INTEGRATED RF-OPTICAL TT&C FOR A DEEP SPACE MISSION

T. Dreischer (1), M. Tuechler(1), T. Weigel(1), G. Baister(1), P. Regnier(2), X. Sembely(2), R. Panzeca (3),

*(1) **Oerlikon Space AG***
Schaffhausser Str. 580
8052 Zurich, Switserland
E-mail: Thomas.Dreischer@oerlikon.com, Michael.Tuechler@oerlikon.com,
Thomas.Weigel@oerlikon.com Guy.Baister@oerlikon.com

*(2) **Astrium SAS***
31 rue des Cosmonautes,
31 402 Toulouse Cedex 4, France
E-mail: Pascal.Regnier@astrium.eads.net , Xavier.Sembely@astrium.eads.net

*(3) **GMV Aerospace & Defence S.A***
c/ Isaac Newton 11
28760 Tres Cantos, Madrid, Spain
E-mail: rpanzeca@gmv.com

Abstract – 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 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 liberation points L1 and L2, eventually aiming even at deep space missions such as those being planned to Mars within the ESA AURORA programme. On-board raw data processing could then preferably take place on ground, making use of latest technology further developed during the cruise phase of the probe. Enhanced sensing techniques could be used that generate more science data, and access during flight could be faster. This paper describes an integrated RF-optical TT&C subsystem suited for an application on the Mars Sample and Return mission, based on state-of-the-art technology, with emphasis on the concept design of the on-board optical telemetry transmitter. The integrated architecture provides enhanced downlink capacities through the use of an optical link, while spacecraft navigation and telecommand are ensured by classical RF means.

1. INTRODUCTION

Next to mass and power reduction as one of the main targets of each deep space mission, future TT&C subsystems will have to accommodate the demand for extra link capacity. In addition to investigations on bandwidth-efficient modulations, a move to higher frequency bands is an additional option to be analysed. In this context, the use of optical frequencies for deep space communications is widely considered as a promising solution.

Recent studies conducted by Oerlikon Space under ESA contracts investigate the concept of an integrated RF-optical TT&C subsystem. The advantage of such an integrated RF-optical TT&C subsystem is that it increases the telemetry with respect to the current RF TT&C approach, all while ensuring full TT&C coverage via well-known RF means also at critical mission phases, such as the near Earth cruise phase as well as at target insertion and events of solar conjunction. Together with its partners, Oerlikon Space currently performs the "ROSA" study for ESA that investigates on the benefits of OTM for a possible application on the MSR mission, compared to the required mass/power and volume for the on-board optical transponder. To obtain realistic OTM access figures, cloud-free line-of-sight investigations have been superimposed at each of the local sites considered, based on the database CDFS-II, to round off a realistic application scenario.

Taking a look at the routine ARTEMIS / SPOT4 optical intersatellite link and also considering a variety of existing next generation optical intersatellite link terminal developments, for instance the coherent lasercomm terminal flying on TerraSAR [5], 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 suggests to analyse the useability of today's free space lasercomm systems to provide optical telemetry (OTM) to deep space applications and to estimate the effort required for an adaptation of relevant subsystems to dedicated mission.

2. OTM APPLICATION EXAMPLE: MARS SAMPLE RETURN MISSION

The objective of the Mars Sample Return mission is to collect samples of the Martian soil and to bring them back to Earth. Two composites that are launched separately by two Ariane 5 launchers.

- The first composite consists of a Martian orbiter, and the Earth Re-entry Capsule (ERC).
- The second composite is made of the Descent Module (DM) together with the Mars Ascant Vehicle (MAV), and the carrier. Four main mission phases are distinguished:

I. The launch, transfer and Orbit Insertion of the first composite.
II. The launch and transfer of the second composite, and the landing of the Descent Module.
III. The Mars operations, including the sample collection, the ascent to orbit, the Rendezvous with the orbiter, the transfer operations within the orbiter (sealing and transfer into the ERC) and the Mars Escape Manoeuvre.
IV. Finally the return transfer and the Earth Re-entry of the ERC.

