OPTEL-μ: A Compact System for Optical Downlinks from LEO Satellites

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A modular optical downlink system for 2.5 Gbps downlink rate, named OPTEL-μ, is described which is tailored to micro-satellites, but not limited to. OPTEL-μ is currently developed at RUAG Space under ESA contract, aiming at a miniature space terminal (EQM level) and an adequate optical ground station prototype within the timeframe of about 3 years. A functional description of the OPTEL-μ system is given and the principal concept of operations is described, involving methods how to obtain observation data from a distributed Optical Ground Station network. Use cases are described and estimates are calculated for the required amount of optical ground receiver sites to achieve sufficient clear sky availability for a required downlink volume in 24 hours. A Gaussian approximation on downlink volume availability is derived from more than 3000 consecutive days of recorded cloud coverage data available for a pre-selected number of sites at preferred locations. An outlook is provided on further growth potential of the OPTEL-μ system.

I. Introduction

Over the next years, spacecraft operators plan to launch multiple earth-science missions that will send data from low-Earth orbits to ground stations at up to 3 Gbps, aiming for data throughputs of 10s of terabits per day. Such downlink rates exceed the capabilities of current S-band and X-band frequency allocations used for observation data downlinks. The ITU has allocated 1.5 GHz for direct downlinks in K_a-Band and developments are under way to exploit this frequency band for the growing demand on bandwidth (reference 1).

In parallel to the RF domain, unregulated optical frequencies offer a useful downlink complement to a variety of mission scenarios. In 2010 RUAG Space started with support from ESA the development of a complete system called OPTEL-μ, comprising a miniature space terminal and a ground terminal for optical space-to-ground downlinks from Low Earth Orbit. The OPTEL μ system aims at direct-to-ground laser communications. The miniature space terminal follows the request for the elementary features smallness, robustness and versatility with the aim to serve a variety of satellite platforms.

In the following two sections, a functional description of the OPTEL-μ system is given and a simplified model is derived for prediction of the required amount of optical ground receiver sites to achieve sufficient clear sky availability for a given downlink volume in 24 hours. For comparison to the model, a Gaussian approximation on downlink volume availability is shown. Latter was derived from comprehensive analysis over more than 3000 consecutive days of recorded cloud coverage data, used for assessment of a pre-selected number of site locations. Given the downlink performance characteristics, the principal concept of operations for data access based on laser communications downlinks is described, involving methods how to obtain observation data from a distributed Optical Ground Station network. An outlook of further growth potential of the OPTEL-μ system is provided, followed by a brief performance summary.

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II. Functional description 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, space segment and ground segment, like shown below in Figure 1. An optical space terminal (ST) performs downlinks to a network of optical ground stations that is dimensioned to ensure sufficient cloud-free line-of-sight access to collect all downlink data. Each optical ground station contains an optical ground terminal (OGT) that forms the matched counter part of the ST. Potential site locations of the optical ground network have been carefully pre-selected, based on historical analysis over 8 years of cloud coverage conditions using the cloud depiction and forecast system (CDFS-II).

