Proc. International Conference on Space Optical Systems and Applications (ICSOS) 2012, 3-1, Ajaccio, Corsica, France, October 9-12 (2012)

Design of the ESA Optical Ground Station for Participation in LLCD

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***Abstract*— This paper presents the optical design modifications and implementations in ESA's Optical Ground Station (OGS) to participate in the Lunar Laser Communications Demonstration (LLCD) with NASA's Lunar Atmospheric and Dust Environmental Explorer (LADEE) spacecraft. Due to very stringent optical isolation requirements the transmitter and receiver systems are separated geometrically and a sophisticated alignment scheme has been devised, which is presented. Both the transmitter and the receiver designs are optimized for maximum throughput and the expected link margins are given.**

***Keywords*— optical communications; laser communication terminal; deep-space communications; optical ground station**

I. Introduction

Laser communication technology developments started in the European Space Agency (ESA) in the mid of the 1970s and have continued ever since. In 2001 the world-first optical inter-satellite communication link was demonstrated (SILEX) between the ARTEMIS data-relay satellite in geostationary orbit (GEO) and the SPOT-4 Earth observation satellite in low earth orbit (LEO) [1][2][3][4][5]. The Japanese space agency JAXA joined in the inter-satellite communication experiment with its OICETS satellite in LEO and the French department of defense demonstrated a bidirectional communication link from an aircraft [6][7][8].

SILEX was an important milestone demonstrating that the stringent pointing and tracking accuracies required for laser communication can be mastered in space; although the technology used for SILEX was not able to compete with state of the art radio communication technology in terms of mass (160 kg) and data rate (50 Mbps).

A second generation of Laser Communication Terminals (LCT) with a mass of 35 kg has therefore been developed by the German Space Agency (DLR). They have been launched in 2007 on two LEO spacecrafts (TerraSAR-X and NFIRE) and are demonstrating inter-satellite communication links at 5.6 Gbps over a maximum distance of 6,000 km [9].

The European Data Relay Satellite (EDRS) system will utilize a modified LCT version for its LEO to GEO inter-satellite communications links, which will have a mass of 54 kg and enable data rates of 1.8 Gbps over 45,000 km. EDRS will provide an increase in data availability and use a coherent transmission and reception technology based on a wavelength of 1064 nm.

As an independent check-out facility for LCTs in space, ESA developed the Optical Ground Station (OGS) at the Observatorio del Teide (OT) on Tenerife, Spain. The OGS is used to commission and test laser communication terminals, such as those on the ARTEMIS, OICETS, TerraSAR-X and NFIRE satellites. It is now being prepared to test the LCTs onboard the Alphasat, EDRS-A and EDRS-C satellites.

The first European lunar satellite, SMART-1, was launched in 2005 into a geostationary transfer orbit (GTO) and used electrical propulsion during perigee passes to periodically increase its apogee altitude until caught by lunar gravity. Laser link experiments were performed during apogee passes when the electric propulsion was switched off and SMART-1 was able to turn its camera towards Earth and valuable open-loop pointing acquisition and tracking procedures were exercised.

This document presents the design adaptations that will be implemented in the Optical Ground Station (OGS) and its 1 meter telescope to cooperate in NASA's Lunar Laser Communication Demonstration (LLCD). A Lunar Lasercom Space Terminal (LLST) will be installed onboard the Lunar Atmospheric and Dust Environment Explorer (LADEE) spacecraft and will demonstrate high bidirectional data rates optical links from lunar distances (see Fig. 1).

The paper is organized as follows: In Sect. II the LLCD project is introduced and specifications of the interest are pointed. Next, the OGS is described in Sect. III. Finally Sect. IV discusses the design of the OGS adaptations for the LLCD including: optical, mechanical, and alignment solutions for the high power and accuracy demonstration demands.

II. The Lunar Laser Communications Demonstration

The LLCD shall demonstrate high speed (up to 622 Mbps downlink and up to 20 Mbps uplink) optical communications from the LADEE spacecraft, which will study the pristine state of the lunar atmosphere and dust environment using three science payloads [11].

