

# **Enhanced Data Return from Lunar Farside using RF-Optical TT&C**

T. Dreischer, M. Tüchler, K. Kudielka and G. Baister  
Oerlikon Space AG, Schaffhauserstrasse 580, Zürich CH-8052, Switzerland

D. Giggenbach and F. Moll  
German Aerospace Center (DLR), Institute of Communications and Navigation,  
Oberpfaffenhofen, P.O. Box 11 16, D-82230 Wessling, Germany

## **Summary**

Science return and high bandwidth communications are key issues to support the foreseen endeavours on spaceflights to the Moon and beyond. For a given mass, power consumption and volume, laser communications can offer an increase in TM bandwidth over classical RF technology allowing for a variety of new options, specifically to missions that require very large distances, such as to the Moon and even beyond. This increase in TM data rate allows for more raw scientific data to be sent back to Earth where data processing can be performed on ground. Enhanced sensing techniques could be used that generate more science data and access during flight could be faster. This paper presents an overview of proof of concept test results obtained for optical telemetry return in a field test campaign together with ESA in October 2007. Based on the results obtained, a sample mission is outlined that shows an optical relay on a HALO trajectory at lunar farside, using an integrated RF-optical TT&C transponder concept.

## **1. Introduction**

Taking a look at the routine ARTEMIS / SPOT4 optical intersatellite link [1] and the novel coherent lasercomm demonstration on TerraSAR [2], there exist today a variety of space qualified optical intersatellite link terminal technologies, and European industry is successfully demonstrating to cope with the very challenging accuracy requirements for pointing, acquisition and tracking demanded by the small divergence of laser beams. This encourages the idea to exploit the recent achievements on optical communications in near-Earth orbits also for supporting missions to the Moon and beyond.

Pure space-based telemetry relays, for instance from the Moon to a GEO satellite, are limited by the achievable optical antenna size and mass on both spacecraft. On-ground antennae can be at least about ten times larger in diameter which still outperforms the effect of atmospheric channel disturbances. Based on [3], for the price of an NGST-Rebuild spacecraft, one could afford an optical subnet of eight or nine 10m class Optical Ground stations (OGS). Latter provide a significant advantage over a single Earth-orbiting optical relay as the OGS network can

provide multi-spacecraft support whereas at comparable cost the Earth orbiter as a single spacecraft can only track a single deep space satellite at a given time. Moreover, a 10m class OGS subnet can be established gradually, spreading cost over time, based on state-of-the-art technologies that are sufficient to support interplanetary optical communications

Today's technologies allow for adapting existing free space lasercomm systems for use in an optimal communications subsystem for a lunar relay mission. Since 2003, Oerlikon Space has been investigating together with ESA the optimal use of lasercomm for an integrated RF-optical TT&C subsystem for deep space applications [4]. Next to initial laboratory testing, proof of concept field tests have successfully been carried out in October 2007 to validate the achievable data transfer of 10 Mbps under worst case conditions for a simulated link distance of 1.5 million kilometres. A follow-up test campaign is planned for September 2008, this time targeting at 300 kbps over 400 million kilometer link distance, including atmospheric turbulence effects at the receiver optical ground station.

In the following sections we introduce the principal concept of a hybrid RF-optical TT&C subsystem, followed by the description of results from a breadboard development project (DOLCE) to validate the use of pulsed laser communications for optical telemetry from deep space. An extrapolation is then given for an assumed HALO mission at the farside of the Moon that is used for permanent data relay to the Earth. Long-term cloud-cover data is analyzed to identify the optimum number, positioning and combination of optical ground station telescopes to ensure optimum availability. The impact of the turbulent atmosphere on different PPM receiver technologies is evaluated and taken into account in the link budget.

## **2. System Concept for RF-optical TT&C**

The need to provide operability and deep space mission coverage via well-known RF means has lead to an integrated approach, using a hybrid RF / Optical TT&C system where the optical link is used exclusively for sending science data to Earth, the on-board optical terminal mainly being used as a high-rate optical transmitter. The advantage of such an integrated system is that it increases the telemetry with respect to current RF TT&C approaches, whilst ensuring full TT&C coverage during the entire mission. Also at critical mission phases, such as the near Earth cruise phase as well as target insertion and solar conjunction, operability via well-known RF means can be ensured

As shown below in Figure 1, the link architecture comprises three elements, an RF Earth station, an optical ground station and an on-board RF-optical TT&C subsystem that consists of a classical RF part and the optical TM subsystem. Depending on the required telemetry rate, mass and volume of the optical TM subsystem can vary considerably. The RF link is permanently available in both directions and can be used to trigger times of high rate optical telemetry transfer.