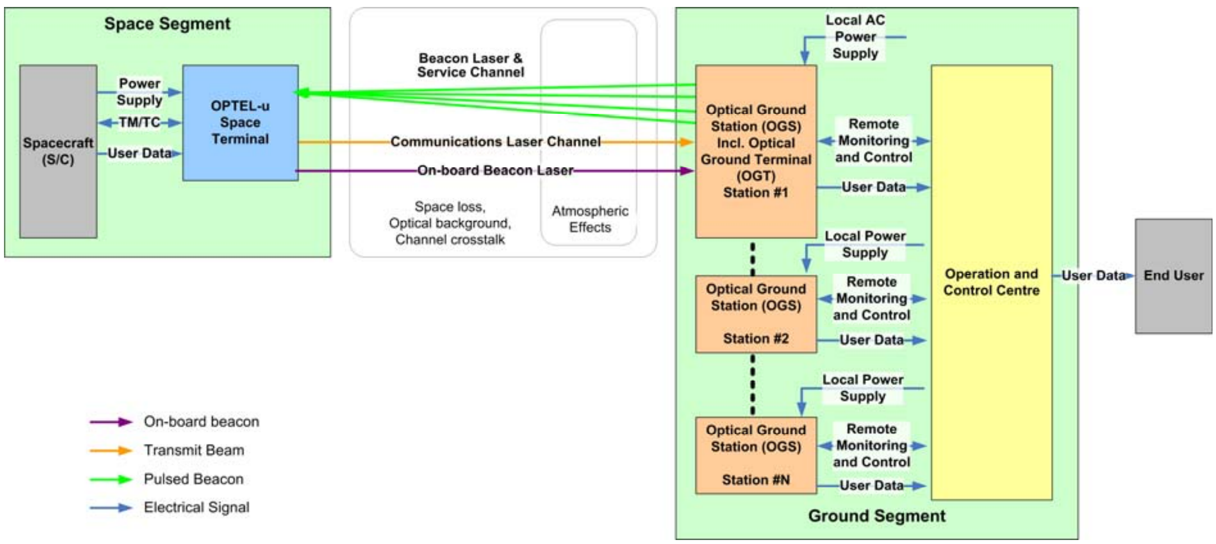

Figure 1. OPTEL μ system Block diagram.

A. The Space Terminal

The Space Terminal (ST) provides spatial access to the optical ground station and it maintains optical line-of-sight during a passage. A pointing mechanism provides hemispherical field-of-regard (FoR). Latter is somewhat larger than required for a LEO downlink and it can be used to additionally assist possible S/C attitude offsets w.r.t. a genuine Nadir-pointing configuration. The OPTEL-μ Space Terminal maintains line-of-sight also to the optical ground station during S/C attitude maneuvers.

In addition, the ST carries out all data transmission. To do this, Mass Memory data is loaded into an internal buffer of the ST that provides 100 Gbyte of storage. Automated repeat request from the optical ground terminal will lead to re-transmits if OPTEL-μ buffer memory content.

The ST 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 toward micro-satellites as well as an add-on for larger LEO platforms. The preliminary design of the OPTEL-μ Space Terminal achieves a mass below 5kg and its volume stays below 5500ml. The average power consumption during optical downlinks with two optical channels amounts to 45W which is a significantly low value for a 2.5 Gbps downlink system.

B. The Optical Ground Terminal

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 beacon laser that is customized, based on well known LIDAR technology. The ground beacon laser is used by the ST for optical line-of-sight tracking and for ARQ data exchange. International laser safety standards form an inherent portion of the OGT design. The nominal ocular hazard distance (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. For NOHD design, the OPTEL-μ system orients at international safety standard IEC60825-1:2007.

Under full optical uplink power, the current OGT design baselines CLASS 1M classification for an assumed exposure time of 10 seconds. This means, it is eye-safe to stand in front of the emitting telescope and directly look into an uplink beacon beam, but without magnifying glasses like, e.g. binoculars.

As the design aims at minimum ground elevations angles >25°, no horizontal emission happens anyway. Therefore only airspace around the OGT needs to be monitored, for instance to avoid that a helicopter crew might look for 10 seconds or more into the uplink beam with a magnifying glass. For a genuine optical link to a LEO satellite, moving at an angular speed of about 1°/sec in both axes, such a case is considered rather exceptional. However, even such exceptions can be handled safely with standard means

C. The Optical Link

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 an ST and an OGT comprises at least three different optical frequencies. The baseline system offers two optical channels, each capable of 1000 Mbit/s useful data transmission at BEP>10^-9 over up to 1000 km link distance. Both optical channels can be used simultaneously. A combination of On-Off Keying and Pulse Position Modulation is applied for optimal exploitation of optical channel capacity under varying link conditions, such as e.g. ground elevation angle and resulting link distance.

