International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

Analysis of large optical ground stations for deep-space optical communications

M. Reyes Garcia-Talavera

C. Rivera

G. Murga

I. Montilla

et al.

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105630Z · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304253

ANALYSIS OF LARGE OPTICAL GROUND STATIONS FOR DEEP-SPACE OPTICAL COMMUNICATIONS

M. Reyes Garcia-Talavera[1], C. Rivera[2], G. Murga[3], I. Montilla[1], A. Alonso[1]
[1]Instituto de Astrofisica de Canarias, Tenerife, Spain. [2]ISDEFE, Madrid, Spain. [3]IDOM, Bilbao, Spain.
mreyes@iac.es

I. INTRODUCTION

Inter-satellite and ground to satellite optical communications have been successfully demonstrated over more than a decade with several experiments, the most recent being NASA's lunar mission Lunar Atmospheric Dust Environment Explorer (LADEE). The technology is in a mature stage that allows to consider optical communications as a high-capacity solution for future deep-space communications [1][2], where there is an increasing demand on downlink data rate to improve science return. To serve these deep-space missions, suitable optical ground stations (OGS) have to be developed providing large collecting areas. The design of such OGSs must face both technical and cost constraints in order to achieve an optimum implementation. To that end, different approaches have already been proposed and analyzed, namely, a large telescope based on a segmented primary mirror, telescope arrays, and even the combination of RF and optical receivers in modified versions of existing Deep-Space Network (DSN) antennas [3][4][5]. Array architectures have been proposed to relax some requirements, acting as one of the key drivers of the present study. The advantages offered by the array approach are attained at the expense of adding subsystems. Critical issues identified for each implementation include their inherent efficiency and losses, as well as its performance under high-background conditions, and the acquisition, pointing, tracking, and synchronization capabilities. It is worth noticing that, due to the photon-counting nature of detection, the system performance is not solely given by the signal-to-noise ratio parameter.

To start with the analysis, first the main implications of the deep space scenarios are summarized, since they are the driving requirements to establish the technical specifications for the large OGS. Next, both the main characteristics of the OGS and the potential configuration approaches are presented, getting deeper in key subsystems with strong impact in the performance. The different configurations are compared from the technical point of view, taking into account the effect of atmospheric conditions. Finally a very preliminary cost analysis for a large aperture OGS is presented.

II. DEEP-SPACE MISSION REQUIREMENTS

The deployment of an optical deep-space network implies considerable investment costs. Therefore, the design of the ground stations network must take into account the current prediction needs for the different mission scenarios in the long term, providing enough flexibility for potential growth. A possible strategy is designing the optical ground stations based on the worst case scenario requirements, so that the performance will scale accordingly for more favorable cases. This approach lacks perspective, mainly since modulation and detection schemes are not optimized for an all-scenario case using current technology. Fortunately, the cost of the ground station is mostly given by the infrastructure, i.e., the size of the effective aperture. Studies from NASA/JPL suggest that optical communications could be designed to operate above 250 Mbps for the near-Mars scenario [6], being 100 Mbps from 1 AU the targeted benchmark value for ESA [7]. Here we adopt the 1 AU hypothetical scenario to derive the high-level requirements, but maintaining the compatibility with the 250-Mbps solution for the near-Mars scenario. In particular, both the 250-Mbps and 100-Mbps data rates can be scaled from 0.42 AU to 1 AU and vice versa, respectively, assuming that either 16-Pulse-Position-Modularion (PPM) or 32-PPM modulation with a 0.5-ns slot width is used. M-PPM is known to be a power efficient modulation, being M the modulation order that coincides with the peak-to-average power ratio of the signal.

Table 1 summarizes the expected performance and key parameters for three representative scenarios including the abovementioned 0.42 AU and 1 AU scenarios. The operating wavelength for the downlink in all cases is 1550 nm, whereas the minimum Solar-Earth-Probe (SEP) angle can be set as low as 7º with barely link degradation. From these results, the 10-m class telescope seems an adequate solution to fulfil existing proposed requirements at both 0.42 AU and 1 AU. Note that, regardless the design of the optical ground station, operations must be prepared to accommodate the large path loss changes of about 12 dB (e.g., for the Mars scenario) and background changes within two orders of magnitude.

The flight laser terminal assumed for calculation purposes is based on a 22-cm diameter telescope, with a transmitted power as high as 5 W.

