A modular solution for routine optical satellite-to-ground communications on small spacecrafts

M. Bacher, T. Dreischer, M.Mosberger, B.Thieme
RUAG Space, Opto-Electronics & Instruments Department
RUAG Schweiz AG, Schaffhauserstrasse 580
8052 Zürich Switzerland
Michael.Bacher@ruag.com

Abstract— **A 2 Gbps commercial optical downlink solution, named OPTEL-μ, is discussed that is tailored, but not limited, for use on small satellites around 150kg and more. Depending on mission needs, scalable options are available, e.g. for a further increase of data volume per downlink, for higher robustness against jitter or even for downscaling if merely access to optical spectrum is considered. The OPTEL-μ baseline product of the space segment part is targeting 4.5 kg, 4.5 liters and 45 W for the space terminal. This paper describes the baseline architectural concept of the entire OPTEL-μ system. Emphasis is given to modularity in view of available on-board resources and footprint.**

OPTEL-μ, optical communications system, 2 Gbps, OOK, PPM, optical ground terminal, ground network, modular design

I. INTRODUCTION

Small satellite's prime contractors and operators are currently looking for innovative solutions allowing for increased data download capabilities at comparable on-board resource constraints. One possible solution is to increase the data rate per downlink. Plans for multiple earth-science missions are reported in [1] that will send data from low-Earth orbits to ground stations at up to 3 Gbps, aiming for data throughputs of >10 terabits per day. The ITU has allocated 1.5 GHz for direct downlinks in Ka Band and developments are under way to exploit this frequency band for the growing demand on bandwidth. In parallel to the RF domain, unregulated optical frequencies offer a useful downlink complement to a variety of mission scenarios which have been thoroughly investigated by ESA and NASA [2]. Current commercial laser communications terminals use coherent detection and support intersatellite links at Gbps data rates in near-Earth mission applications [3]. State-of-the-art benchmark in-orbit demonstrations of optical downlinks using direct detection are carried out by NASA, scheduled from Moon to Earth for 2013, followed by GEO-to-Earth in 2016 [4]. In this context, RUAG Space started 2010 with support from ESA the development of a commercial system for optical space-to-ground downlinks from Low Earth Orbit that is named OPTEL-μ [5]. The OPTEL-μ system comprises a miniature space terminal and a network of low-cost, large aperture ground terminals. The space terminal mainly addresses the needs of the emerging market of small satellites. Primary features such as smallness, robustness and versatility were included into the space terminal's design for serving a variety of satellite platforms. Intended for commercial usage, modularity is a key feature that was implemented throughout the entire OPTEL-μ system. As the focus is on small satellite applications, the OPTEL-μ building blocks enable the use of optical downlink frequencies at reduced technical complexity and budgetary entry level. This closes a current gap toward existing space laser communications applications that rather aim at ultimate data rates, pushing technical limits. Alongside, though not in focus of the OPTEL-μ design, its modularity inherently allows for adapting the primary use cases by exchanging part of the existing building blocks, thereby reducing overall development effort. The following section II describes the concept of the overall OPTEL-μ optical downlink system and its key performance features. Section III highlights ways to exploit the growth potential of OPTEL-μ toward higher optical downlink data rates. Section IV contains basic features of the modular space laser communications terminal. A concluding section V wraps up key characteristics and provides an outlook on the development roadmap.

II. GENERAL DESCIPTION OF THE OPTEL-μ SYSTEM

The OPTEL μ system operates for laser communications downlinks from low earth orbit to ground in the 1550nm band. It comprises both, a space segment and a ground segment. An optical space terminal downlinks from Low Earth Orbit (LEO) to an optical ground terminal (OGT) that forms part of a globally distributed network consisting of several OGTs. The network is dimensioned for sufficient cloud-free line-of-sight access to collect all downlink data in a useful time interval. Main idea of the OPTEL-μ system is to offer a complementary service to those missions that require high-bandwidth telemetry but allow for relaxed timeliness requirements. It extends the availability of high rate downlinks at small on-board footprint also to small- and micro-satellites.