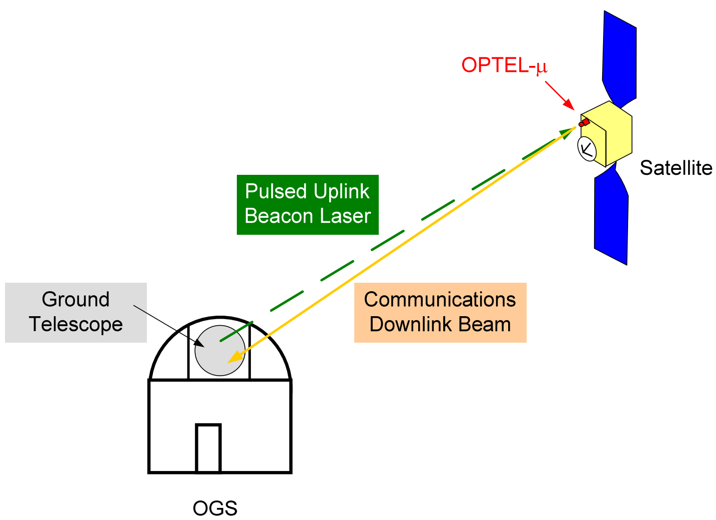

Figure 2. Optical downlink scenario from OPTEL μ.

1) An uplink beacon laser provides an optical reference for ST's line-of-sight plus ARQ information with via pulsed uplink.
2) A communications beam from a ST is received at the OGT placed inside the OGS

<u>OPTEL-μ Key Features</u>

- LEO altitudes: 400km-900km
- Space Terminal
  mass,power,volume: 45W average, 5.0kg, 5600ml
- Ground Temrinal
  aperture size 0.6m
  zenith angle range <70°
- Downlink Rate: 2 channels simultaneous 2x 1.25 Gbps, OOK
- Communications Wavelength band: 1520nm .. 1570nm
- Uplink beacon: Laser Safety Class 1M, 1030nm / 1064nm, 16-PPM ARQ

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 1000 km link distance. Both optical channels can be used simultaneously. The direct detection system has to cope with variations of space loss, atmospheric scintillation effects, background noise and (longer) link distances. Uplink beacon channel information is used for optimal data rate adjustment during a downlink and data rate is scaled for optimal exploitation of channel transmission characteristics. Coding rates are 7/8, 3/4 and 1/2 corresponding to user data rates of 1Gbps, 850Mbps and 500Mbps. For even lower data rates the modulation format can be switched down to 8-PPM which provides higher energy efficiency than OOK.