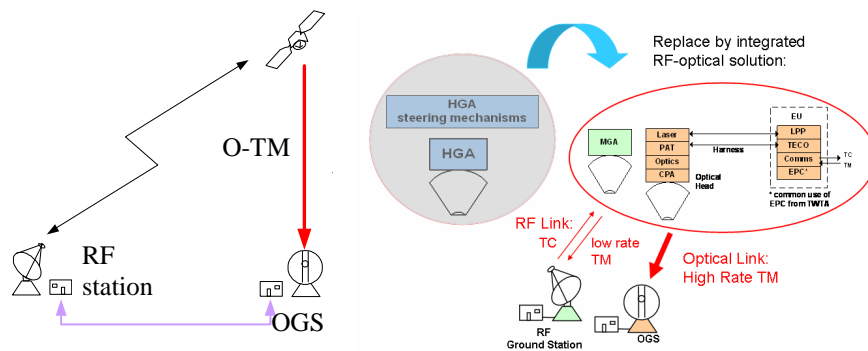


Figure 1. Replace RF TT&C by integrated RF-optical TT&C at same mass and power

### 3. Field Test Results from ESA Project DOLCE

Based on such a hybrid RF / optical concept, a proof of concept field test campaign was carried out in 2007 under the ESA project DOLCE (Contract No. 19753/06/NL/PM), successfully demonstrating a 10 Mbps downlink over scaled 1.5 million kilometres link distance between the two islands La Palma and Tenerife, as indicated by Figure 2. A transmit laser was located at the parking lot of the Nordic Optical Telescope and the receiver was placed at ESA OGS, Izaña.

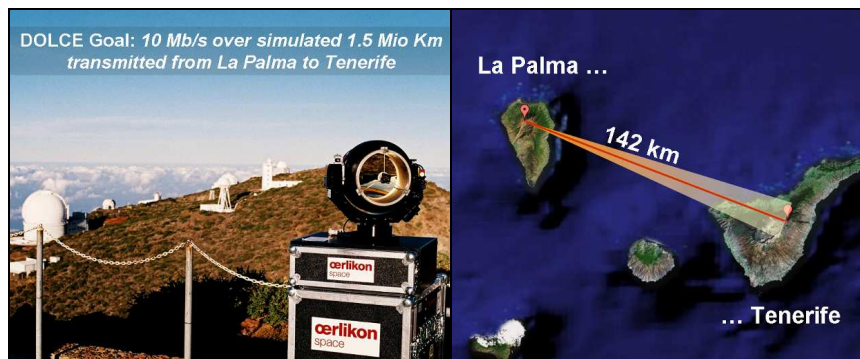


Figure 2: DOLCE inter-island link: 10 Mbps over simulated 1.5 Mio. km to 1 m OGS

As shown in Figure 3, the mission scenario included a science spacecraft at Liberation Points L1 or L2 which transmits optical telemetry with a 135 mm telescope to the ESA Optical Ground Station on Earth with a 1 meter telescope. During the simulated link, the crossed horizontal path between the islands involved 144 km of atmospheric turbulence, much more than expected for a nominal link from Liberation Points L1 or L2. This has proven the robustness of the chosen modulation format to atmospheric disturbances.



Figure 3: DOLCE mission scenario - optical telemetry link from L2 to OGS on Earth

The deep space laser communications terminal design for telemetry links from L1 / L2 back to the ESA optical ground station (OGS) is based on a pulsed laser communications subsystem using a PPM format. A wavelength of 1059 nm has been implemented. It matches efficient average-power limited amplifiers and sensitive, high-bandwidth, large-area photo detectors. Pulse-position-modulation uses short duration, high peak power pulses as a communication protocol selected due to the high receiver sensitivity that can be achieved when detecting optical pulse information within a noise limited system as is the case within optical links through the atmosphere.