*Figure 1*depicts the main elements of an optical downlink scenario for the OPTEL-μ system. A ground beacon laser provides both, an optical reference for space terminal's line-of-sight steering plus coded information on a service channel for optimizing the optical downlink performance during a passage by automated repeat requests. The space terminal's communications beam is received at the optical ground terminal that is part of an optical ground station, either installed fix or configured transportable.

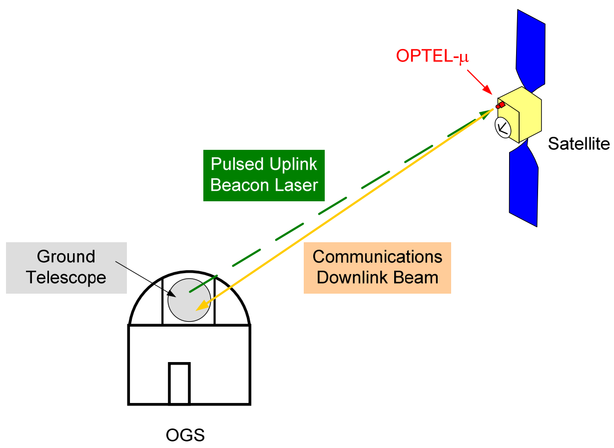

Figure 1 Optical downlink scenario, key elements of OPTEL µ system

The OPTEL-µ system implements a bi-directional, asymmetric laser communications link. Next to a high bandwidth downlink, a low rate return channel is implemented as uplink for automated repeat request. The optical link between a space terminal and an OGT comprises at least three different optical frequencies. The baseline system offers two optical channels and both optical channels can be used simultaneously. The communication subsystem ensures reliable transmission of the data with 2.5Gbps raw / 2Gbps user data rate over two optical channels (1Gbps each) at BER>10^{-9} over up to 1300 km link distance. The direct detection receiver on ground has to cope with variations of free space loss, atmospheric scintillation effects, optical background noise and scattering impact at high zenith angles, hence, longer link distances. Automated repeat requests (ARQ) together with information on current channel throughput are coded onto the optical uplink beacon channel and used on space terminal level for optimal data rate adjustment during a downlink. Data rates are then scaled for optimal exploitation of channel transmission characteristics. Coding rates are 7/8, 3/4 and 1/2 correspond to user data rates of 1Gbps, 850Mbps and 500Mbps. The nominal modulation format used by the OPTEL-µ system is on-off keying (OOK). Enhanced robustness to atmospheric channel distortions is achieved by an optional change of the modulation format during a downlink to pulse position modulation (PPM). PPM provides higher energy efficiency than OOK and allows for optical link optimization at high zenith angles and, hence, stronger atmospheric turbulence. Corresponding system key parameters are listed in TABLE I.

TABLE I. KEY FEATURES OF THE OPTEL-µ SYSTEM

Level	**Features, Parameters and values**	
	Feature	***Value***
System	Suported LEO altitudes	400km 900km
	Downlink Wavelength	1525nm .. 1565nm
	Uplink Wavelength	1064nm
	Channel Data Rate (Raw / User)	1.25 / 1.0 Gbps
	No. of optical downlink channels	2
	No. of optical uplink channels	1 (service channel)
	Downlink modulation format	OOK / 8-PPM
	Uplink modulation format (for ARQ)	16-PPM
Space Terminal	3 physical units, goal spec	4.5kg, 4.5ltr, 45W
	Field of Regard	70deg cone angle (option: hemispherical)
	Transmit wavelength band	1525nm .. 1565nm
	Space beacon laser (optional)	808nm
	Internal buffer memory size	100– 200 Gbyte
	Mass Memory I/F	SpaceWire (alternatives availabe)
	Power I/F (unregulated)	24V up to 36 V DC
Ground Terminal	Mount configuration	ALT-ALT
	Field of Regard	0-90° El, 0..360°
	Telescope diameter	0.6m
	4-beam pulsed uplink beacon	1064nm (Laser Class 1M)

OPTEL-µ key features & parameters, preliminary design status

A. *Primary Use Cases*

Three main use cases are identified for the optical downlink system OPTEL-µ.