Table 1. Key high-level parameters for the downlink used as a reference in the subsequent analysis of the optical ground station concept for deep-space optical communications. Code rate can be obtained by comparing link capacity with maximum achievable transmission rate for the PPM modulation

Scenario driver	Data rate (Mbps) (M=16 / 32 for 1 AU case)		Minimum detected signal power (pW)		Mean detected background counts per slot	Aperture diameter (m)
	0.42 AU	1 AU	0.42 AU	1 AU		
250 Mbps at 0.42 AU	250	44 / 62	20	3.5	0.0464	7
10-m class telescope	337	82 / 105	40	7.1	0.0948	10
100 Mbps at 1 AU	366	100 / 125	53	9.4	0.1253	11.5

III. OPTICAL GROUND STATION: OVERVIEW AND CONFIGURATIONS

Telescopes designed for optical communications must basically satisfy three essential functions to handle the downlink, namely, collect signal energy as much as possible, reduce background noise as much as possible, and be able to point to the spacecraft position with sufficient accuracy. The system parameters relevant for the telescope design are associated with the link budget calculations. In particular, the signal is affected by efficiencies and losses corresponding to the various telescope subsystems, as well as by the collection area and the size of the blur circle (atmospheric seeing and optical image quality). The background noise mainly consists of the sky radiance (especially during day time operation), stray light and other extended and point sources (e.g., planets and stars in the receiving field of view), being the critical factors the collection area, the field of view (FOV) both for the detector and telescope, and the optical bandwidth. The rejection of the off-axis illumination due to scattering/reflection from surface roughness and contamination (i.e., stray light) is described by the bi-directional scatter distribution function (BSDF). Polarization is also usually filtered to reduce the background noise contribution. The key large OGS parameters include therefore the effective aperture diameter, the FOV, the optical throughput, the optical bandwidth, the detection efficiency and the blind pointing accuracy, as listed in Table 2. Some of these parameters are now treated in more detail.

A. Effective Aperture

The effective aperture diameter is the main driver of the telescope cost. The search for an inexpensive solution maintaining the required performance leads to different configurations, as explained in section I. To start evaluating the option of a single large aperture, a first reference is the last generation of astronomical telescopes. On the one hand we have a generation of general purpose 8-10m telescopes as VLT, Subaru, Gemini, LBT, Keck and GTC. These telescopes have reached collecting areas from 40 to 100m^2 on a single mount with a very good optical quality in several arcmin FOV, which avoids degrading the atmospheric quality of the best sites in the world. However, all these telescopes have complex wavefront control systems and their cost is higher than 100M€. On the other hand, the Hobby-Ebberly and SALT telescopes have been developed providing collecting areas of approximately 80m^2 with a cost below 50M€. This cost saving comes from the very specific purpose, spectroscopy survey, that permits an extremely simple mount and optics design whose validity for deep space optical communications has to be evaluated, considering the fact that the declination travel range could be limited to the ecliptic.

In the most inexpensive range are the MAGIC telescopes in the Observatory Roque de Los Muchachos (ORM) in La Palma, which reach ~240m^2 collecting area with less than 10M€ cost. This reduced cost is mainly derived from the very relaxed optical performances required for their specific use to detect Cherenkov light, achieving a 1.8arcmin full width half maximum (FWHM) Point Spread Function (PSF). Despite the large OGS has to operate also during bad seeing conditions, not requiring the excellent image quality of the general purpose 8-10m class telescopes, the MAGIC optical quality is too poor requiring a large FOV that does not allow to reject background properly.

The main design driver for a large aperture OGS with certain optical quality is the already mentioned SEP angle, down to 7º, needed to maintain contact with the deep-space satellite (probe) during the maximum possible time. The required day and night operation also pushes to consider solar telescopes as a reference for the large OGS design. The next generation of solar telescopes with optical apertures of 4m, includes the Daniel K. Inouye Solar Telescope (DKIST, USA) and the European Solar Telescope (EST, Europe). These telescopes are designed to point directly to the Sun, so that the solar radiation comes from small angles with respect the optical axis, always illuminating the telescope in the same symmetrical way, and it is easy to safely include specific systems to reject the unused Sun light. However, the thermal problem becomes an issue more difficult to be solved in the large OGS that is going to be unevenly radiated by the Sun in different parts of the telescope structure and in all these conditions the telescope performance shall be granted. In this changing situation, the shadowing produced by a dome can simplify the thermal and safety problems, but implies the investment in a classical dome to protect the telescope, discarding the open air (cheaper) operation. These solar changing conditions are not only a problem for a large OGS, but also for the other configurations.