Simulations of the BER performance for the pulsed laser communications link with a user data rate of 10 Mbps have shown that the optimal receiver sensitivity of -70 dBm for a BER of  $10^{-6}$  can be achieved with the parameter set in Table 1.

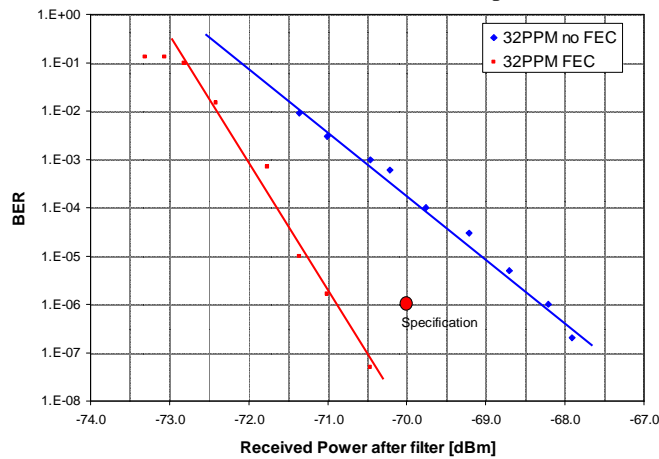


Figure 5: Specified and achieved DOLCE Receiver Sensitivity

Modulation alphabet size	32-PPM	Slot duration	10 ns
Laser pulse duration	10 ns	Symbol period	370 ns
User data rate	10.0 Mbps	Emitted Tx optical power	1 W

**Table 1: PPM Symbol Definition for DOLCE**

A comparison of the link budgets for the deep space link from L1 / L2 with that of the DOLCE inter-island communication link experiment is shown in Table 1. In deriving the link budgets it has been assumed that the aggregate excess loss, due to atmospheric propagation and technical implementation, remain the same in both cases. In our opinion this assumption is valid since the OGS implementation could remain as it is and for elevations  $>15^\circ$ , the atmospheric loss and scintillation will be more benign due to a shorter path in the atmosphere, without any turbulence close to transmitter like during the DOLCE tests.

Parameter	DOLCE I2CL			Liberation Point L2		
	Value	Unit	Remark	Value	Unit	Remark
Tx power	14.0	dBm	25mW	30.0	dBm	1W
Tx antenna gain	45.6	dB	$G = \frac{8}{\theta^2}$ $\theta = 14.8\text{mrad}$	116.5	dB	$G = 0.8145 \frac{\pi^2 D^2}{\lambda^2}$ D = 0.25m
Free-space loss	-244.5	dB	$\left(\frac{\lambda}{4\pi z}\right)^2 z = 142\text{km}$	-325.0	dB	$\left(\frac{\lambda}{4\pi z}\right)^2 z = 1'500'000\text{km}$
Rx antenna gain	129.1	dB	$G = \frac{\pi^2 D_r^2}{(D/m)^2} = 1.016^2 \cdot 0.33^2$	129.1	dB	$G = \frac{\pi^2 D_r^2}{(D/m)^2} = 1.016^2 \cdot 0.33^2$
Power on Rx aperture	-55.8	dBm		-49.4	dBm	

**Table 2: Comparison of DOLCE I2CL and L2 link budgets ( $\lambda=1058\text{nm}$ )**

The Tx power was set so as to achieve a stable link at the OGS at a data rate of 10 Mbps with 32-PPM. The measured receiver sensitivity was -68.9 dBm at the DOLCE APD. For the above conditions the extrapolated Rx power at the entrance aperture of the ESA OGS is -55.8 dBm. If we calculate the extrapolated Rx power at the OGS aperture for a link from L2 then the expected Rx power is -49.4 dBm. The downlink from the L2 therefore has a link margin of 6.4dB with respect to the sensitivity limit evaluated in the DOLCE I2CL.

#### 4. Sample Mission Example: “Data Relay from Lunar Farside”

The successful results of the DOLCE test campaign suggest investigating its potential for optical link topologies in the Earth Sun system. Already in 1966, NASA proposed to use HALO trajectories near the Moon for data relay. A very interesting scenario is to place a HALO at the lunar farside, thereby allowing for transmitting telemetry permanently to the Earth while receiving data both, from Moon orbiting spacecraft and from lander vehicles on the backside of the Moon.