The LLCD project is being undertaken by NASA's Goddard Space Flight Center and MIT Lincoln Laboratory. A mobile optical ground station will either be located in the White Sands Complex (WSC), New Mexico, or on the

Haleakala volcano on Maui, Hawaii. The Jet Propulsion Laboratory and ESA will participate involving their own specific ground facilities, namely the Optical Communication Telescope Laboratory (OCTL) on Table mountain in California and the OGS in Tenerife. The three ground station approach will demonstrate increased link availability by site and weather diversity. The geographic location of the European and the American ground stations enables mutually exclusive operation.

The launch of LADEE spacecraft is scheduled for August 2013. The LLCD network can be summarized as:

- *Lunar Lasercom Space Terminal* (LLST), weighing ~30 kg, with a 10 cm diameter telescope and ½ Watts of average transmit power.
- *Lunar Lasercom Ground Terminal* (LLGT). 3 optical ground stations are currently planned for LLST data reception and (optionally) to transmit data towards the LLST and perform ranging measurements (Fig. 2).
- *Lunar Lasercom Operations Center* (LLOC) for LLST control. The LLOC will also coordinate all laser link sessions and provide the ephemeris data for telescope pointing towards the LLST, which includes the point ahead angles (PAA).

The LLST will be operated for a total of 16 days during the commissioning and testing phases of LADEE, which is scheduled to last 1 month. During this period, the satellite will be in a ~2 hour lunar orbit at an altitude of about 250 km. LLST operations are limited to 15-20 minutes per orbital pass, so 3-5 laser communication link opportunities per day are expected [12][13]. Thereafter the LADEE science phase will begin and no more laser communication links are scheduled.

A summary of the LLCD operational parameters for the communication link with the OGS are shown in Table I.

TABLE I. LLCD SPECIFICATIONS

Parameter	Detail	Value	Unit
Range	Lunar distance	362,570 - 405,410	km
Wavelength	Downlink	1550.12 ± 0.1	nm
	Uplink Communication	1558.17 ± 0.02	nm
	Uplink Acquisition	1567.95 ± 0.1	nm
Modulation	Downlink	16-PPM	
	Uplink	4-PPM	
Data Rate	Downlink (up to for GCT)	155	Mbps
	Uplink (optional)	20	Mbps
Downlink Irradiance	At border of atmosphere	0.17 - 1.7	nW/m^2
Uplink Irradiance	At LADEE spacecraft	36 - 63	nW/m^2