Telescope arrays provide a convenient way to expand effective aperture size without suffering significant additional performance degradation. This performance degradation can be described by a combination loss parameter that incorporates the effects of tracking and synchronization errors, as well as the additional corresponding losses. Results shown later have been obtained taking into account that the margin of error for the tracking estimation increases as the aperture diameter of the individual element decreases. The adaptation of existing RF antennas to optical communications also supposes an attractive alternative to reduce costs. The main shortcoming is that the FOV for this approach is much larger than for the standard telescopes, leading to high noise background during day-time operation.

B. Receiver and Telescope Field Of View

Diffraction-limited operation is not required for optical communications, and as first approach wavefront control technologies (active optics, adaptive optics), that can reduce the FOV required by the receiver to catch all the satellite photons, will not be considered. The receiver FOV then is closely related to the blur circle size. Blur size is determined by different factors, including the atmospheric and dome seeing, the gravitational sag of the primary mirror, and the surface quality, as well as other mechanical and thermal effects of the system. In general, the FOV for detection should be designed to operate in an atmospheric seeing-limited regime. In this case, the FOV is related to the seeing FWHM, so that FOV≈1.52·FWHM to encircle 80% of signal energy. Since typical seeing values for telescope sites reach 20-25 μrad for low pointing elevations, FOV should be limited to roughly 30-38 μrad. If the other factors were not compensated (e.g., the contribution of surface roughness or gravity sag can amount to values as high as 100 μrad), the blur size could be in the range of 200 μrad. The telescope FOV is, on the other hand, limited by acquisition. Acquisition probabilities of ~99% are achieved for 3σ values of full angular pointing errors.

Table 2. Representative parameters for various optical ground stations configurations. The values shown in the table have been obtained from calculations assuming typical operating conditions, and serve as a reference for the telescope design.

Parameter	Single large telescope	Telescope array	Modified RF antenna
Field of view (signal)	30 μrad	30 μrad	250 μrad
Field of view (acquisition)	300 μrad	300 μrad	6 mrad (TBD)
Effective aperture diameter	10 m (M=32)	13 m (M=64) 10.5 m (M=64, optimized) 9.5 m (M=32, SR=0.8)	45.5 m (M=64) 28.5 m (M=64, optimized)
Optical bandwidth	0.1 nm		
Optical throughput	0.35		
Combination loss	-	0.35–1.5 dB (depending on implementation)	-
Blind Pointing accuracy (rms)	<50 μrad (<5 μrad referencing a standard pointing star)	<50 μrad (<5 μrad referencing a standard pointing star)	1 mrad (TBC)
Background noise	0.05 W/m^2·sr·nm		
Detection efficiency	50%		
Remarks	-	Synchronization and tracking algorithms to reduce combination loss	Large detector size can be optimized taking into account PSF

C. Configurations Comparison

The performance of different configuration approaches (i.e., single telescope, telescope array, and modified RF antenna) is compared in Fig. 1. Here we can observe that telescope array can provide similar results to the single-telescope solution, whereas the modified RF antenna reaches the 100 Mbps requirement at 1 AU for very large effective aperture diameter. The cost for the modified RF antenna should be nevertheless considerably lower. Therefore, the cost analysis and the possibility of future expansion become critical factors to determine the optimum solution. One key aspect in the analysis is the distribution of both signal and background photons collected by the receiver at the focal plane [8][9]. In the case of telescope arrays, the performance can be increased at lower cost than for large apertures by using adaptive optics correction. The optimization of modified RF antennas is attained by adjusting the detection FOV (optimum FOV for the scenario in Fig.1 is obtained when encircling 75% of signal energy, whereas 99.9% is covered by the full detection FOV) [10]. Note that results shown in Fig. 1 include a 3-dB communication margin, and have been computed using the values provided in Table 1 and Table 2 (note also that the peak-to-average power ratio, i.e., the value of M, has been changed to improve performance).