- During "Eye-in-the-sky" operations, where visual remote sensing data are immediately downloaded to a single ground terminal, nearby to the observed site, clear sky conditions are needed for the observation and therefore an optical link is inherently feasible.
- A second case comprises a low-footprint add-on to existing RF equipment. The OPTEL-µ space terminal then facilitates along-track capacity planning of telemetry peak loads.
- Due to its smallness, OPTEL-µ finally helps increasing mission data downloads for small satellites. Main idea for this third use case is to introduce a complementary telemetry payload that uses minimal on-board DC power, mass and volume and covers on-demand downlink volumes of around 400 Gbyte within 24 hours for a pre-selected, globally distributed network of 7 optical ground stations at >90% clear sky probability. A fully deployed network of 12 low-cost optical ground stations could support >750 Gbyte downlink data in 24 hours at a clear sky downlink availability of >95%.

The unique feature of narrow optical beam diameters at the ground receiver can directly be used to secure optical downlinks. In addition, when combined with a user specific identifier code on the uplink beacon channel, OPTEL-µ downlinks become inherently interception-proof. The downlink spot diameter on ground depends on transmit divergence, orbit altitude and zenith angle and typically is in the order of a few hundred meters.

B. Miniature space terminal's preliminary design

The miniature space terminal establishes line-of-sight to the optical ground station during a passage. A pointing mechanism provides near hemispherical field-of-regard (FoR). Depending on accommodation constraints, part of the FoR can be used to additionally assist possible S/C attitude offsets. The OPTEL-μ space terminal maintains line-of-sight also to the optical ground station during S/C attitude maneuvers. In addition, the space terminal carries out all data transmission. On-board Mass Memory data is loaded into an internal buffer of the space terminal that provides 100 Gbyte of storage, possible to upgrade toward 200 Gbyte. Two optical downlink channels can be operated separately and simultaneously. Automated repeat request from the optical ground terminal will lead to re-transmits of OPTEL-μ buffer memory content.

To ease satellite integration, the space terminal is designed in modular way, aiming at a minimal on-board footprint and allowing for maximal flexibility w.r.t. accommodation. Latter extends the usage of the OPTEL-μ system to serve both, micro-satellites as well as becoming an add-on next to existing RF telemetry payloads on larger LEO platforms. The design of the OPTEL-μ space terminal aims at a goal specification of about 4.5kg in mass in a volume around 4500ml. The average power consumption during optical downlink operation with two activated optical channels amounts to 45W, which is considerably lower than in high data rate RF downlink systems.

Figure 2 OPTEL μ space terminal, 3 main units, rapid prototyping models (from left: Optical Head Unit, Laser Unit, Electronics Unit)

C. The Ground Terminal Prototype

The Optical Ground Terminal (OGT) receives up to two optical downlink channels simultaneously, applying coarse wavelength de-multiplexing. Designed for remote operability and low installation cost, the OGT uses a 0.6m receiver aperture and provides a ground based multi-beam beacon laser that bases on proven LIDAR technology. The optical receiver is part of the backend module that is placed in the Cassegrain focus of the optical tube assembly.

The ground beacon laser is included into the backend module. It supports the space terminal's optical line-of-sight tracking and provides service channel data exchange and negative acknowledge that cause re-transmission in case data packages were not received.

In the ground terminal design, careful consideration was given to laser safety aspects and international laser safety regulations, such as IEC60825, with the aim of reducing the nominal ocular hazard distance (NOHD) to a minimum. The NOHD depends on emitted irradiance which again strongly depends on the required slant range to be covered as a function of mission altitude and ground elevation angle.