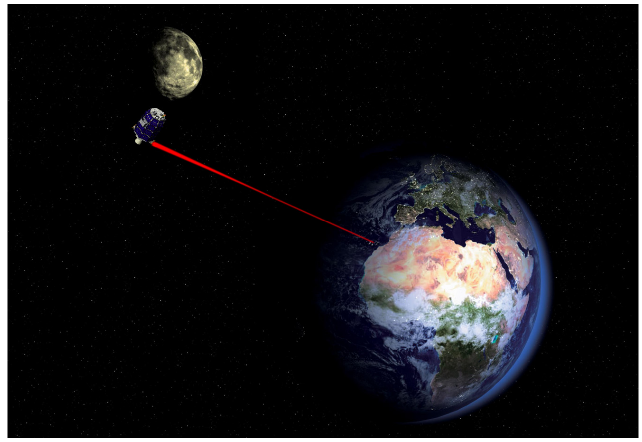


Fig. 1. Lunar laser communication scenario

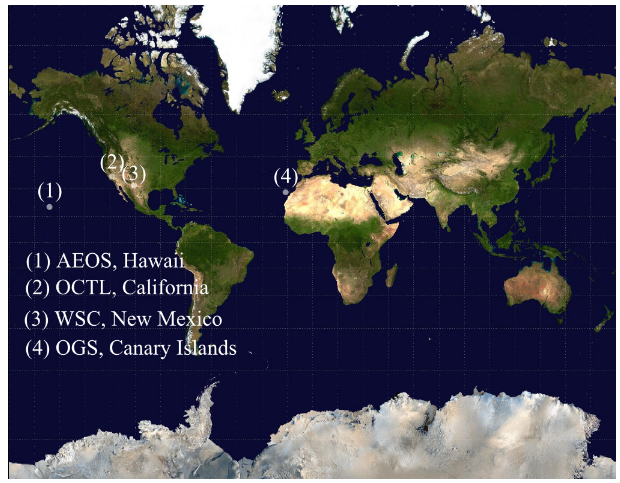


Fig. 2. Lunar Lasercom Ground Terminal

Fig. 3. The Observatorio del Teide

Fig. 4. The OGS building

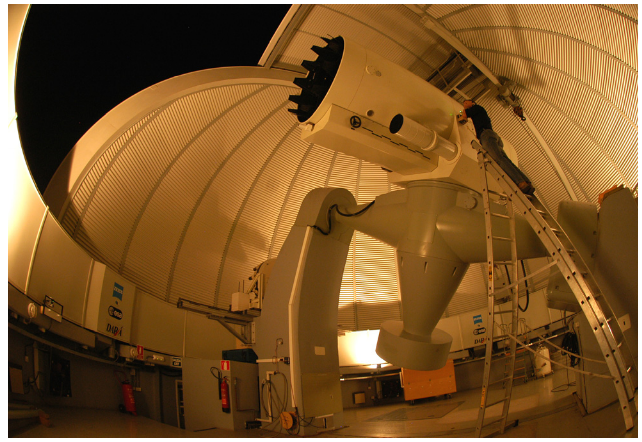


Fig. 5. The OGS telescope in the open dome

III. The ESA Optical Ground Station

The European Space Agency Optical Ground Station is located at the Observatorio del Teide (OT) in the Canary Islands (Tenerife, Spain). Its main purpose is to check out and commission laser communication terminals onboard orbiting spacecraft. In addition the OGS is used for Space Debris, asteroid and near Earth object (NEO) detection and for standard astronomical observations (Fig. 3 and 4).

The Canary island archipelago also offers the opportunity to perform inter-island experiments. From the island of La Palma, at a distance of 142 km, novel laser communications systems and quantum communications (entanglement and teleportation) experiments are being performed.

Table II indicates the location of the OGS and its main Ritchey-Chretien/Cassegrain telescope system parameters (Fig. 5).

TABLE II. Optical Ground Station Specifications

Parameter	Value	Unit
Geographic logitude	16° 30' 36.36"	West
Geographic latitude	28° 17' 58.29"	North
Altitude above sea level	2,393	m
Telescope diameter	1,016	mm
Focal length	13,300	mm

IV. Optical Ground Terminal Design

This section presents the design implementations in the OGS that are required to participate in LLCD. First, link margins are discussed, then receiver and transmitter designs are described. Finally the alignment sequence and the pointing strategy are discussed.

The downlink budget for the acquisition and tracking camera (ATC) is presented in Table III and for Intensified Photo-Detector (IPD) in Table IV, while the uplink budget is presented in Table V.

The downlink budget for the ATC assumes a minimum irradiance from LLST (at the start of acquisition) of 0.17 nW/m^2 (-67.7 dBm/m^2) at the top of the atmosphere, which is put in relation with the expected background noise sources from the blue sky brightness (at daytime) and from the sun-illuminated lunar surface, taking an illuminated ATC pixel area of 60 µm into consideration.

TABLE III. Downlink Budget for ATC

Parameter	Value	Unit
Specified min. irradiance from LLST at the border of the atmosphere	-67.7	dBm/m^2
Atmospheric transmission loss	-1.44	dB
Rx transmission loss (100% on ATC)	-3.15	dB
Rx antenna loss factor per unit area	-1.42	dB/m^2
Power at ATC	**-73.7**	**dBm**
Background from lunar irradiance	-102.2	dBm
Background from blue sky brightness	-99.3	dBm

TABLE IV. Downlink Budget for IPD

Parameter	Value	Unit
Specified min. irradiance from LLST at the border of the atmosphere	-57.7	dBm/m^2
Atmospheric transmission loss	-1.44	dB
Rx transmission loss (90% on IPD)	-3.60	dB
Rx antenna loss factor per unit area	-1.42	dB/m^2
Power at IPD	**-64.2**	**dBm**
Background from lunar irradiance	-77.8	dBm
Background from blue sky brightness	-74.9	dBm

