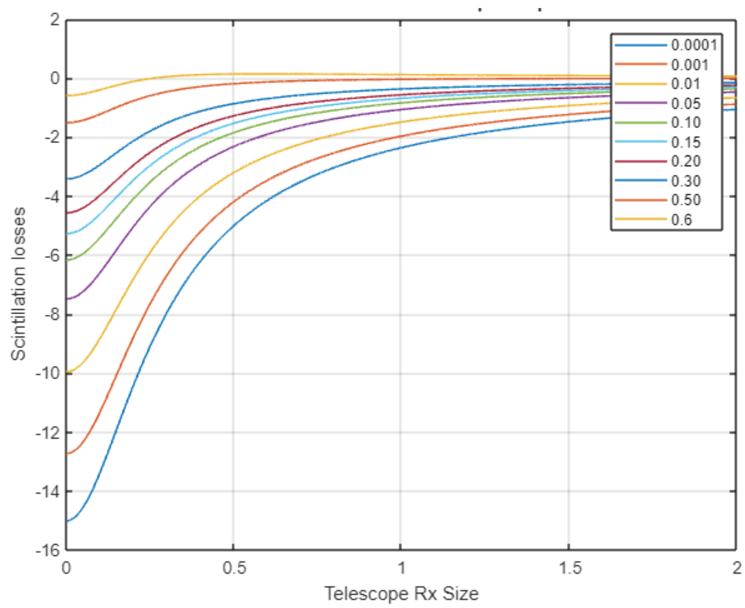

Figure 5. Scintillation losses versus telescope reception size in different available time

4. METHODS TO IMPROVE THE LINK. ADAPTIVE OPTICS

Adaptive Optics are commonly used in ground-based telescope to compensate for the light distortion caused by the atmosphere and to minimize the wavefront error, this mitigates the effect of the atmospheric turbulence. Also AO improve the coupling of the optical beam into a single mode fiber.[10] The Adaptive optics (AO) module is designed to be mounted in the Nasmyth focus of a Ritchey-Chrétien 700mm aperture telescope with a f/12 focal ratio. This telescope has a central obstruction of less than 30

All the parts of the AO system are fitted inside a box, except the controllers for the electronic devices. The box is limited in size and weight and will be closed and isolated to protect the optical elements inside. The main elements of the system are a Fast steering mirror (FSM) to correct the Tip/tilt, a deformable mirror (DM) to correct higher order aberrations installed at the telescope exit pupil, a coupling relay to couple the light to a SMF fiber, a magnification relay for feeding signal to the wavefront sensor, and the plenoptic camera, consisting of an array of microlens mounted at the back focal length of an objective lens. Additionally, the system has a calibration source that can be inserted into the path with a flip mirror and a multi-mode fiber laser to be used as a beacon, launched with the telescope, and inserted into the path with a dichroic mirror. A schematic view of the AO system is shown in the next figure.

The data signal to be coupled into a single mode fiber has a wavelength of 1550nm while the correction channel for the plenoptic camera wavefront sensor has a wavelength of 850nm. The combination of these two wavelengths sharing same optical elements is problematic. Achromatic doublets have been used to reduce the on-axis spherical aberration, some restrictions have been imposed: the signal to be coupled has priority over the optical elements, so all the coatings on the shared path have been selected accordingly to the 1550nm wavelength.