The OGT design complies with laser classification "Class 1M", which is considered eye-safe and poses no threat to the human eye. Observations with magnifying optical instruments (such as e.g. binoculars) could potentially be harmful in the vicinity of the ground terminal. However accidental observations by public observers on ground can be excluded due to the zenith angle limitations of the OGT of 70°, thus emission at low elevation angles is prevented by the OGT design itself. National aviation regulations might require additional coordination, monitoring and/or safety installations, to ensure that any potential danger can be excluded also for observers with magnifying optical instruments in low flying aircraft and helicopters. However, even such exceptions can be implemented safely with standard means that are well known e.g. from satellite laser ranging stations

The OGT prototype is shown in Figure 3. Its design follows also a modular approach. Primarily, a self-standing optical ground terminal has been built for pedestal-mount configuration aiming for permanent installations in a ground station, like shown in the left part of Figure 4. To facilitate adding further optical ground terminals to the existing network, the ground terminal's backend optics module is self-contained, in order to ease a possible combination with existing small astronomical telescopes at low duty (around 40cm to 80cm in diameter) and also with accessible satellite laser ranging stations. In minimum configuration, only the communications receiver, uplink beacon laser and optical link controller need to be taken from the OGT prototype for a possible combination with existing telescope infrastructure.

Part of the OGT prototype, consisting of optical tube assembly plus backend optics and electronics were already successfully tested under worst case atmospheric conditions over a 55km near-horizontal atmospheric path, using a transmitter on a mountain top. Figure 3 shows the fixed installation (without mount) during testing on Dübendorf airfield (LSMD). Prior to the test campaign, Laser Class 1M certification was obtained for the fully integrated assembly.

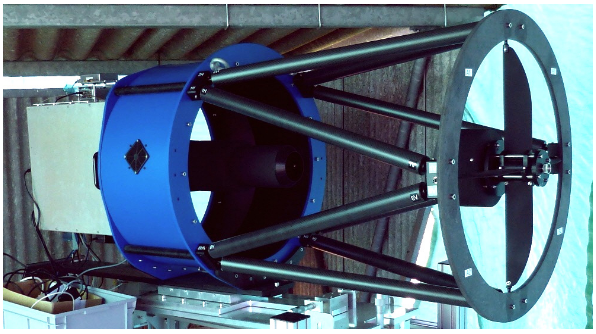

Figure 3 OGT ptototype for OPTEL-μ in a test stand during a long term evaluation on effects of a 55km atmospheric link (shown without mount)

Specifically for portable applications as described above for use case 1, the optical tube assembly plus backend optics are designed to fit existing commercial portable high accuracy tracking mounts that carry 60cm (24 inch) optical telescopes, as shown below in the right part of Figure 4.

Figure 4 Mount examples: fixed and transportable
(left: RUAG OGT mount, right: CineSextant of Photo-Sonics, Inc.)

D. *Concept of Operations and predicted Downlink Volumes*

Assuming mainly Earth Observation satellites with high performance sensors collecting considerable amounts of data, the operational concept for an optical downlink of on-board stored data for use cases 2 and 3 will differ from current operational models used in RF technology. The laser communications differs significantly from the traditional X-band, because an operational ground system consisting of a set of optical ground stations and satellites requires different overall approach for a user's access to on-board data.

Given the statistical nature of an optical downlink, it is obviously not adequate to report a cloud-interfered pass as failed to the customer wait for the customer to reschedule and request a new pass. Instead, the data service and its technical implementation need to take into consideration the statistical nature of the link and provide a "network layer" to the satellite owner [6]. Below this layer, ground resource time is dynamically scheduled and allocated to different satellites, depending on their latency needs, on-board memory status, previous cloud interruptions and geographical location.

With a transition away from the pass-oriented view of the ground service, a new concept where the data is in focus is required, in other words, users need to request rather a "file" than a "passage". For proper design of the optical ground receiver network, one important criterion for the selection of site locations next to clear sky conditions is cost-efficient data connectivity. A comprehensive analysis has been performed by RUAG with support of GMV S.A., using the CDFS-II cloud data base with over 3000 consecutive days between the years 2002 and 2010. Details are described under [8] and a cumulative summary is provided in Table II and Table III.