TABLE V. UPLINK BUDGET

Parameter	Value	Unit
Transmitted average power (4 x 40 W)	52	dBm
Tx antenna gain (D = 35 mm)	96.91	dB
Tx transmission loss	-0.45	dB
Tx pointing loss	-1.44	dB
Free space loss	-309.86	dB
Rx antenna gain per unit area	127.11	dB/m^2
Irradiance at LADEE	-35.73	dBm/m^2
Required irradianc at LADEE	-42	dBm/m^2
Link margin	**6.27**	**dB**

The downlink budget for Intensified Photo-Detector (IPD) assumes a tenfold higher irradiance from LLST (when the tracking phase has started) of 1.7 nW/m^2 (-57.7 dBm/m^2) at the top of the atmosphere, which is also put in relation with the expected background noise sources from the blue sky brightness (at daytime) and from the sun-illuminated lunar surface, taking a much larger IPD detector size of 1 mm diameter into consideration. As will be explained later the received power is split such that 90% reach the IPD and 10% the ATC.

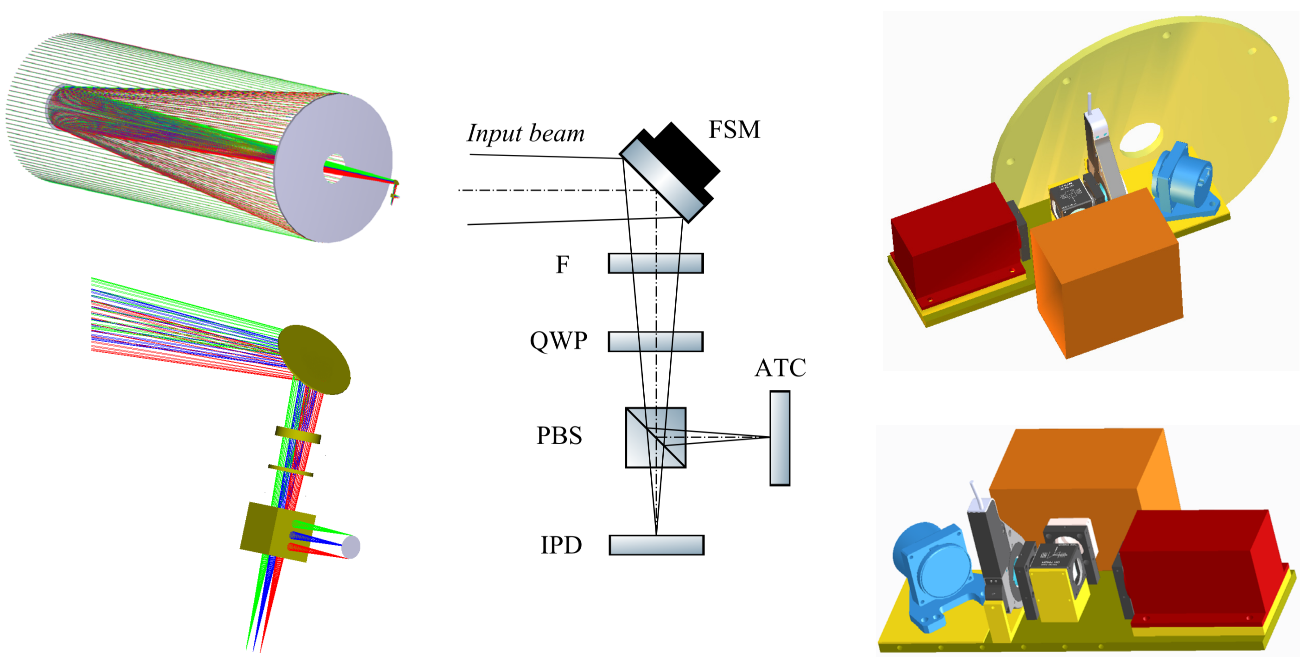
For the uplink budget the LLCD Interface Control Document (ICD) specifies an irradiance requirement at the LLST of 63 nW/m^2 (-42 dBm/m^2) and with a transmitter power of 160 Watts a link margin of 6 dB is expected [14]. The divergence of the transmit beams is 57 µrad, which reduces the pointing requirements.