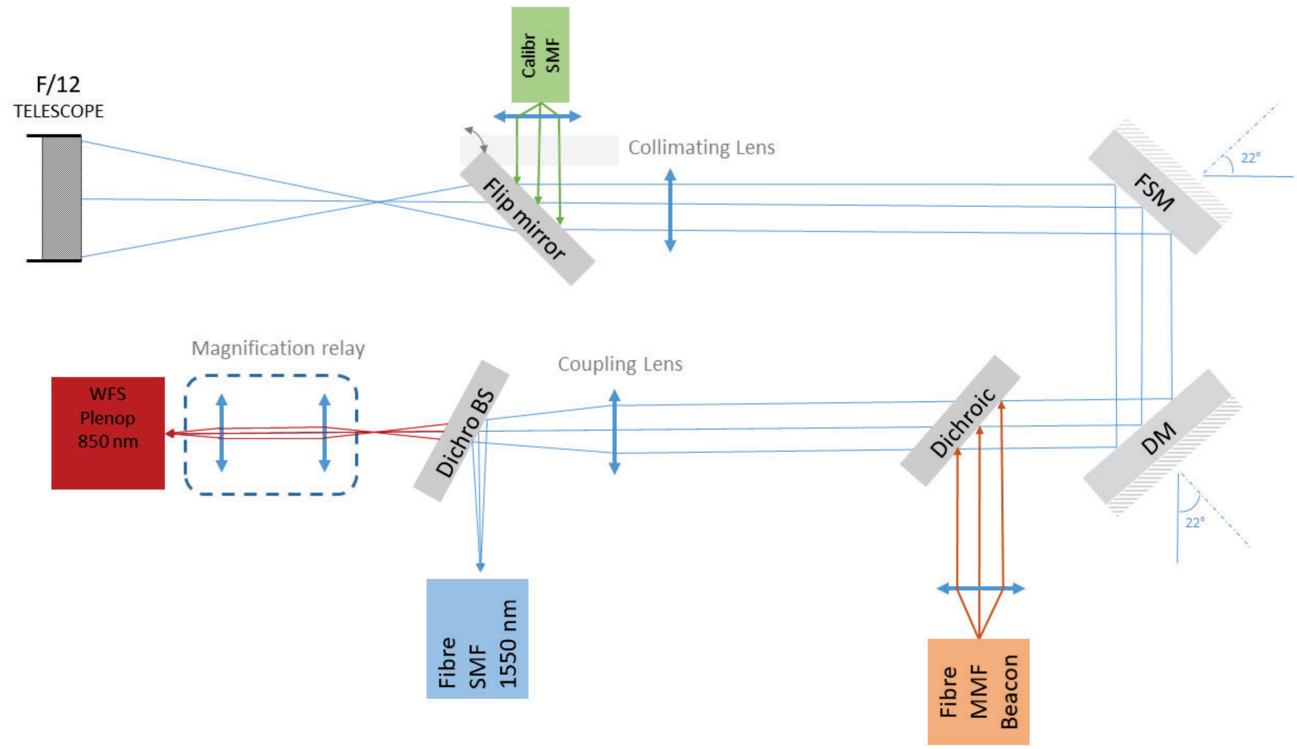

Figure 6. Schematic view of the Adaptive Optics module for TOGS

As stated previously, the system is intended to be used in several scenarios, mostly horizontal links during daytime, that has the strongest turbulence. Simulations performed by our group show how a plenoptic wavefront sensor delivers better correction for strong turbulence than a typical Shack-Hartmann (SH).[11] Typical Fried parameters (r0) for the operation of the optical link are expected to be in the range between 2cm (strong turbulence) up to 15cm (weak turbulence).

5. TOGS SYSTEM ARCHITECTURE

The TOGS designed and developed by IACTEC, include functionality for terrestrial and bidirectional LEO to ground links. Terrestrial links include communications between buildings, mountains, islands, or any other kind of horizontal link between two ground station, and LEO links include both ground-to-satellite and satellite-to-ground, in order to share quantum keys between both.

The scheme we proposed for our TOGS is BB84 discrete variable protocol as baseline, with four different linear polarization (H/V/+/-).[12] We split the system design in 3 parts: Mechanical design, that include dome, holders, trailers and all the transportable parts, optical subsystem, that include Telescope, “AliceBox“ and “BobBox”, and electronics subsystems that include the data post processing. “AliceBox” include the sender of the quantum key, and “BobBox” include the receiver of the quantum key, this box shared parts like telescope.