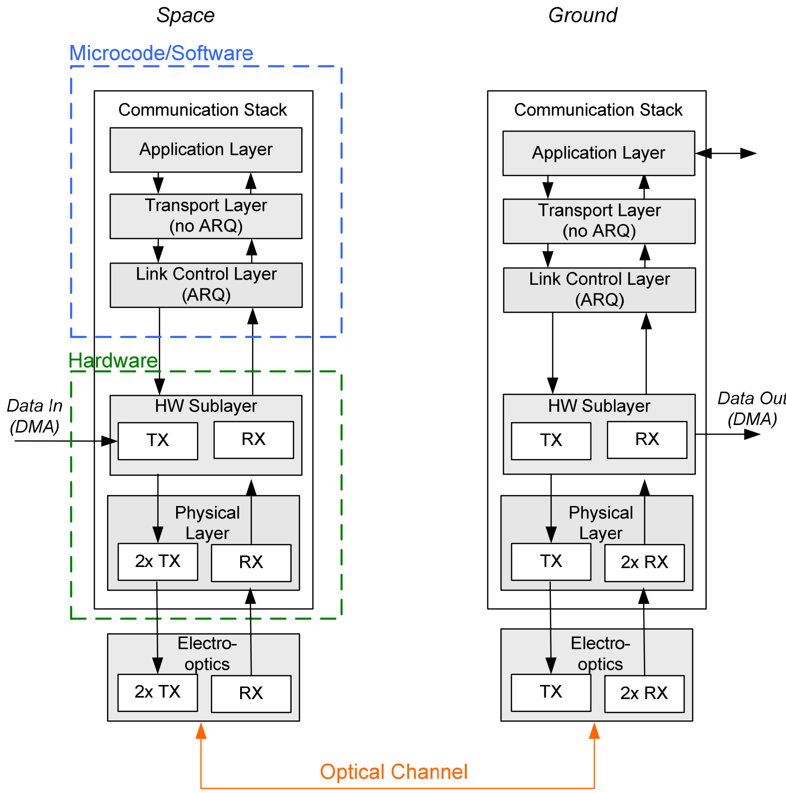

Figure 7. Block diagram OPTEL-μ Link Layer Architecture

The block diagram in Figure 7 shows the link layer architecture of the OPTEL-μ communications subsystem. The link to the mass memory (MM) of the host S/C is handled by an adaptable interface which can be configured in customized way to address the expected variety of S/C interfaces.

The downlink data is buffered in the space terminal before transmission. Once the downlink channel gets available, the data is passed to the protocol stack on the communication controller, co running in soft- and hardware. There, the data is grouped into packets in order to be able to synchronize, identify and validate the data at the receiver. An intensity-modulated optical uplink beacon is used as low speed optical feedback service channel (ARQ) requests erroneous packets for retransmission. The BER of the final received user data where detected errors occurring on the channel are already corrected by the ARQ mechanism is designed to 1 bit error per 1E15bits, assuming that data is stored in the internal buffer no longer than 5 days before readout.

D. Security aspects – no need for optical downlink encryption

The unique feature of narrow optical beam diameters can directly be used to secure optical downlinks. In addition, when combined with a user specific identifier on the ARQ uplink beacon channel, OPTEL-μ downlinks become interception-proof.

The downlink spot diameter on ground depends is a function of transmit divergence, orbit altitude and ground elevation angle. For the described OPTEL-μ space terminal, Figure 5 below shows the resulting beam diameter as function of ground elevation angle for a 700 km altitude sun synchronous LEO mission. Following from the calculation formula behind Figure 5, the ground spot diameter scales linearly with altitude.

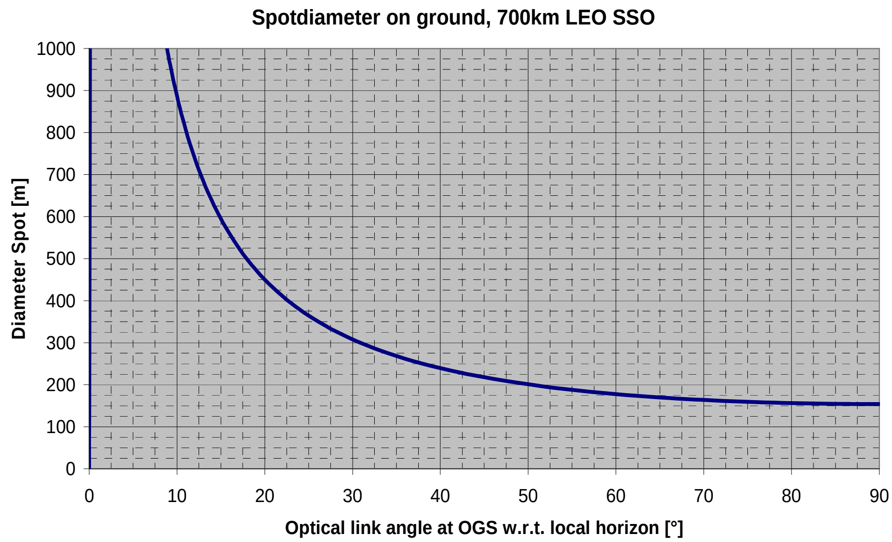

Figure 5. OPTEL-μ spot diameter as function of ground elevation angle.