A. Receiver Design

Due to the weak signal irradiance (see Table III) from the LLST in lunar orbit, the OGS optical receiver design is driven by the need to minimize losses and is therefore installed in the Ritchey-Chretien/Cassegrain focus where the least number of optical elements are present (2 reflective surfaces).

Figure 6 shows the data receiver, an Intensified Photo-Detector (IPD), and the acquisition and tracking camera (ATC) which are located at the primary focus as well as some additional elements, namely a tip/tilt fast steering mirror (FSM) to adjust the point ahead angle (PAA), a narrow band-pass (2.4 nm FWHM) interference filter (F), a computer-rotatable quarter-wave plate (QWP) and a polarizing beam splitter (PBS). As the receive beam is circularly polarized the QWP and PBS pair enables continuous adjustment of power ratio between IPD and ATC. During the initial satellite acquisition all power is directed towards ATC, until the mutual irradiance at both terminals increases. Then the optical power towards the ATC is reduced (to the minimum level required to perform telescope pointing corrections) in favor of providing maximum power to the data receiver.

The design does not include a fast tip/tilt compensation loop, because a data receiver's field of view (FOV) of 75 µrad is assumed to cover all potential angles of arrival fluctuations.

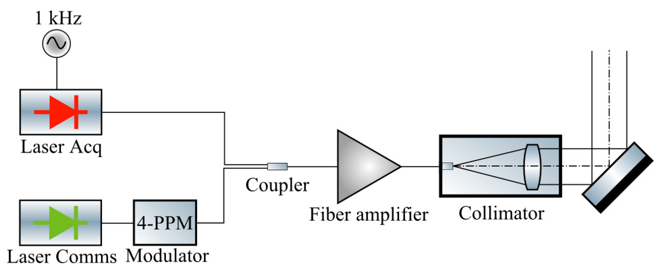


a) Optical simulation layout

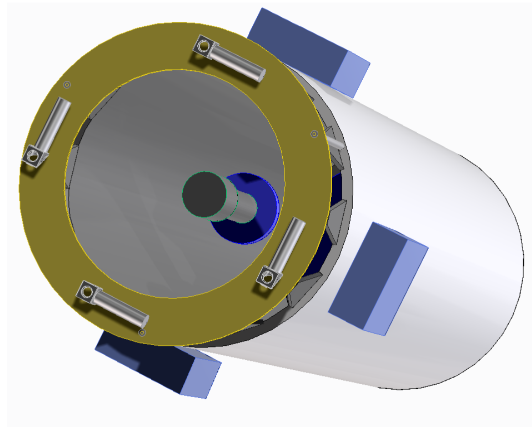
b) Optical components layout

c) Mechanical design of the focal plane

Fig. 6. Receiver Design



a) Block diagram of one of four transmitter laser systems that will be used for the LLCD. The fiber coupled acquisition and communication seed lasers are combined and connected to a high power fiber amplifier. The amplified laser radiation is then collimated and transmitted towards the target.



b) View of the telescope aperture with the four laser collimators and 90 degrees deflection mirrors mounted on a ring structure. The fiber amplifier boxes are mounted to the side of the telescope tube.

Fig. 7. Transmitter Design

B. Transmitter Design

The design of the transmitter system is driven by the stringent optical isolation requirements associated with a lunar communication link. Four individual transmit apertures with 35 mm diameter are mounted onto a ring structure that is attached to the telescope aperture. Four collimation packages, shown in Fig. 7, transmit beams towards angularly adjustable mirrors, which deflect the beams by 90 degrees. Each collimation package is connected to a 40 Watt fiber amplifier (Manlight) with a 0.18 numerical aperture fiber. The high power amplifiers are driven by four individual laser diode pairs (Thorlabs) of which the acquisition laser is modulated with 1 kHz (as required for LLCD acquisition) and the communication laser with 4-PPM modulation at 20 Mbps. The transmitter concept with four mutually incoherent beams that cannot interfere themselves in the far field should considerably reduce scintillations at the spacecraft.