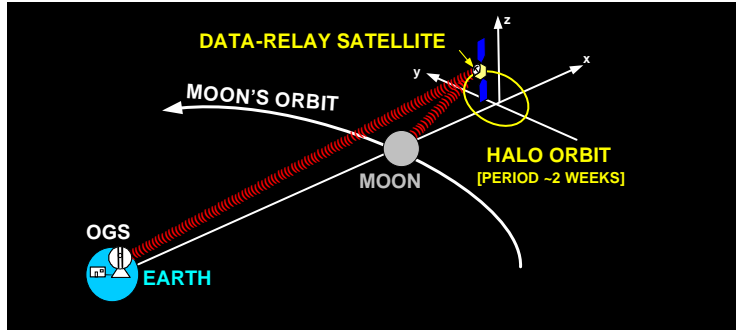


Figure 6: Data relay from HALO at the Moon: direct downlink via optical telemetry

An example HALO trajectory from ESOC was analysed briefly for this paper, leading to the trajectory profiles shown below in Figure 7.

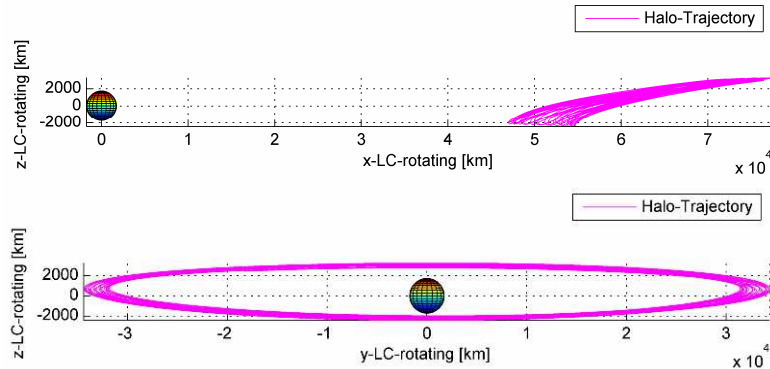


Figure 7: HALO trajectory data from ESOC for optical link analysis

Interestingly, there only pointing coverage is required, assuming an Earth pointing attitude of the data relay satellite, like shown in Figure 8.

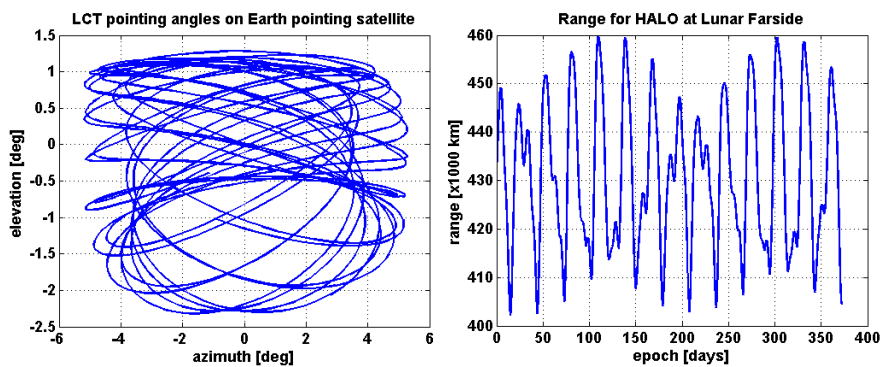


Figure 8: Pointing angles and range on HALO at Lunar Farside, Earth pointing

#### 4.1: Link Budget for Optical Telemetry from Lunar Farside

For Earth based optical telescopes, reception at daytime conditions will lead to background contribution by the daytime sky, followed by sunlight partially reflected by the Moon in the receiver's field-of-view. A *worst case daytime* link was analysed, with a standard 10 nm optical filter bandwidth at 1059 nm, close Sun-Earth-Probe angle of 6 deg. A MOPA laser with 55 MHz PRF has been used, providing 6 ns pulse width and maximal pulse energy of 5  $\mu$ J, 1 W average power.

Based on the experience from [1] and taking into account above parameters, Table 3 shows two optical link budgets, assuming a 10 cm telescope in space segment and a 1m OGS at 2.5 km altitude or a 0.4m OGS at 600 m altitude.