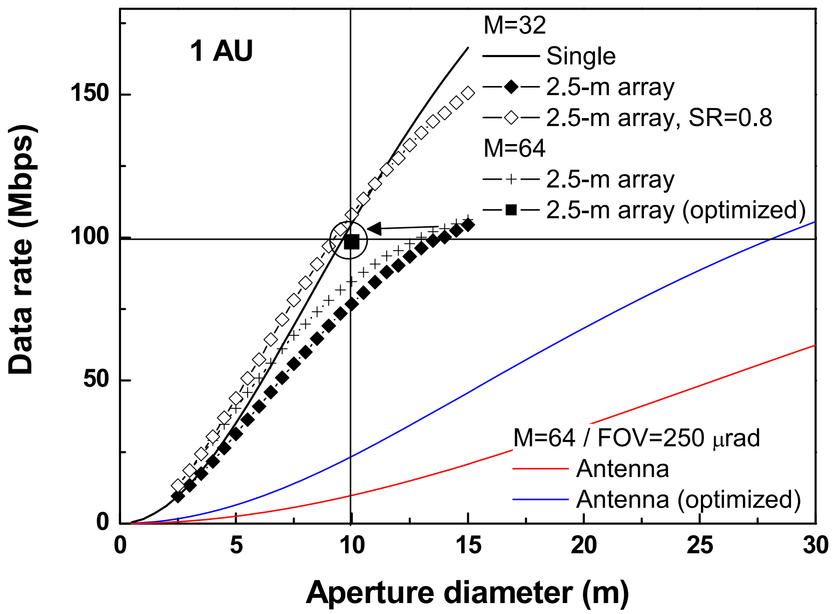

Fig. 1. Achievable data rate as a function of effective aperture diameter for single telescope (single), telescope array (array) and modified RF antenna (antenna) configurations assuming a code efficiency of −0.97 dB. The encircled dot has been obtained using the approach from [8][9]. SR in the open-diamond curve label denotes Strehl Ratio (adaptive optics correction).

IV. KEY SUBSYSTEMS CHARACTERISTICS

The analysis of some of the main subsystems of the OGS for deep space is addressed in this section.

A. Adaptive Optics

The need of an Adaptive Optics (AO) system in a Large Aperture OGS mainly depends on the specific deep-space mission. As a reference, a basic configuration of a 1-meter telescope, observing in 1064 nm, pointing at zenith, with a turbulence coherence length of r_0=10 cm at 550 nm, will deliver a performance of Strehl ratio=0.02. Several deep-space mission scenarios considered for the OGS, like coupling the received signal to a single mode fiber for optical preamplification, require a Strehl ratio of at least S=0.3, which can only be achieved correcting the wavefront by means of an AO system.

Assuming some standard parameters for the AO system, the complexity to achieve S=0.3 can be analyzed. Using a Shack-Hartmann Wavefront Sensor (WFS), with 1 kHz frame rate, 2 frames close-loop delay (from detector readout to deformable mirror positioning) and Fried geometry, we can estimate the WFS subaperture size on sky and therefore the number of degrees of freedom required. With an r_0= 10 cm at 550 nm, the maximum WFS subaperture size to comply with S=0.3 is shown in Table 3.

Table 3. WFS subaperture size on sky to comply with S=0.3 for different wavelengths and elevations

Pointing elevation	Receiver wavelength	Subaperture size on sky
Zenith	1550 nm	d_0=31.3 cm
Zenith	1064 nm	d_0=19.93 cm
20º elevation	1550 nm	d_0=16.44 cm
20º elevation	1064 nm	d_0=10.47 cm

As can be seen, a realistic subaperture around 30 cm will not reach S=0.3 in a wide range of elevations. For low elevation, 15-cm subaperture will still comply at 1550 nm but not at 1064 nm. It has to be emphasized that using an $r_{0=}$10 cm at 550 nm is a conservative choice for a good astronomical site, considering that it is equivalent to a seeing of 1.14". Statistics of several years give a seeing better than 1" at ORM (La Palma) 85% of the year [11]; similar statistical values have been published for Teide Observatory (Tenerife) [12]. This means almost every clear night the AO requirement can be complied in all the operational elevation range with 15-cm subapertures at 1550 nm. This is equivalent to having 7x7 degrees of freedom in a 1m telescope (commercially available systems), or 67x67 in a 10m telescope (in the limit of the present technology).

In addition to the complexity, we have to face the fact that to compensate atmospheric turbulence the Tracking System (tip-tilt compensation) and the AO system (high order compensation) require an intense light source (Guide Star - GS) in the field of view (FOV) close to the target satellite to be used as a reference to measure the wavefront error. Ideally, in the case of optical communications, the reference should be the satellite transmitter, but this implies the use of part of the downlink communication signal for AO, being not possible in all the cases. If we analyze different scenarios, the baseline reference star changes.