In order to minimize their output fiber length (to avoid non-linear effects such a stimulated Brillouin scattering) the four amplifiers are attached to the side of the telescope tube, while the seed laser and their modulation systems are located in the dome area and connected to the amplifier modules via long polarization maintaining fibers.

C. Receiver/Transmitter Alignment

In order to align the optical axes of transmitter and receiver a high precision (<1 arcsecond) corner-cube retro-reflector (CCRR) bar (Fig. 8) will be placed in front of each 35 mm diameter transmit beam such that the retro-reflected beam enters the telescope aperture. A retro-reflector bar can be seen as a cut-out of a large CCRR that is used for lateral displacement of the retro-reflected beam, while maintaining perfect parallelism. With the FSM set to its zero position, each transmit beam is individually centered on the acquisition and tracking camera (ACT) by aligning its 90 degree deflection mirror. Diffraction will enlarge the point spread function (PSF) on the camera from each transmit beam by a factor of 30 beyond the PSF diameter from the satellite, which needs to be taken into account during alignment. However, the diameter represents the true far field divergence of each transmit beam.

Once all four beams are located at the same position on the acquisition and tracking camera (ATC) aligned is achieved.

D. Pointing, Acquisition and Tracking

To start acquisition the OGS telescope points in open loop towards the nominal position of the LLST, the pointing direction of which is given by a satellite tracking file distributed by the LLOC a couple of hours before the link experiment. The lasers are switched to full power and the point ahead angle is adjusted via the FSM. The QWP is rotated such that all power is deflected onto the ATC. At the UTC start time of the link session the OGS telescope performs a spiral scan around the nominal satellite position with increasing diameter such that the irradiance drop in the far-field is no more than 50% of maximum irradiance.

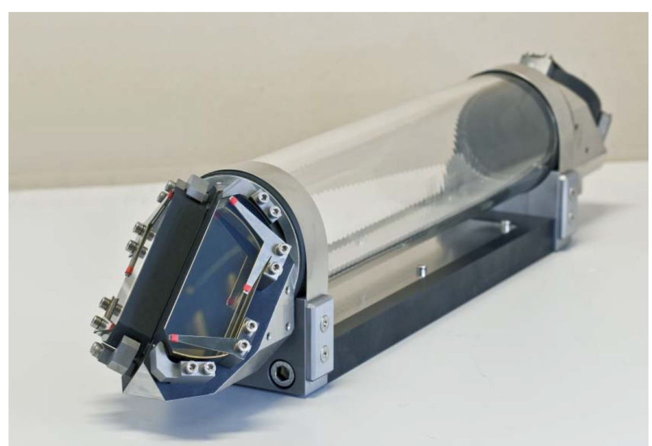


Fig. 8. Corner-cube retro-reflector bar with 50 cm length and 50 mm aperture

As soon as the LLST is illuminated, it directs its own laser beam towards the OGS and upon detection the telescope gimbal stops its spiral scan and centers the LLST beam on the ATC. Finally the QWP is rotated such that minimum power (that is required for tracking error compensation) is deflected towards the ATC and the power on the IPD is maximized.

For initial acquisition the OGS will scan its pointing uncertainty cone, where each point in the far field needs to be illuminated for 1.5 seconds and the duration of the scan shall not exceed 4.5 minutes [14]. With the divergence of transmit beams of the OGS an uncertainty area with a diameter of around 500µrad will be covered.

V. Conclusions

The technical adaptations and design implementations required in ESA's Optical Ground Station to participate in the Lunar Laser Communication Demonstration (LLCD) with NASA's LADEE spacecraft have been presented. The design combines maximum telescope throughput with minimum cross talk between transmitter and receiver.

The transmitter and receiver alignment strategy has been explained and a link budget calculation performed, which includes external noise sources from the blue sky brightness and the sun-illuminated lunar surface.

Acknowledgment

The authors would like to thank John Rush, Donald Cornwell, Joseph Kovalik from NASA and Klaus-Jürgen Schulz from ESOC for helpful discussions.

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