TABLE II. DOWNLINK DATA VOLUME FROM THE OPTEL-μ , 4 SITES

Downlink volume from 700km LEO, SSO, 4-site network			
Probab.	***Contact [min] in 24 hours***	***[Gbyte/24h]***	***[Tbit/24h]***
95%	10	120	1.0
90%	15	180	1.4
50%	28	336	2.7

a. LEO downlink volume based on CDFS-II data base analysis, 8years, 3000 consecutive days

TABLE III. DOWNLINK DATA VOLUME FROM THE OPTEL-μ , 7 SITES

Downlink volume from 700km LEO, SSO, 7-site network			
Probab.	***Contact [min] in 24 hours***	***[Gbyte/24h]***	***[Tbit/24h]***
95%	26	312	2.5
90%	33	394	3.1
50%	44	533	4.3

a. LEO downlink volume based on CDFS-II data base analysis, 8years, 3000 consecutive day

III. GROWTH POTENTIAL OF THE OPTEL-μ SYSTEM

The following three sub sections highlight three different methods that can be applied to increase the downlink data volume when using the OPTEL-μ system. Different features among the approaches allow for using them either separately of altogether

A. *Adding an optical channel*

The baseline OPTEL-μ system is designed for two active optical channels, using direct detection OOK/PPM with a CWDM ground receiver. The same approach can be extended in space segment with a third optical channel, either to provide a 2-over-3 redundancy or to increase the downlink capacity per passage by 1 Gbit/s useful data rate. A delta design would be required, using the same hardware as implemented for the 2-channel system, but extended to 3 channels, thereby increasing mass and volume when compared to the baseline. If the third channel is operated in addition to the other two, additional power is required for the Space Terminal.

B. *Adapting the modulation format*

The current baseline selection for the OPTEL-μ system uses OOK which is optimal for low complexity, low maintenance ground operations in remote control. On a longer term, the same laser modulator used in the current space terminal could be re-configured mainly electrically to act not as OOK, but as DPSK transmitter. In contrast to OOK, DPSK requires higher implementation complexity in the space transmitter, like a phase modulator and differential pre-coding. Higher data rates also require faster buffer memory readout. The option to implement all this has been considered already in the current OPTEL-μ space terminal design. On ground, an OOK receiver works well without removal of Zernike modes by only making use of aperture averaging [7]. DPSK demodulation compares the relative phase of differentially encoded symbols where phase coherence is only required for the time duration between the differentially encoded symbol. This eliminates associated phase-locking challenges especially for reception through the turbulent atmospheric channel. However, to fully exploit the ~+3dB sensitivity gain of DPSK over OOK requires operation of fiber-coupled DPSK receivers on ground, making inherent use of optical pre-amplifier technology which needs removal of sufficient number of Zernike modes for single mode fiber coupling. Once ground based adaptive optics for laser comm's receivers get available in industrialized performance, a delta design of the OPTEL-μ system toward DPSK is estimated today to lead to a 2-fold increase of optical downlink data rate at comparable on-board power consumption with a slight increase of on-board mass in case a larger buffer memory is used. On ground, the current OPTEL-μ ground terminal design allows for a double-mount configuration. Instead of counter balance mass, a second optical tube assembly dedicated to DPSK reception will then be used together with the old one. This covers transition phases, when OOK systems are still operational in space and DPSK systems start to get established.

An overview on expected optical downlink performance using the OPTEL-μ system is depicted in Figure 5. The expected downlink data rate is shown versus link distance, both for the nominal OOK and PPM implementation and for an optional future DPSK system. FEC is used to achieve $>10^{-9}$ BER and data rates are scaled along link distance using ARQ.

The prediction bases on sensitivity measurements carried out at RUAG Space for a direct detection photo receiver. It includes lumped losses for transmitter, receiver, molecular absorption and transmitter pointing loss allocation. In addition, channel losses are included that vary with zenith angle, like power scintillation margin and sub-visible cirrus cloud attenuation. Assumed is an optical ground terminal altitude of 400m above sea level. Latter allows for sufficient flexibility w.r.t. site location selection.