In the frame of the present ROSA study, the emphasis is on mission phase III, focussing on the orbiter, since the hybrid RF-optical TT&C system shall be designed for the link between orbiter and Earth. During that third phase, the current MSR mission parameters lead to extreme boundary conditions on link distance, solar conjunction and daytime access times. It thereby contitutes an interesting example for pointing out the benefits and limitations of an OTM application in deep space, based on 2007 state-of-the-art technology.

2.1 OTM Objectives

Although the main objectives of MSR are not dedicated to collecting a high amount of science data, there are extended useability aspects and benefits that could be provided by embarking an OTM terminal, thus leading to an increased mission return.

1. First, an opportunity of highest observability during the operational phase is given, when assuming an extended use of the LIDAR to search and track the canister on ground.
2. Second, using OTM enables to downling an extended set of engineering data about the challenging rendezvous (RV) mission phase.

2.1.1 TT&C Subsystem Functional Specifications

The extended useability provided to the mission shall be traded versus the overall required mass, power and volume for an integrated RF-optical TT&C subsystem. optical telemetry transponder

Table 1: Summary of functional specifications for integrated RF-optical subsystem

Target Specification	RF system	Optical system
Main functions	Uplink communication Low and medium data rate telemetry Radio-navigation	High-data rate communications
Downlink Data rate	10 bps with LGA over the mission 4 kbps with MGA	70 kbps nominal 320 kbps (target)
Uplink Data rate	2 kbps	N-A
Datalink budgets	3 dB (nominal) 0 dB (worst-case and mean – 3s)	BER ≤ 10^-6
Mechanism	1 dof from -240 deg to -60 deg	Azimuth: -210 deg to +30 deg Elevation: ± 1 deg
AOCS accuracy	0.2 deg, 0.2 deg/s	0.05 deg, 0.005 deg/s
Micro-vibration environment	3 µrad for frequencies higher than 10 Hz	
Mass allocation (target)	35 kg	25 kg
Power allocation (target)	100 W	50 W

2.2 Pointing and Access Analysis

Orbital parameters for analysis are based on MSR, Phase A2. They were adjusted to worst case parameters, in order to obtain OTM access figures under worst case conditions. The baseline parameters are depicted below in Table 2. Orbital perturbation was also considered as it consequently influences the geometrical visibility. For the selected orbits, a realistically good accuracy has been achieved by simply including the J2 effect, due to the oblateness of Mars.

Table 2: Orbital parameter set for pointing and access analysis (nominal S/C attitude)

Mission Phase	**Orbit type**	**Dimension** (km)	**Inclination** (deg)	**RAAN** (deg)	**Arg. of Peric.** (deg)	**Initial Epoch**	**Final Epoch**
Operational	elliptical	1300x500	45	worst case	worst case	09/08/2021	09/10/2021
Rendezvous	circular	500x500	45	worst case	N/A	09/10/2021	09/12/2021

2.3. OTM System Architecture

The principal idea of an RF-optical TT&C system architecture was already described in [3], [4]. The present paper points out characteristics related to the MSR example, including the influence of local weather statistics for a large number of selected site locations. In addition, OTM rates for an optional usage of small OGS diameters are investigated.

The OTM system design philosophy was driven by economical reasons, aiming to shift costs as much as useful to the ground segment, while relaxing the resource allocations in space segment. This OTM concept design follows basically the modular design approach as described in [3], [4]. Results from the former ESA study "O-DSL" (ESA Contract No. 17088/03/NL/LVH) are taken into account.

In the following, based the functional requirements, an initial design concept is proposed for an OTM transponder on MSR, based on state-of-the-art and including hardware and subsystems that have been developed in Europe, mainly under ESA projects, whenever possible, in order to avoid ITAR issues. This seed design takes into account results of the mission analysis and from the optical link budget analysis and it is complemented by an optical ground station terminal.