For Moon and L2 the downlink communication signal is bright enough to use part of it for the tracking and AO system. For Mars and Jupiter, where we are in a "photon-starved" regime, photons of the communication signal will not be available for the tracking system nor for the AO system. Using the planet as a "extended reference source" could be possible if the angular separation with the satellite is not more than a few arcseconds, but if the separation is much larger than the isoplanatic angle, an artificial laser guide star (LGS) is required. The use of LGS relaxes the required amount of light of the reference for any mission, even though a Natural GS is still needed in the FOV for tip-tilt correction. There are two main effects that affect the performance of AO systems using LGSs: the cone effect and the residual tip-tilt jitter.

The cone effect is due to the finite altitude of the LGS, which is generated in the mesosphere emitting a spherical wavefront that does not pass through all the turbulence the satellite light is crossing. The cone effect induces a systematic degraded correction and thus limits the improvement of the image quality. It becomes more significant for shorter wavelengths, for larger telescopes and for high altitude seeing.

If a LGS is used, the NGS for tip-tilt correction may be faint and far off-axis. The residual error of the tip-tilt correction with the NGS is called tip-tilt jitter and depends on θ_{NGS} , the angular separation with respect to the axis. Simulations have been carried out for the two sets of deep-space scenarios of interest, to evaluate the expected performance. The results are shown in Table 4.

Table 4. RMS error in a LGS system due to tip-tilt jitter and cone effect, and relative performance with respect the Strehl ratio using a NGS (i. e. satellite light) as AO reference, S_{NGS}

	λ (nm)	Tip-tilt jitter rms (rad^2)	Cone effect rms (rad^2)	Telescope Diameter (m)	θ_{NGS} (arcsec)
Case 1 Moon, L2	1550	0.05 (0.95xS_{NGS})	0.02 (0.98xS_{NGS})	1	20
	1064	0.12 (0.89xS_{NGS})	0.05 (0.95xS_{NGS})		
Case 2 Mars, Jupiter	1550	0.36 (0.70xS_{NGS})	0.14 (0.87xS_{NGS})	6	60
	1064	0.75 (0.47xS_{NGS})	0.29 (0.75xS_{NGS})		

We can conclude that the cone effect is a systematic and relatively small error, and that the main error introduced by a LGS system is due to the tip-tilt jitter if the NGS off-axis angle becomes large. The additional degradation in Strehl ratio due to the use of a LGS-based AO system in the large aperture OGS can be tolerated within the error budget, for a NGS up to 60" off-axis and 1550 nm, if the requirement is to achieve a total Strehl ratio of 30%. An additional important conclusion is that receiving at 1550 nm is an advantage from AO performance (or AO simplicity) point of view, for NGS and LGS systems.

B. Uplink functionality

The main reasons for having a laser system at the large OGS are to provide a beacon to assist the on-board terminal Pointing, Acquisition and Tracking (PAT), and to provide optical uplink transmission (basically low-rate command capability).

For short-distance scenarios (Moon, L2), a laser for the uplink is commercially available in several technologies, being the required laser power is tens to a hundred W. For long-distance scenarios (Mars, Jupiter), uplink beacons require several kW average power, available in 1030 nm – 1064 nm technologies. This is an additional reason for choosing 1550 nm technology for the downlink, although using 1030 nm – 1064 nm for the uplink has stronger implications concerning laser safety regulations.

Therefore, key requirements for the uplink laser are:

- Average output power of several kW, power tunable, power stability of tens of W.
- Operating wavelength of 1030 nm or 1064 nm, adequate to optimize the Tx/Rx wavelength isolation both on ground and at the satellite (1550 nm is assumed for the downlink).
- Wavelength control: wavelength control requirements are determined by different factors. The bandwidth of the signal shall be within the bandpass of the on-board narrow band filter used to isolate the Rx path and reduce the background effects. Baseline filter bandwidth is in the order of 0.1 nm, so that a laser wavelength tuning resolution of ±0.02 nm and stability of ±0.02 nm is needed. The spectral bandwidth shall be ±0.05 nm FWHM. Another aspect to be taken into account is the maximum expected shift in wavelength due to the Doppler shift between the relative motion of Earth and spacecraft.
- Beam quality goal of $M^2 <1.2$, $M^2 = 2$ acceptable, the tunable output power can cope with small increase in beam divergence.
- Beam divergence shall be tunable within a realistic range (between 20 and 40 μrad – TBC), that allows to cover different atmospheric turbulence conditions and different average power settings, keeping the required irradiance margins at the on-board telescope aperture. Another reason for using 1550 nm for the downlink is that, assuming the uplink optics deliver a certain beam waist, uplink divergence will be larger for 1550 nm than for 1064 nm.