As a consequence, optical downlinks for the described OPTEL-μ system facilitate secure downlinks without the need for on-board encryption which usually has to be accounted for both, concerning mass, power and cost in addition because a downlink data stream is not encrypted per default.

E. Three Uses Cases

Three main use cases are identified for the OPTEL-μ system. In so-called "Eye-in-the-sky" operations, visual remote sensing data is immediately downloaded once it is gathered. Visual remote sensing is linked to clear sky conditions and an optical link is inherently feasible. In a second case, the OPTEL-μ Space Terminal may serve as a low-footprint add-on to existing RF equipment, thereby facilitating along-track capacity planning. Due to its smallness, OPTEL-μ may help to increase mission data downloads for micro-satellites. Bearing in mind that downlink data rate requirements exceed the frequency allocations in X-band and S-band, the idea is to place a complementary telemetry payload that uses minimal on-board DC power, mass and volume and that could be used to cover on-demand downlink volumes between 5 to 20 Tbit per day (see also section V) for a fully deployed network of 12 low-cost optical ground stations. An optimized network of 7 OGS can obtain almost 4 Tbit per day at 90% clear sky probability. Latter requires then a careful OGS placement which is explained further in chapter III.

III. Approach to Clear Sky Availability

Cloud statistics are available in various data bases that either contain ground based measurements or satellite based statistics or even both. A comprehensive set that allows for an initial impression has been gathered for the years 1971 to 1996 gathered by C. Hahn und S. Warren of Washington University (reference 2). Zonal average numbers suggest a selection of site locations at latitudes around 30° South or 30° North. Temporal variations due to different seasons of the year and diurnal deviations influenced by the Sun need to be considered. Among typical effects are for instance monsoons season in India area or seasonal clouds coverage that is higher during autumn-spring time in temperate areas or lower cloud coverage at North Pole in June – July. In general, high cloud coverage at equatorial regions during all the year leads to unfavourable locations at those latitudes. Compensating effects require placement of sites at both hemispheres, like high cloud coverage at tropical regions from May to August in northern hemisphere, and from December to March in southern hemisphere due to rain seasons. Such rather general trends have to be combined with local geographic information case by case. Therefore, a detailed cloud coverage analysis has been performed by RUAG with support of GMV S.A., using the CDFS-II data base. A comprehensive evaluation of cloud measurement data from the years 2002-2008 was used to derive clear sky condition statistics of 7 pre-selected ground station locations. The study involved analysis of daily contact time for all selected locations, assuming a strawman mission on a 700km sun-synchronous LEO satellite.

The probability of clouds blocking an optical link at preferred locations stays between 25% and 40% within 24 hours. A large OGS network leaves less choice for ideal site conditions than a smaller one, because next to weather conditions as one of the most stringent criteria for the selection of site locations, cost-efficient data connectivity plays a role. By adding a sufficient number of ground stations in various places with uncorrelated weather, the availability of optical downlink data can be significantly increased. If the weather at the stations is uncorrelated, the probability to have cloud blockage at k out of n stations is given by a binomial distribution and the probability to have clear sky at k_0 or more stations is equivalent to the probability to have clouds at k_0 or less stations which yields

$$P_{n,k\le k_0} = \sum_{k=0}^{k_0} \binom{n}{k} p_o{}^k (1-p_0)^{n-k} \tag{1}$$

p_0 = Probability for clouds (no link) at a station
n = Number of stations
k = Number of stations with cloud blockage
$P_{n,k}$ = Probability that exactly k out of n stations have line-of-sight contact