2.3.1. Choice of OGS locations and classes

Different OGS locations with two different classes of ground antenna size were taken into consideraiton, including local site weather statistics. 4m class stations were selected due to their large amount and wide distribution of locations, allowing for an OGS network. 10m class stations have been chosen, hypothesing that a part-time usage during daytime would be feasible in a shared manner, additionally limiting the SEP angle to ≥8 deg, to prevent sunlight from falling inside the dome and warming up the OGS interior. Minimum elevation constraints follow recent study results from [3].

Table 3: Ground Stations and constraints definition

Parameter	**RF**	**Optical**
Ground Station	Cebreros New Norcia	La Palma Calar Alto VLT Mount Paranal Keck Kitt Peak
Minimum Elevation	10 deg	15 deg
Solar Exclusion Angle	2.8 deg	8 deg

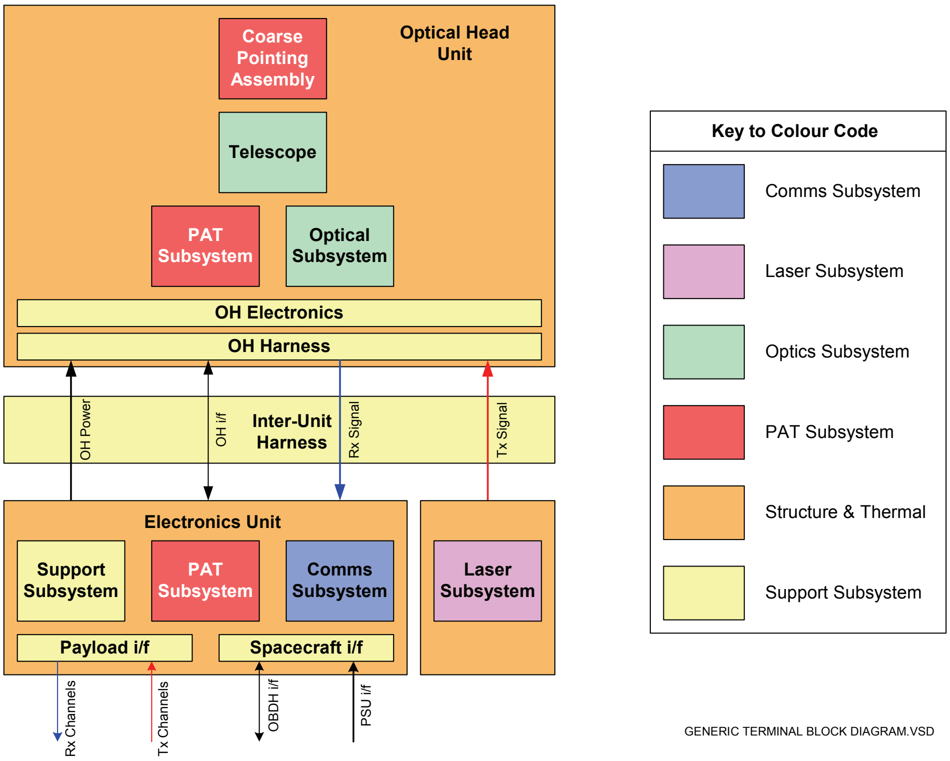
2.3.2 Definition of the on-board OTM concept design

The OTM on-board system concept takes into account the platform specific constraints of the MSR spacecraft, such as pointing DOF, assumed S/C attitude accuracy and microvibration jitter. Results from optical link analysis on pointing geometry, access times and achievable data rates influenced optical antenna sizing. The resulting OTM transponder fulfils the functional specifications for MSR listed in Table 1. Taking into account the pointing requirements and possible available space for accommodation, the optical terminal needs to be located near to radiators. Therefore the prefered accommodation concept has split the OTM terminal into three units that provide flexibility for installations at separate locations of the spacecraft with different thermal needs:

- Optical Head Unit (OHU).
- Laser Unit, including Loop Heatpipe (LU).
- Electronics Unit (EU).