A good reference for specifying uplink beam parameters is the empirical data collected by ESA OGS at Tenerife in optical link campaigns with ARTEMIS satellite [13]. The nominal divergence of the uplink from ESA OGS (at Teide Observatory) to ARTEMIS satellite was variable between 3.6 μrad and 27 μrad, for a laser at 847 nm with $M^2=2$. An uplink widening factor (beam spread) due to the propagation through the atmospheric turbulence was estimated from the additional losses at the satellite receiver. The beam widening was computed applying theoretical models [14], and compared with experimental measurements on the atmospheric Rayleigh scattering and the far field pattern at ARTEMIS [15]. The results were correlated with atmospheric turbulence strength, determining a beam widening factor of 1.2 for a seeing of 0.8", a typical value of an astronomical site (75% percent of the clear nights at an astronomical site are better than this value [11]), and a widening factor of 1.75 for seeing conditions of 1.45", equivalent to $r_0=8$ cm at 500 nm (90% percent of the clear nights at an astronomical site are better than this value [11]).

Photon counting detectors on board require a stable received signal level that the uplink system shall achieve by using aperture diversity to mitigate atmospheric turbulence effects that contribute to scintillation (mainly beam wander [15]). A minimum of four uplink transmitting subapertures shall be used, separated enough to be uncorrelated from the turbulence spatial point of view (namely, separation larger than the typical r_0 at an astronomical site at Tx wavelength, i.e., 22 cm at 1064 nm and 35 cm at 1550 nm). The signal of the different subapertures shall be also delayed enough to avoid interference between them when the beams overlap in the atmosphere. If a Tx-Rx common optical path configuration is used in the large OGS, the n (four) incoherent apertures shall be configured symmetrically around the telescope central obscuration [15]. The possibility of using different optical paths for Tx-Rx demands the consideration of larger divergences (and consequently higher power) since the tip-tilt correction measured in the downlink cannot be applied to the uplink. Nevertheless, due to the large Point Ahead Angles (PAA) involved in deep-space scenarios (up to 600 μrad), the tip-tilt measured in the downlink could not be valid for the uplink. Different Tx-Rx optical paths have on the other hand the advantage of simplifying the post focal optical design, because isolation of both signals is not needed. The size of the transmitting apertures shall cope with the range of laser divergences.

C. Downlink detectors

The use of a high-power efficiency modulation, PPM, combined with a direct-detection scheme is particularly suitable for deep-space communications since photon efficiency can be traded with bandwidth. As it can be observed in Table 1 and Fig. 1, the PPM channel capacity is better optimized with symbols consisting of a large number of slots (higher M values) in the case of power-starved links or under high background conditions, whereas symbols with a small number of slots (lower M values) are preferred for shot-noise-limited operation. Obviously, saturation of capacity appears at high capacity values due to the limited modulation bandwidth. This detection scheme is, in general, developed using photon-counting detectors.

The main parameters for the design of photon-counting detectors include their detection efficiency, their size (basically, the angular size defined by the FOV for detection), their temporal-handling capabilities (both in terms of bandwidth and timing jitter), their intrinsic dark count rates, and their saturation constraints. Most parameters depend on material and/or device technology. However, specific detection techniques and structures have also been realized to mitigate the limitations imposed using conventional technology (e.g., negative feedback or dividing the device area into multiple pixels to avoid blocking). It is worth noticing that, in principle, the optimum detector size increases with the aperture diameter of the telescope (e.g., due to the change in the focal length) and as the background noise level decreases. A similar behavior is expected when the atmospheric seeing conditions become more severe. These dependences can be used to improve the system performance, taking advantage of adaptive spatial filtering and/or adaptive optics techniques (see, for example, the results shown in Fig. 1) [16]. Required values for the basic photon-counting detector parameters are summarized in Table 5 [6][10][16][17]. Currently, Superconducting Nanowire Single-Photon Detectors (SNSPDs) offer the best approach to develop high-performance photon-counting detectors as those required for deep-space ground receivers. In fact, a successful demonstration using this technology was carried out in the framework of the Lunar Laser Communications Demonstration (LLCD) for links operating at 622 Mbps and high power efficiencies.