		1 m OGS, 2.5 km alt.	0.4 m OGS, 600m alt.
Lunar Farside Optical Link Budget	wavelength	$\lambda$ [nm]	1059
	link distance	L [km]	461'000
	average transmit power	$P_T$ [dBm]	30
	TX antenna diameter	$D_T$ [m]	0.1
	TX telescope efficiency (Schiefspiegler)	$\eta_T$	1
	TX gain	[dB]	109.4
	TX losses	$A_T$ [dB]	-1
	TX pointing loss	$e_T$ [dB]	-3
	free-space loss	[dB]	-314.8
	atmospheric transmittance	$A_{atm}$ [dB]	-2
	RX antenna diameter (nominal)	$D_R$ [m]	1
	RX telescope efficiency, obscuration	$\eta_R$	0.9
	RX gain	[dB]	128.9
	RX loss incl. Scintillation Loss	$A_R$ [dB]	-7
	receive power at detector (optical)	[dBm]	-59.4
	background power at detector incl. attenuation by atmosph.+ Rx path, SEP = 6.0°, 2.2km alt., 10 nm filter	[dBm]	-61.1

Table 3: Link Budget Calculation for Daytime Downlink from Lunar Farside

#### 4.2. Availability aspects and resulting optical TM capacity per day

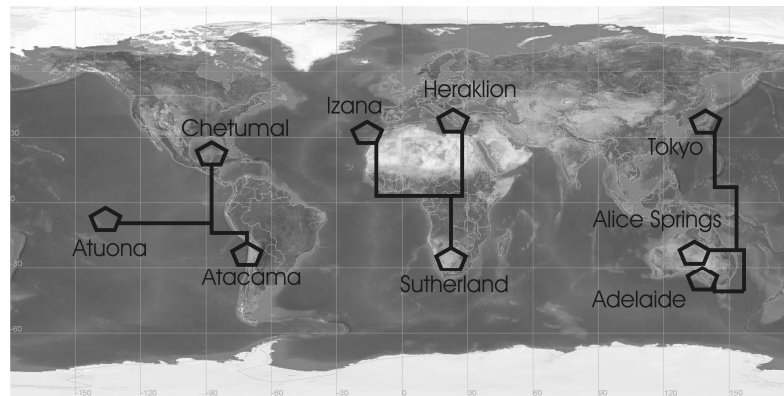
The concept of optical data return links from space has been proven by the experiment KIODO [5]. However, the optical down link to earth is only working without blocking clouds in the line of sight. To mitigate link blockage by clouds, OGS-sites must be chosen at favourable locations regarding cloud coverage. Furthermore, multiple OGS-sites with uncorrelated cloud cover statistics should be combined in an OGS-subnet to boost the overall system availability ("OGS-diversity concept"). This concept has been treated in detail by examining long-term cloud cover statistics of several potential global OGS sites [6]. In the following a first analysis of availability of the HALO ground station network is given. This is done by using ground observations of cloud coverage<sup>1</sup> over a period of ten years nearby the places of interest which are mainly astronomical sites in operation like on Tenerife (Teide Observatory), on Crete (Capella observatory), the Atacama desert (Paranal Observatory) or Sutherland (South African

<sup>1</sup> This measurement gives the possibility of a first analysis of the link availability. A more comprehensive analysis can be done by using several data sources like data from earth observation satellites. This is a matter of ongoing research.

Astronomical Observatory). To enable a permanent lunar downlink, the rotation of the earth requires typically three OGS-subnets for 24/7 operation [3]. Here each subnet comprises three ground stations as illustrated in Figure 9. For simplicity of the analysis it is assumed that every subnet has a line of sight to the satellite for eight hours. Following [8], the distances between the sites are assumed to be long enough to show uncorrelated weather conditions.