The basic functions of an OTM terminal were described in previous publications [3], [4], [7] and are thus not repeated here. Instead, selected key characteristics are reflected corresponding to specific needs for MSR. Most of the OTM transponder electronics aboard the probe is contained in a box mounted internally on one of the spacecraft radiators. The expected allowed temperature range is similar to that of other S/C electronic equipment. The laser bench has a large dissipation, a low maximum allowed temperature (about 30°C) and needs sufficient temperature stability. Therefore the laser bench needs a large dedicated cold radiator area and an efficient heat link to the radiator (heat pipes or fluid loop), together with a precise temperature control system. Such a prototype Loop Heat Pipe thermal control system for a laser bench system has been developed and tested by EHP /OSZ in the frame of the ESA project "ISLFE".

Fig. 1: Generic Optical Terminal Block Diagram, 3 sub-units + harness



The Optical Head at last is located outside of the S/C and packed in Multi-layer Insulation for protection against the external environment. The OTM on-board terminal is supposed to get its power from the EPC for the RF TT&C subsystem. A power share mode is required to shuffle the electrical power to either of the two telemetry transponders once getting operational. A minimum power comsumption is required for the OTM transponder once in standby mode.

2.4 OTM Application Example based on ESA Developments

Interestingly, apart from its communication- and laser subsystem, the OPTEL 25 GEO terminal from Oerlikon Space constitutes a solution example for an OTM transponder on MSR that provides many required hardware items in a high level of maturity. Oerlikon Space was developing optical inter-satellite link terminals for GEO crosslink applications through the ESA co-funded ISLFE project. The flight design and performance of the ISLFE terminal were verified in the first instance through the production of an Engineering Breadboard (EBB) for a complete optical head and associated electronics. Specific attention was paid to verifying the low mass, compact design and performance characteristics of the optical head.

The geometry of the optical head with wide angle pointing capability at very low mass, as well as the modular design approach and the universal architecture of the terminal controller fit well in the required OTM on-board concept. Figure 2 on the following page depicts an adequate location of this optical head, providing the required DOF in coarse pointing during the operational and rendezvous mission phases of MSR. In addition, Figure 3 shows how the required hardware items for the on-board OTM transponder on MSR could be provided by today's available subsystems and modules developed under frame of the ESA project ISLFE.

Fig. 2: Accommodation example for a suitable, existing lightweigt Optical Head hardware on the MSR orbiter