AliceBox and BobBox are a modular box each one, with the optical components inside that mount in the Nasmyth focus of the telescope. Figure 7 shows an schematic of the TOGS architecture with signal and components

6. TOGS DRAFTS

We studied previous designs for optical communications ground stations[13141516]We had many iterations before the final design. From 2021 to 2022, we iterate design in order to get the best design suited to do QKD with

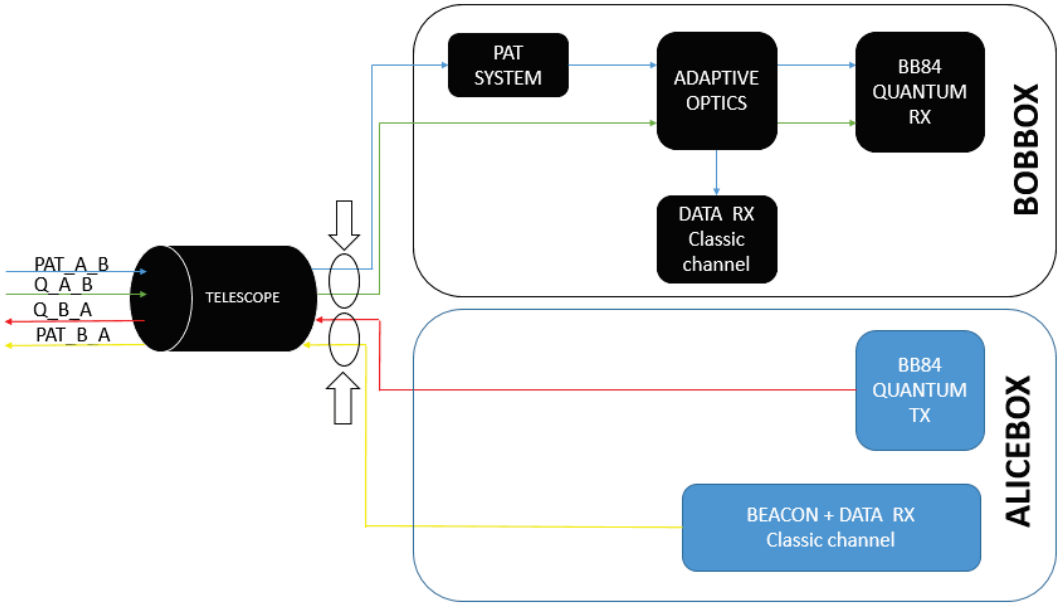

Figure 7. TOGS system architecture

transportability capability. Figure 8 shows how the IACTEC ground station design envolved in time since the initial concept.

Finally, we decide for a model with two mobile parts and one fixed part. The final dimensions are 2.400 x 3.714 x 4.280 mm (width, height, depth) with hydraulic legs in order to get more stability, so the size is 38 m^3 and weighs 1.737 Kg.

7. MECHANICAL DESIGN

One of the most important parts of the design is the transportability capability. The mechanical design needs to fullfil the following requirements:

a) Dimensions suitable to drive on Spanish roads.

b) Vibrations need to be minimised. Wind shake or vibrations produced by energy generator equipment will affect the accuracy of the transmission.

c) Ground stability. It is important to have automatic or manual compensation for ground roughness.

d) Protection of the elements will be transported. All elements will be enclosed for protection

e) The telescope shall be able to point bellow horizon. In order to perform "horizontal" links we might need to need to point bellow the horizon, if we are in a higher altitude with regard to the other station.

f) Optimised coverage to get the greatest number of targets without moving the unit.

The main components of the TOGS are described bellow:

7.1 Trailer with hydraulic legs

Light trailer with four hydraulic legs, and two axes, to avoid the vibrations in the mobility. Figure 9 show this part.