Table 5. Recommended values for some relevant photon-counting detector parameters

Detection efficiency	Dark count rate	Timing jitter FWHM	Remarks
50%	<100 kHz	<50 ps	Array >8x8 to reduce blocking losses

V. FIRST COST CONSIDERATIONS

The practical large OGS has been defined to have an effective diameter between 8.7m and 10m to comply with the communication requirements. As already discussed, the collecting area can be achieved by means of a single telescope of 8.7m diameter or by an array of smaller telescopes (e.g. four 4.4m diameter telescopes). As the cost of the telescope goes to the 2.6 power of the diameter, the savings associated to an array of telescopes can be significant. Furthermore, a four meter class telescope can be operated with a conventional monolithic mirror and without any active optics (aperture sizes below 5 m can avoid it), reducing the complexity; and the recurrent cost can be divided among a large number of units to be fabricated (a small series).

Assuming the cost law developed in [18], while the cost of a "generic" optical telescope of 8.7m can be on the range of 100M€, the cost of four 4.4m telescopes can be less than 70M€. The word generic is mentioned as the cost law used does not take into account the complexity associated to a specific type of telescope. This cost saving by using several small telescopes to achieve a total aperture is shown in Fig. 2.

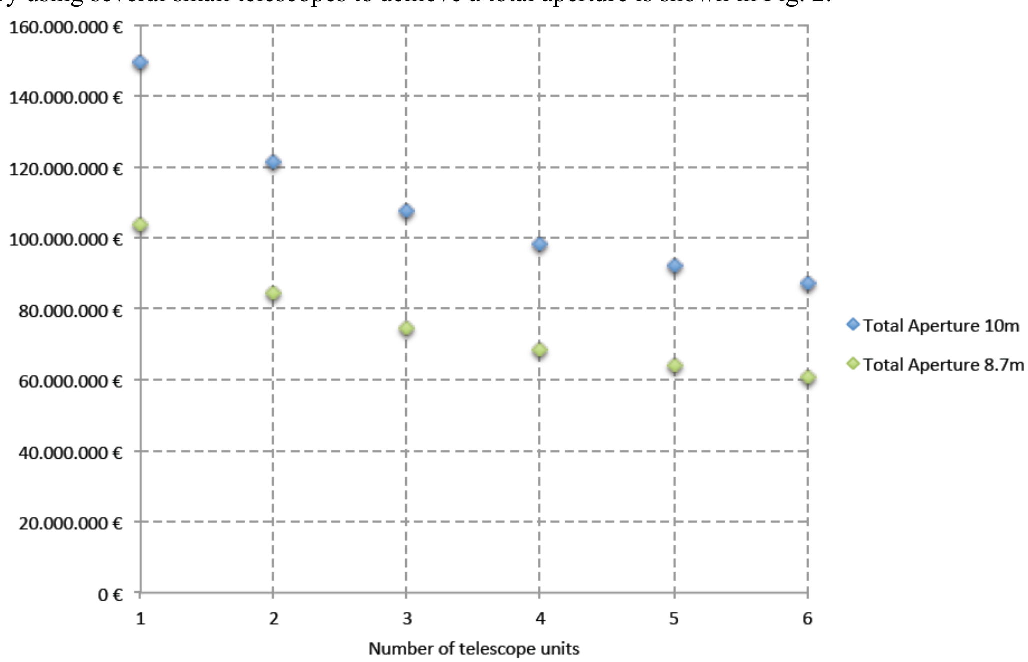

Fig. 2. Cost law for a large OGS of 10m effective diameter (blue) and 8.7m effective diameter (green), as a function of the number of telescope elements (i.e., one element means a single telescope, and a higher number assumes a telescope array configuration).

VI. CONCLUSIONS

In summary, the analysis presented in this paper has shown that in order to satisfy the minimum requirements imposed for deep-space optical communications, large effective aperture telescopes in excess of 7 m must be used. This type of large aperture telescopes exhibits specific features with respect to other existing telescopes devised for astronomical applications that have been studied from both the qualitative and quantitative points of view. Our results indicate that the different configurations analyzed can lead to feasible solutions, being the array of telescopes the preferred option to balance the needs of performance with cost. The adaptation of RF antennas to optical communications has been presented as a promising approach, still at an early stage. In addition, we have addressed the key aspects of main OGS subsystems, providing useful information and illustrative values of high-level parameters that can serve in future telescope design.