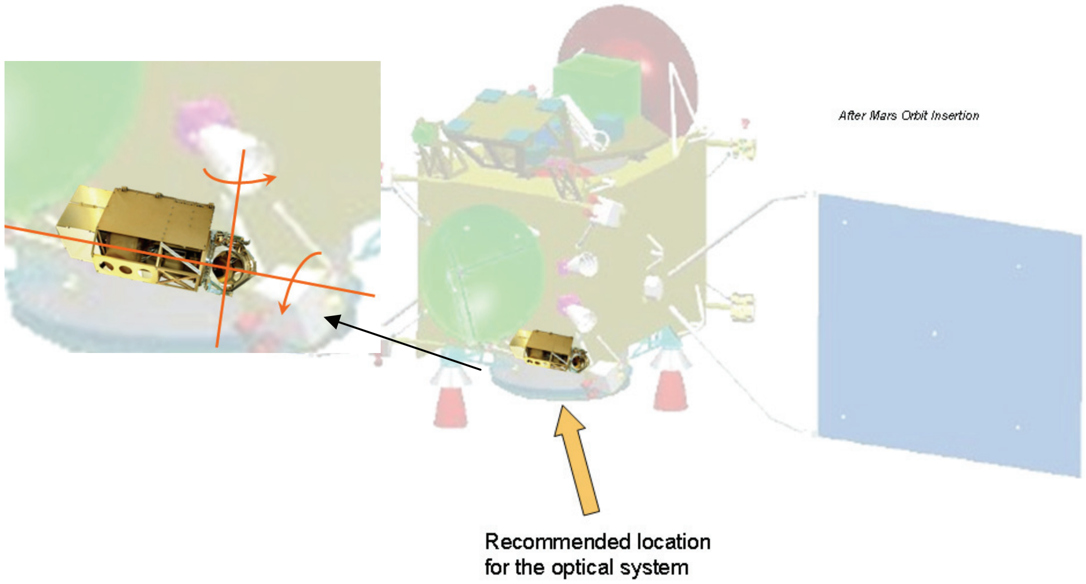
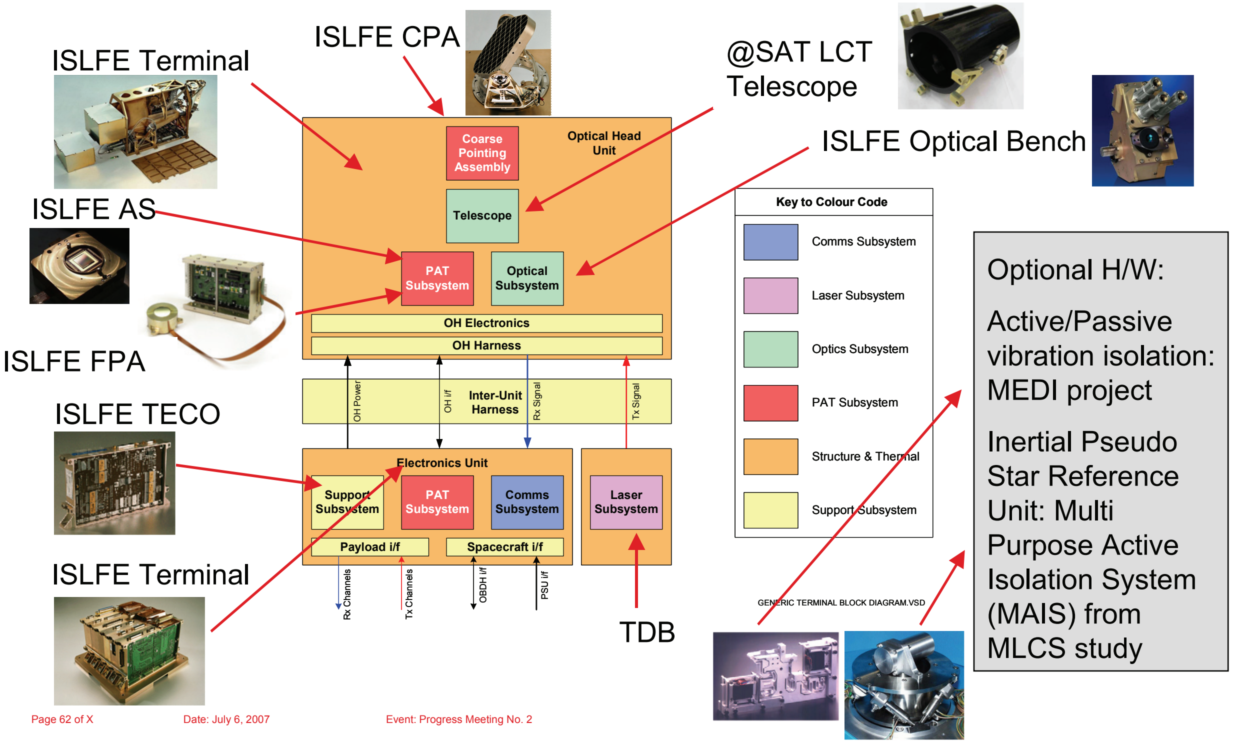


Fig. 3: OTM on-board concept design: available hardware from ESA developments



2.4.1. Optical Beam Steering

Optical beam steering shall be provided by a cascaded control loop consisting of a coarse pointing assembly and a fine pointing assembly [7]. The absolute pointing direction is determined via Earth image convolution on an active pixel sensor (APS) in two axis orthogonal to line-of-sight [1]. Jitter cancellation is then added via a fast control loop that references on the APS readout and that includes inertial sensor assistance for increasing the image sensor bandwidth by approximately a factor 3 to 5. Initial simulations that already include non-linear effects like friction, D/A noise and noise equivalent angle of the APS show a benign characteristics of the optical beam steering loop. In case the assumed microvibration characteristics would become more severe, sufficient options are provided by state-of-the-art optical beam steering tecnologies for free space laser communications in space.