Here we analyze the mean availability of the following OGS-combinations:

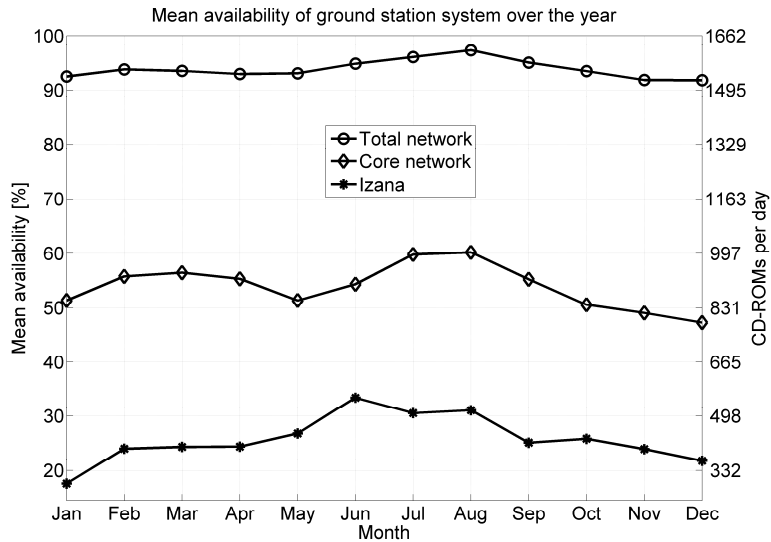
- 1) A single OGS on Tenerife (Izana).
- 2) Three OGS distributed around the earth with approx.  $120^\circ$  longitude separation. These form the core network and are assumed at Chetumal (Mexico), Heraklion (Crete), and Adelaide.
- 3) Three OGS-subnets of three OGSs each, with approx.  $120^\circ$  longitudinal separation as depicted in Figure 9.



**Figure 9: Global distribution of ground stations. The network is grouped into three clusters each comprising three ground stations. The core network contains Heraklion, Adelaide and Chetumal which are approximately separated by  $120^\circ$  longitudinally.**

When calculating for an 8 hour operation per day per OGS-subnet (implying typical minimum elevations of  $15^\circ$  to  $20^\circ$ ) and a 9 hour operation of the single-OGS at Tenerife, the resulting availabilities and throughput are shown in Figure 10. As a reference a data rate of 100 Mbit/s is chosen that can be easily obtained with the presented link budget.





**Figure 10: OGS-network availability and mean daily throughput (CD-ROMs á 650 MB) over the year for three setups. A data rate of 100 Mbps is assumed. Data from ground observations of cloud cover over a period of ten years are used. The low availability of a single OGS in Izana is given by the reduced visibility to the moon due to earth's rotation.**

Obviously, an availability above 90% can be guaranteed all-season with the three-cluster network. It has to be noted that link unavailability due to cloud blockage is a temporary situation (lasting only minutes to few hours), this requires only short buffering of the data stream on the orbiter until the link is established again.

#### 4.3: Conclusions

State of the art technology is available today that allows mission planners to consider missions to the Moon using an optical TM subsystem, comprising a 1m OGS located at an astronomical observation site like Izana, Tenerife or a 0.4m OGS placed at an arbitrary site, e.g. a rooftop of a university building that would allow us to obtain TM capacities of several hundreds of Gbytes per day via optical telemetry. A total network of 1m class OGS together with a 10 cm optical TM terminal at the Moon could fill almost 1'500 CD-ROMs per day. The optical TM subsystem would form part of a hybrid RF – optical TT&C terminal that uses an optical transmitter based on the same MOPA architecture as successfully tested in the ESA project DOLCE [2]. Another aspect is to couple the received light into a singlemode fiber at the receiver by means of adaptive optics to make use of fiber-preamplification before detection. This would boost receiver sensitivity by about +6 dB, allowing even larger data rates on the downlink without having to increase transmit power or the receiver aperture. Currently, Oerlikon Space is developing for ESA a representative PPM breadboard for an even higher link distance of 400 million kilometers, to be tested in autumn 2008 on the Canary Islands.

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## Acronyms and Abbreviations

BER	=	Bit Error Rate	OGS	=	Optical Ground Station
ESA	=	European Space Agency	OOK	=	On-Off Keying
ESO	=	European Southern Observatory	OSZ	=	Oerlikon Space, Zurich
HGA	=	High Gain Antenna	PPM	=	Pulse Position Modulation
MGA	=	Medium Gain Antenna	TM	=	Telemetry
MOPA	=	Master Oscillator, Power Amplifier	OTM	=	Optical Telemetry