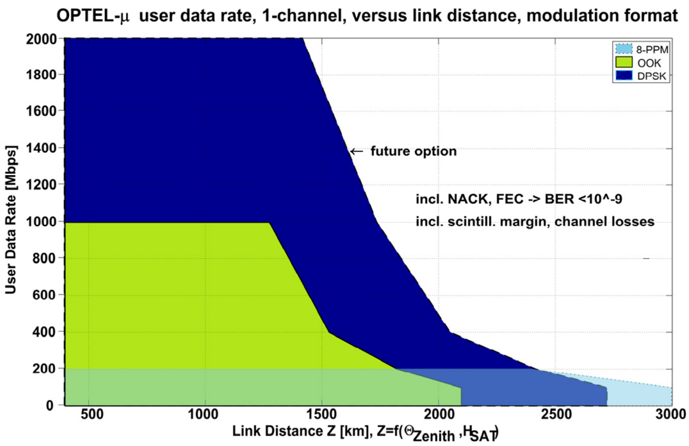

Figure 5 Data rate achieved by OPTEL-μ system per channel versus link distance. Nominal modulation formats OOK and 8-PPM, future option: DPSK

C. *Scalable optical downlink using identical hardware*

An alternative growth approach toward larger available S/C on-board resources uses several instances of the identical space terminal hardware combined with a corresponding amount of optical ground terminals (OGT) per downlink site. This approach eliminates the need for any re-design or delta-design, thereby achieving a cost-minimized approach toward directly scalable optical downlink capacity. Key is to combine the two features of narrow spatial separation characteristics of a fixed OGT receiver cluster with temporal separation on the pulsed optical uplink used per single OGT to support space terminal tracking and ARQ. Latter results in a kind of optical frequency reuse, combined with time multiplexed operation of multiple links. A patent on this approach is pending.

For direct-to-Earth optical downlinks, several OPTEL-μ terminals are combined to scale up in a linear way the achievable downlink data (-rate) per passage. The downlinks are directed simultaneously from multiple identical OPTEL-μ space terminals embarked on the same satellite in orbit to a closely located cluster of identical low cost optical ground terminals placed at one site location, like shown in Figure 6

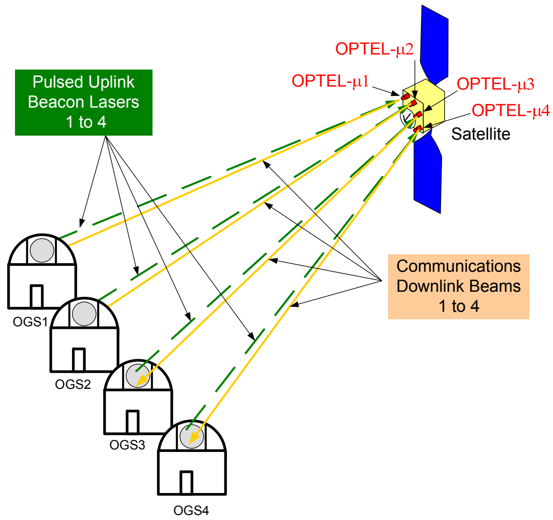

Figure 6 Multi-terminal downlink using identical hardware –the example shown provides 10 Gbps with 4 transmitters and 4 receivers, all implicitly redundant

Small optical beam diameters on ground allow for narrow spatial separation distances between single ground stations without mutual interference. An example for a separation between multiple identical Optical Ground Stations is shown in Figure 7. It uses a 700km SSO reference and assumes zenith angles limited to 60°.