2.4.2. Laser Communications Subsystem

The communications subsystem consists of a PPM encoder that runs in the RF modulator unit and a laser modulator driver to trigger the PPM pulse generation in the Q-switch laser subsystem. The TM interface is bit-synchrouus with clock distribution. For the large link distance, peak powers achieved by pulsed fiber amplifiers in average power limitation mode are considered too low, specifically when considering the additional constraint of close SEP angles on ground that lead to rather high background radiation. Therefore, the baseline laser subsystem for MSR foresees a Q-switch laser for communications that is able to generate small pulses <6ns with highly accurate pulse jitter <0.3ns. As baseline for parametric analysis, a commercially available diode pumped Nd:YVO4 laser with 6W average power at 40kHz repetition rate, TEM00 profile, and pulse energies between 500 µJ and 200 µJ was chosen.

2.4.3 On-board O-DSL Terminal Mass, Volume and Power Estimates

The volume and mass estimation of the preliminary on-board O-DSL terminal are listed below in Table 4. Different levels of maturity were included, leading to an overall contingency margin around 17 %.

Table 4: On-board O-DSL Terminal Mass and Volume estimation, 17% contingency included

Item	Mass	Volume
Optical Head Unit (OHU)	20’430 g	26 x 80 x 38 cm^3
Electronics Unit (EU)	1020 g	about 30x10x30 cm^3
Laser Unit, Q-sw (LU)	5850 g	25 x 53 x 20 cm^3
Inter-Unit Harnesses	1200 g	n.a.
Total incl. 17.3% contingency	28’500 g	n.a.

A detailed analysis of all modes and combinations with hot and cold cases is required for a detailed estimation of power consumption. Average values estimated at this early state, mainly based on hardware data available from the ISLFE project, amount to 30 W average power consumption in standby mode and <120 W average power consumption during OTM communications at highest repetition rate, obtained via power sharing between RF-TM and OTM hardware.

2.4.4 OTM link analysis

The optical link analysis has been carried out for both, operational and rendezvous phase, taking into account the seasons and local weather statistics of the analysed OGS sites. About 20% of all OTM accesses occur with SEP angles rather close to the Sun (~8deg), and about 80% of all OTM accesses stayed well off SEP values >10deg. In the folloing link budget, the worst case blue sky background noise level was selected for analysis, in addition to the fraction contributed by planet Mars in an OGS FoV of 60µrad. The chosen customised Si-APD detector (Perkin Elmer C-30659-1060-R8B) is commercially available with ultra low noise stabilisation in thermo-electrically cooled mode. The optical filter was selected from the laser altimeter design at BepiColombo, with 1 nm FWHM, 80% transmissivity at 1064 nm.

2.4.4.1 Atmospheric effects and cloud free line-of sight aspects

From [3], the results of an extensive atmospheric turbulence analysis for different OGS antenna diameters and various elevation angles down to 15 deg (local horizon system) were selected as baseline to determine the required detector fiwld-of-view for each OGS class (4m or 10m).

Given the optical ground stations and taking into account the nominal orbit of the MSR mission phases, CFLOS probabilities were generated to obtain an estimation of the availability of each OGS during the mission.. For the computation of global cloud cover percentages, the CDFS-II cloud database has been used.