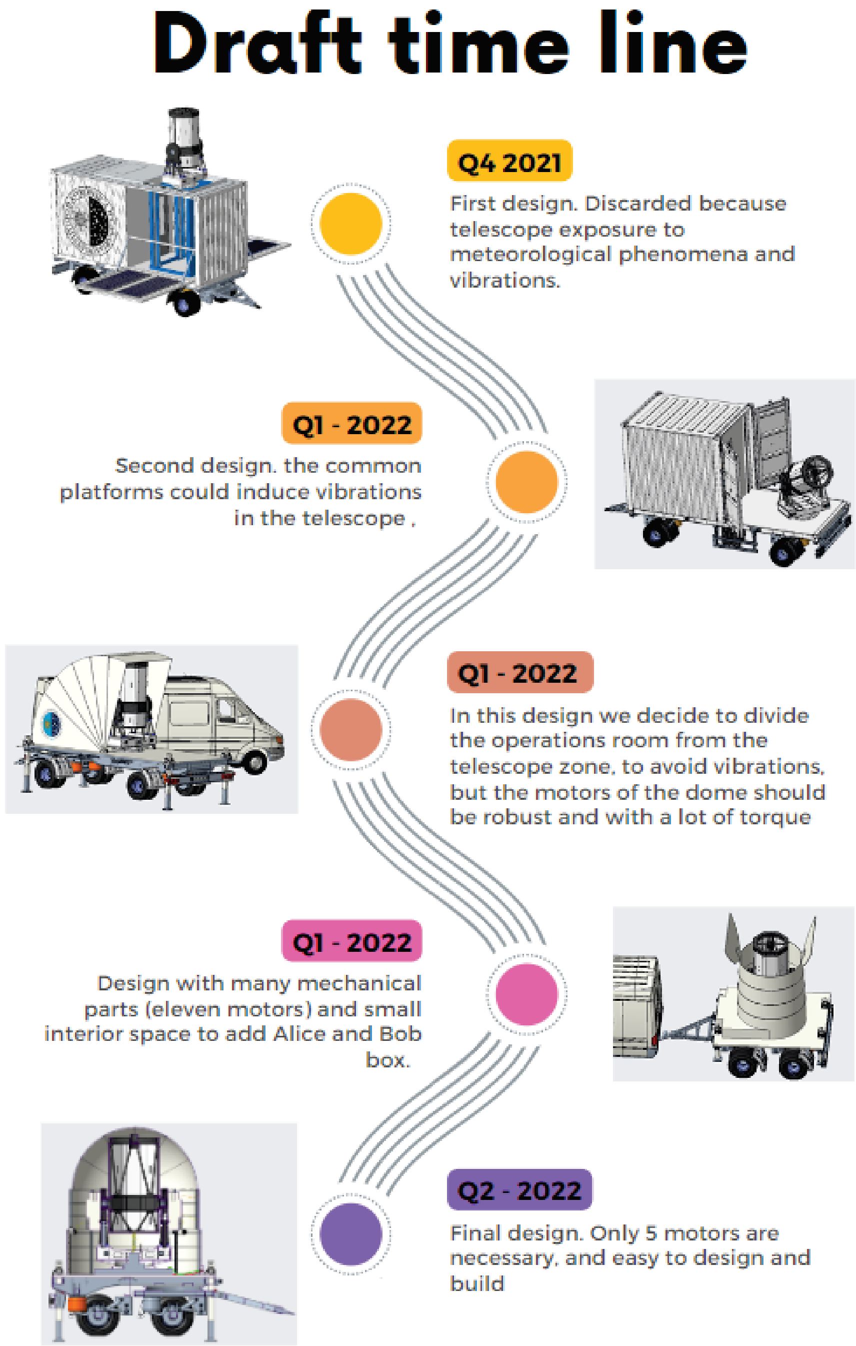

Figure 8. Diferents drafts in time

7.2 Telescope

The goal was to build a transportable optical ground station capable of supporting missions from/to LEO and horizontal links. Therefore the telescope needs to have sufficient aperture to collect enough photons together with the capability of tracking LEO satellites precisely.[17] We select a 0.7 meter aperture, with f/12, Ritchey-Chretien optical design. The telescope is optimized in central obstruction with less than 30% for improved image contrast and has a dual Nasmyth focus in order to mount the Adaptive Optics and transmitter key systems.The figure

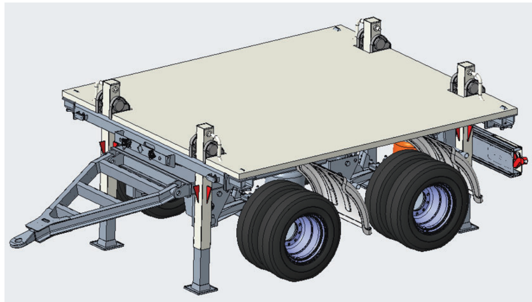

Figure 9. Light trailer with hydraulic legs

10 show the telescope embedded in the trailer.