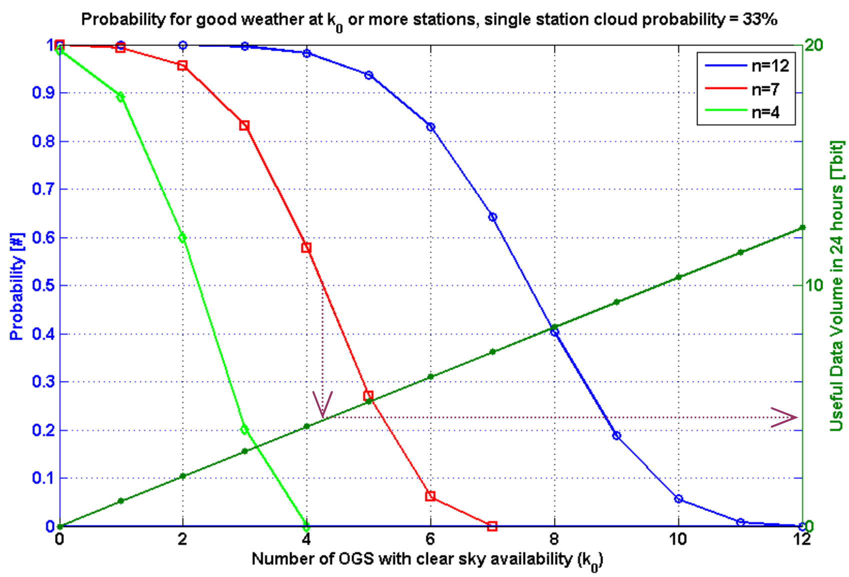

Figure 3. Binominal Distribution Model for prediction of downlink volume from one Space Terminal. ***Contact times use simulated downlink passages for a strawman mission in 700km SSO. Downlink data rates are extrapolated based on accredited link budget formula, using receiver sensitivity data measured at RUAG.***

The theoretical model described in equation (1) is in quite accurate agreement with results found by analysing real-world cloud coverage data from 7 pre-selected, however not optimized, site locations. The numerical analysis used cloud coverage data that was stored in the CDFS-II cloud data base over more than 3000 days between the years 2002 and 2010. A Gaussian fit to accumulated contact durations results in an average of 44.4 min per day.

Receiver sensitivity measurements in a laser communications testbed at RUAG Space were carried out at various modulation formats, including FEC and confirmed the data rate performance described in section I.C. After deduction of coding and synchronization overhead, further deducting 20% contingency margin at this early state of development, for 80% of the maximal useful data rate over an entire passage, the average useful data volume predicted from CDFS-II cloud analysis achieves comparable values within less than 5% to a binomial distribution, both, for a 4 station network and for a 7 station network. Latter is indicated by the arrows in Figure 3.

Depending on the mission needs, the downlink volume could be further increased using approaches described in section V. A sensible estimate is to expect further growth margin by a factor 4 for an enhanced OPTEL-μ system when compared to its nominal version described here (single space terminal, 2 channels, to single ground terminal).

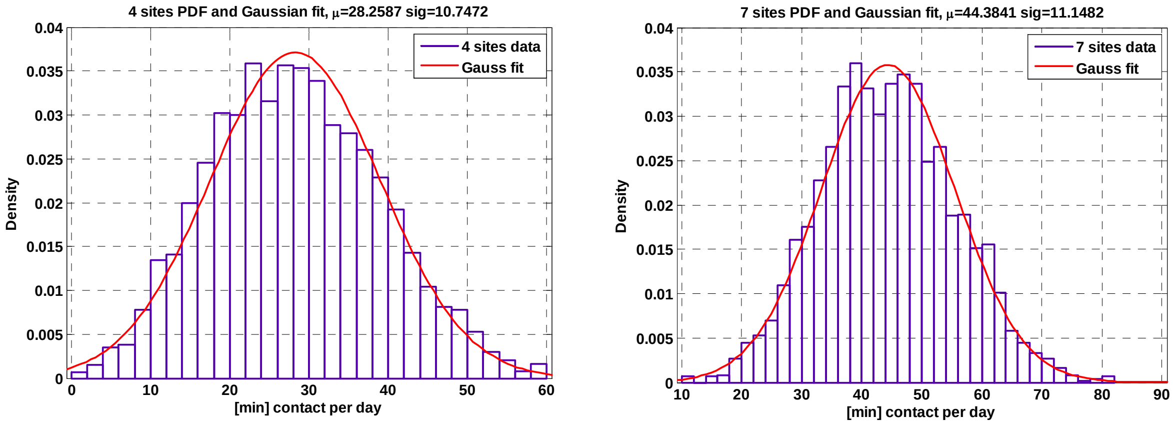

Figure 4. Optical downlink scenario from OPTEL μ.