Fig. 4: Cloud-free line-of-sight availability for analysed Optical Ground Stations

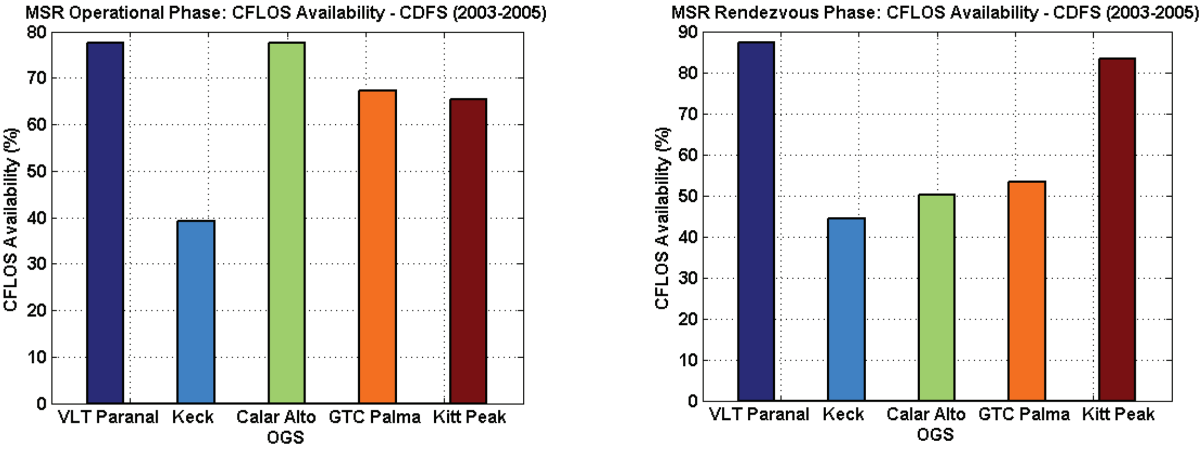


Table 5: ***Daytime*** optical TM link budget, 1064nm, Turbo-Product Code, rate 0.8, coded BER = 10^{-6}

Item	10m-class OGS, 316 kbps at 2.7 AU	4m-class OGS, 51 kbps at 2.7 AU
TX antenna diameter	0.135 m	0.135 m
TX telescope efficiency ('Schiefspiegler' type)	1	1
TX gain	112.0 dB	112.0 dB
TX path losses	-1 dB	-1 dB
M^2 loss for active Q-switched laser	*-3 dB*	*-3* dB
TX pointing loss	-2 dB	-2 dB
free-space loss	-373.4 dB	-373.4 dB
atmospheric transmittance	-0.8 dB	-0.8 dB
RX antenna diameter (nominal)	10 m	4 m
RX telescope efficiency, obscuration	0.9	0.9 dB
RX gain for 10m, 90% telescope efficiency	148.9 dB	141.0 dB
RX loss	-4 dB	-4 dB
receive power at detector (optical)	**-85.4 dBm**	**-93.3 dBm**
background power at detector incl. -4dB attenuation by Rx path, 2000 μW/cm^2/sr/um, *3km alt., SEP ~8deg*	**-59.6 dBm**	**-62.4 dBm**
Mars flux at 294.6 Mio km, fully inside detector FoV, incl. -4dB attenuation by Rx path	**-68.9 dBm**	**-76.9 dBm**
required optical power on detector	**-87.8 dBm**	**-96.8 dBm**
link margin	**2.4 dB**	**3.5 dB**

2.4.4.2 OTM Performance Summary for MSR

Taking into account the achievable data rates at worst case daytime link conditions close to the Sun, and superimposing the CFLOS statistics shown in Fig. 4, daily downlink capacity was calculated as shown in Table 6, including an additional allocation of 3% of each single access for establishment of the OTM link.

Table 6: Mass, Power and OTM capacity for MSR, including CFLOS

Parameter	**Preliminary on-board Terminal Design**	
Mass	< 28.5 kg	
Power	< 120 W	
TM per day	> 300 Mbyte > 60 Mbyte	@ 2.6 AU (316 kbps, 10m class OGS) @ 2.6 AU (51 kbps, 4m class OGS)

3. CONCLUSIONS AND OUTLOOK

OTM technology has reached a sufficient level of maturity to be considered as a support to science missions to Deep Space or to the Earth-Sun system. Several ESA activities over the past years have continued in preparing the technologies needed for optical beam steering and control that allow to fulfill requirements for an on-board OTM terminal for MSR already today. Depending on the mission profile, MOPA based laser architectures can be implemented, based on qualified lasercomm flight hardware available in Europe. Q-switched laser subsystems are recommended for a long range mission, as shown for the 400 Mio km example of MSR. Although being selected for planetary lidar at rather low repetition rates, Q-switched lasers for communications purpose only exist today on a commercial basis and have to be space-qualified. Power sharing between RF-TM and OTM will be required.