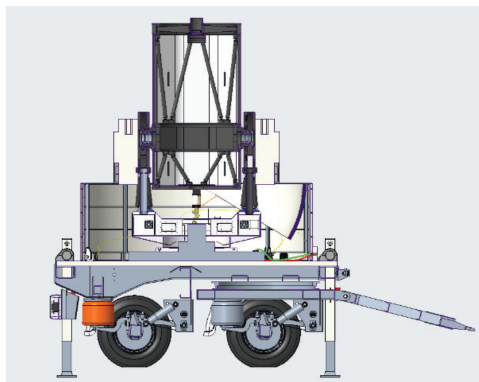

Figure 10. Telescope in the trailer

7.3 Alicebox QKD transmitter

The implementation of the BB84 protocol has been done by using pulses with four polarizations equally distributed in a great circle of the poincare sphere. Four lasers are used in the transmitter to encode the bit value and measurement basis to obtain the states H¿,V¿,+45¿, and -45¿. The beams are combined in a non-polarizing beam splitter and dimmed in a variable optical attenuator. This quantum signal is combined with a beacon signal and sent to the telescope, which collimates the beam over free space towards Bob.

7.4 Bobbox QKD receiver with Adaptive Optics

The receiver has a random beam splitter, which sets the measurement basis and polarizing beam splitters measure the value of the bit. A click on one of the photon-counting detectors set the bit value and base angle of measurement.

The Bobbox and Alicebox mount in each Nasmyth focus of the telescope

7.5 Others

Also we have dome with automatic open and close, holder between telescope and trailer and a conditioned van.

8. CONCLUSSIONS

In this paper, we have described our different designs and approaches for a Transportable Optical Ground Station TOGS, used for terrestrial and LEO satellite links. We expect to do this QKD links demonstration in Q3 2023, with the main goals being:

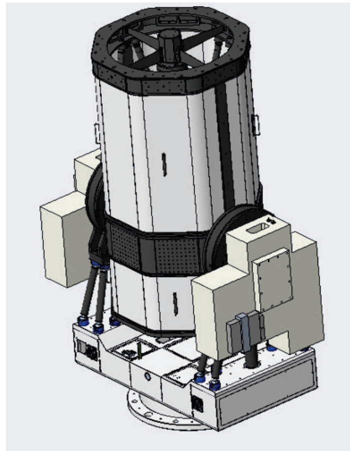

Figure 11. Alice and Bob are mounting in the Nasmyth focus of the telescope

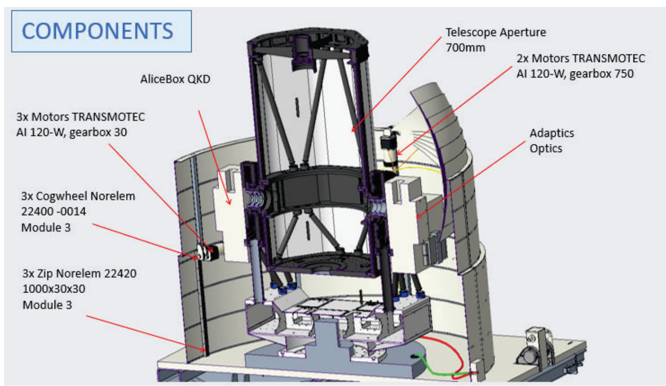

Figure 12. TOGS components

o Partly mitigation of the effect of the atmospheric turbulence with an Adaptive Optics system that incorporates a plenoptic wavefront sensor.

o Testing and development of novel AO systems and algorithms

o Characterisation of the terrestrial optical link and satellite LEO optical link for QKD.

o Active collaboration in other optical quantum experiments

Applications of portable ground stations cover sectors like finance, defense or healthcare, in order to maintain its privacy in the near future when the classic cryptography will beocme threadtened

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