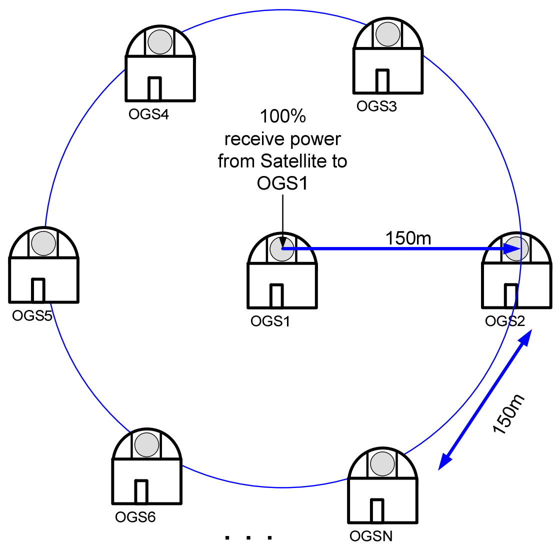

Figure 7 Spatially separated OGS cluster, 150m separation example stays for 60° zenith angle at a 700km SSO reference orbit

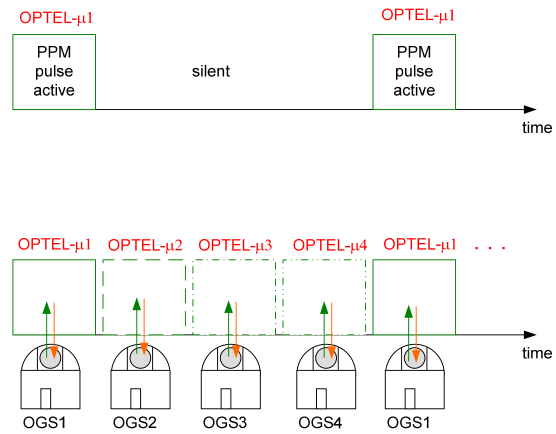

Figure 8 Time division of synchronized uplink laser beacons, OGS 1 beacon is kept silent during other OGS beacons are active and vice versa

Using multiple identical space terminals at the same time over a passage enables a low entry level concerning budget expenses, still provides sufficient growth margin and inherently offers implicit redundancy because the high data rate downlink is spread equally among independent space terminals.

IV. MODULAR SPACE TERMINAL ARCHITECTURE

The design of the OPTEL-μ space terminal follows a modular approach, essentially comprising three main units details of which are explained in [10]. Within each unit generic sub units can be used across the whole product range. The three main units for each OPTEL-μ terminal are

- Optical Head (OH) Unit located outside the spacecraft nominally on the Nadir panel
- Laser Unit (LU) which can be located inside the spacecraft in its communications module (CM)
- Electronics Unit (EU) also located in the CM.

The OH, LU and EU are connected to one another by a harness comprising both electrical and fibre optical cables to transmit the signals between the three main units.

A. *Optical Head Unit*

Figure 9 Optical Head Unit –Rapid Prototype, OPTEL-μ space terminal

The basic function of the OH unit shown in Figure 9 is to provide the beam steering needed to realize the free-space optical link and related pointing, acquisition and tracking functionality. Once PAT conditions are fulfilled, the communications link can be achieved. In addition, the automated repeat request signal derived from the ground beacon uplink is forwarded to the communications control electronics.

The OH mainly comprises a pointing mechanism, and an optical bench, on which the optical assembly is mounted with all the optical sensors and devices needed for acquisition, tracking and communications. Finally, a set of proximity electronics to operate sensors and actuators completes the subassemblies of the optical head. Coarse pointing functionality and pointing accuracy are usually tailored closely to mission needs, such as field-of regard requirements and μ-vibrations impact during optical link operations. The OPTEL-μ Optical Head is optimized for typical LEO-to-Ground downlinks, but can to a certain extent be adapted to other classes of missions.