By adapting today's available hardware for near Earth laser communication missions mainly by software algorithms, optical beam steering concepts for deep space applications may be implemented on basis of Earth image tracking at high readout rates. Sufficient flexibility is provided for higher levels of microvibrations on different spacecraft by an additional use of qualified passive and active isolation mounts, next to classical acquisition and tracking concepts for an open-loop fine steering of the OTM beam. Closer link distances of 0.5 AU could be served by ground based beacons.

Intersting to see from the concrete MSR example, taking into account all obstacles, including also cloud-free line-of-sight constraints, a 10m class OGS usage only during daytime for OTM communications already might be an attractive option for supplementary OTM usage, despite of the constraint of a 8 deg SEP separation. Alternatively, also a network of about three 4m class OGSs could provide about 50% of the 10m class OGS downlink capacity per day.

Currently, Oerlikon Space is developing for ESA a representative PPM breadboard for a link distance of 1.5 million kilometers, scheduled to be tested soon in 2007 on the Canarian islands. Preparations by laboratory tests already showed promising results. Continued activities in the frame of ESA projects at Oerlikon Space will look into details on Earth image tracking and will investigate on the performance of Q-switch lasers for deep space OTM.

4. ACKNOWLEDGEMENTS

The authors acknowledge the work and efforts of the team of Prof. A. Comerón and Prof. A. Rodriguez at Universitat Politechnica de Catalunia who contributed investigations on atmospheric transmission. The authors also express our gratitude to P. Holsters, Z. Sodnik and Dr. M. Wittig at ESA, and to Dr. A. Deich and Mr. U. Wieland at Oerlikon Space AG for their continued support in the execution of this work.

5. REFERENCES

[1] H. Hemmati, "Deep Space Optical Communications, Wiley Interscience, 2006

[2] J.L.Gerner, "Telemetry, Tracking and Command of Satellites-A Perspective", TT&C 2004 Workshop, 7-9 September 2004

[3] G.Boscagli, T.Dreischer, P.Holsters, K.Kudielka, R.Timm, M.Wittig, "An integrated RF-Optical TT&C susbsystem for a mission to Mars", TT&C 2004, 7-9 September 2004.

[4] G. Baister, T. Dreischer, M. Tüchler and E. Fischer, "OPTEL Terminal for Deep Space Telemetry Links", Proceedings of SPIE Vol. 6457, Free-Space Laser Communication Technologies XIX, Jan. 2007.

[5] R. Lange, "Homodyne BPSK-Based Optical Inter-Satellite Communication", Proceed. of SPIE, Vol. 6457, Free-Space Laser Communication Technologies XIX, Jan. 2007.

[6] Baister, G.C. et. al., "The ISLFE Terminal Development Project – Results from The Engineering Breadboard Phase, " 20th AIAA International Communication Satellite Systems Conference, 12th – 15th May 2002

[7] T. Dreischer et. al., "Operating in sub-arc seconds: High Precision Laser Terminals for Intersatellite Communications", SPIE Proc. Vol. 4902 (2002), pp. 87 ff.

6. ACRONYMS AND ABBREVIATIONS

BER = Bit Error Rate
CFLOS = Cloud free line of sight
ESA = European Space Agency
EPC = Electric Power Conditioner
FWHM = Full Width Half Maximum
GEO = Geostationary Orbit
ISLFE = Intersatellite Front End
MOPA = Master Oscillator, Power Amplifier
N-A = Not Applicable
OGS = Optical Ground Station
OTM = Optical Telemetry
OSZ = Oerlikon Space, Zurich
PPM = Pulse Position Modulation
RV = Rendezvous
S/C = Spacecraft
SEP = Sun-Earth-Probe