REFERENCES

[1] H. Hemmati, A. Biswas, and I. Djordjevic, "Deep-space optical communications: Future perspectives and applications," *Proc. IEEE*, vol. 99, pp. 2020-2039, November 2011.
[2] R.J. Cesarone, D.S. Abraham, S. Shambayati, and J. Rush, "Deep-Space Optical Communications Visions, Trends, and Prospects," *Proc. IEEE Int. Conf. on Space Optical Systems and Applications*, pp. 412-425, May 2011.
[3] H. Hemmati, ed., *Deep Space Optical Communications*, John Wiley & Sons, Hoboken: New Jersey, 2006.
[4] A.J. Hashmi, A.A. Eftekhar, A. Adibi, and F. Amoozegar, "Analysis of telescope array receivers for deep-space inter-planetary optical communication link between Earth and Mars," *Opt. Commun.*, vol. 283, pp. 2032-2042, May 2010.
[5] J.R. Charles, D.H. Hoppe, and A. Sehic, "Hybrid RF / Optical Communication Terminal with Spherical Primary Optics for Optical Reception," *Proc. IEEE Int. Conf. on Space Optical Systems and Applications*, pp. 171-179, May 2011.
[6] H. Hemmati, W.H. Farr, A. Biswas, K.M. Birnbaum, W.T. Roberts, K. Quirk, and S. Townes, "Deep-space optical terminals (DOT)," *Proc. SPIE*, vol. 7923, Free-Space Laser Communication Technologies XXIII, 79230C, March 2011.
[7] R.J. Daddato, K.-J. Schulz, and I. Zayer, "Deep Space Science Downlinks via Optical Communication," *Proc. IEEE Int. Conf. on Space Optical Systems and applications*, pp. 8-13, May 2011.
[8] A. Hashmi, A.A. Eftekhar, A. Adibi, and F. Amoozegar, "Effect of tracking errors on performance of telescope arrays receiver for deep-space optical communication," *Proc. IEEE Aerospace Conference*, pp. 1362-1369, March 2007.
[9] A.A. Eftekhar, A. Hashmi, A. Adibi, and F. Amoozegar, "The effect of synchronization errors on the performance of telescope arrays for optical deep space communications," *Proc. IEEE Aerospace Conference*, pp. 1-7, March 2006.
[10] C. Rivera et al, "On the optimization of the optical ground terminal for deep space communications," unpublished.
[11] C. Muñoz-Tuñón, J. Vernin, and A.M. Varela, "Night-time image quality at Roque de los Muchachos Observatory," *A&A Supplement Series*, vol. 125, pp. 183-193, 1997.
[12] B. García-Lorenzo, A. Eff-Darwich, J.J. Fuensalida, and J. Castro-Almazán, "Adaptive optics parameters connection to wind speed at the Teide Observatory: corrigendum," *Mon. Not. R. Astron. Soc.*, vol. 414, pp. 801–809, 2011.
[13] M. Reyes García-Talavera, S. Chueca, A. Alonso, T.Viera, and Z. Sodnik, "Analysis of the preliminary optical links between ARTEMIS and the Optical Ground Station," *Proc. SPIE*, vol. 4821, *Free-Space Laser Communication and Laser Imaging II*, 2002.
[14] L. Andrews and R. Phillips, *Laser Beam Propagation through Random Media,* SPIE Press, 1998.
[15] M. Reyes García-Talavera et al, "Ground to space optical communication characterization," *Proc. SPIE*, vol. 5892, Free-Space Laser Communications V, 2005.
[16] S. Lee, K. E. Wilson, and M. Troy, "Background Noise Mitigation in Deep-Space Optical Communications Using Adaptive Optics," *IPN Progress Report*, vol. 42-161, pp. 1-16, May 2005.
[17] B. Moision and S. Piazzolla, "Blocking losses on an optical communications link," *Proc. IEEE Int. Conf. on Space Optical Systems and Applications*, pp. 368-377, May 2011.
[18] T. Schmidt-Kaler and P. Rucks, "Telescope cost and cost reduction," *Proc. SPIE*, vol. 2871, Optical Telescopes of Today and Tomorrow 635, March 1997.