B. *Electronics Unit Description*

Figure 10 Electornics Unit –Rapid Prototype, OPTEL-μ space terminal

The Electronics Unit is considered a key element of a modular space laser communications terminal. It comprises much functionality that is applicable throughout a variety of mission applications. The primary EU functions are

- Control of the pointing, acquisition and tracking subsystem
- Control of the communications subsystem
- Control of the laser subsystem
- Power supply for the EU, LU and OH sub-units
- Interface to the spacecraft power supply unit
- Interface to the spacecraft TM/TC subsystem
- Interface to the on-board mass memory
- Provide the modulation signal for the Tx optical carrier
- Receive and recover information from Rx optical carrier detected in the OH

The Electronics Unit contains three primary sub-units:

- Controller sub-unit that contains the entire laser control electronics and the terminal control electronics incorporating the main control computer for the terminal, together with the interface circuits
- Communications Electronics sub-unit that contains the digital communications electronics, on-board memory access and terminal buffer memory management
- DC-DC converter sub-unit to provide power supply and regulation functions for the OPTEL-μ space terminal. The DC-DC converter assumes a 24V..36V unregulated interface to the spacecraft power supply unit that fits especially for small satellites.

C. *Laser Unit Description*

The Laser Unit of the OPTEL-μ space terminal consists of two individual physical modules as shown in Figure 11.

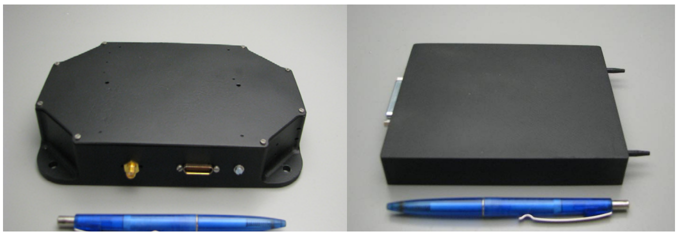

Figure 11 Laser Unit –Rapid Prototype, OPTEL-μ space terminal consisting of 2 modules –pulsed laser transmitter (left) and fiber amp (right)

A Pulse Laser Transmitter (PLT) provides two individually on-off modulated optical channels in the optical C-band. The PLT module is self-contained. It includes all optoelectronics components and is functionally decoupled from the Optical Fibre Amplifier (OFA) module. The OFA module incorporates two individual fibre amplifier stages together with the entire laser drive electronics and the (optional) high power beacon laser and corresponding beacon laser drive electronics.

D. *Modularity as key feature for extended use cases*

The modular architecture of the OPTEL-μ space terminal provides key functionalities in corresponding hardware units that together build up a miniature space laser communications terminal. This approach facilitates an optional adaptation of the OPTEL-μ space terminal toward specific missions and user's needs apart from the nominal downlink case. Taking into account the versatility of the EU, a possible space terminal architecture could make use of EU plus LU, but put in place another optical head that is suited for larger link distances.

Another option could be to add active vibration isolation elements for extending optical downlink usage toward satellite platforms that require special robustness toward micro vibration loads [9].

For downlinks that do not need OOK at high data rate, but still require access to optical downlink frequencies, a similar approach could be taken that uses only the beam steering functionality but emits at another wavelength, e.g. for entangled photons transmission.

V. Summary & Conclusions

A commercial optical downlink solution, named OPTEL-μ, was presented that is tailored, but not limited, for usage on small satellites around 150kg and more. The system incorporates a miniature space terminal with goal specification of 4.5kg, 4.5litres, 45W and a complementary optical ground terminal prototype. The communication subsystem ensures reliable transmission of the data with 2Gbps user data rate over two optical channels (1Gbps each) at BER>10^-9 over up to 1300 km link distance. Three main use cases are identified. Two of them involve a globally distributed network of fixed installed optical ground terminals and one requires a transportable version of the ground terminal. Three individual ways were described to further increase the downlink data rate if mission needs require. Therefore, the current status presented is considered a useful entry stage, addressing market needs for an affordable budget level toward using optical downlink frequencies. The system's versatility marks a starting point of an extended range of possible future applications. The OPTEL-μ development roadmap has successfully passed a preliminary design review and now aims at completion of an Engineering Model by end of 2013. In parallel, possible in-orbit demonstration (IOD) opportunities are being discussed. Target is to obtain flight hardware for an IOD by end of 2015.

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