Gaussian fit over aggregated downlink time for 7-site OGS network using real could coverage data from CDFS-II collected over 8.5 years, simulated downlink passages for strawman mission in 700km SSO

Left: OGS network of 4 sites, Right: OGS network of 7 sites

IV. Concept of Operations for Optical Downlinks

A. Operational Concept

The operational concept for an optical link needs to consider the full strategy of getting the on-board data to the satellite owner processing facility or directly to customer, taking into account the specific characteristics of the link. Three different use cases are presented, direct reception and two use cases based on downlink of on-board stored data. The direct reception operational concept will not be elaborated, as this user is connected to a single OGT and the end recipient of the real-time collected sensor information, a data set that locally will be processed to a level where a decision can be taken.

The operational concept for the downlink of on-board stored data is more complex and will differ from todays operational model. The operational concept is based on a viewpoint for an Earth Observation satellite with a set of sensor that collects a considerable amount of data.

B. Operational concepts for service based X-band service provision

Today the standard way to downlink the onboard sensor data is primary by using radio frequency (RF) links in X-band (8 GHz). Using antennas in the 5-13m range, a reliable link can be established at a bit rate of 300-1200 Mbps. The reliability is near 100% where some technical outages statistically occur due to equipment or communication failures. Todays operational concepts are to a large degree based on these link characteristics, assuming that with a very high likelihood the pass will be successful.

Currently many satellite owners are using ground network services for their communications, where an external provider has a set of multi-mission antennas at different strategic locations around the world.

The satellite owner will interact with this provider by requesting passes for their satellites, a prediction is made at what time the satellite will be over a particular ground station, and this information together with the predicted orbit is sent to the service provider.

Such ground station resource scheduling is usually established in a preliminary version a week in advance of a satellite pass, and then a firm schedule is set a few days in advance. The satellite is pre-programmed to transmit data at these timeslots, and direct feedback during the pass is not always used. As the link has a very high probability of success, both satellite owner and service provider can be confident that the pass, and data transfer will take place at that particular moment.

C. Optical link characteristics and operational approaches

The optical link will differ significantly from the traditional X-band, both in performance and weather sensitivity. The operational concept used today for X-band can work in an early phase with a single station and satellite, but for an operational ground system consisting of a set of OGS and satellites, a different approach is needed.

With the statistical nature of the link, it is not feasible to report a cloud-interfered pass as failed to the customer, and wait for the customer to reschedule and request a new pass. There will be both situations where full cloud coverage are preventing any communication, as well as passes with short interruptions due to small clouds. The service as well as the technical implementation needs to take the statistical nature of the link into consideration and provide a "network layer" to the satellite owner. 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.

D. Data-centric service formulation for optical ground services

With a transition away from the pass-oriented view of the ground service, a new concept where the data is in focus should be introduced. The service formulation should be clear to the satellite owners in order to design the on-board memory accordingly, and to ensure that the needed ground network service is obtained. The ground network provider needs clearly set requirements on how to operate the system in terms of allocating ground resources to the different satellite users.

Although simulations are needed to find the quantitative expression, a starting point should be that the system delivers for example 8 TB of data to a certain network location, over 48 hours, with a probability of 95%. This would give a clear view to the satellite owners, as well as a basis for creating scheduling rules for the ground operator.

E. Implementation

To create an efficient ground network service provision based on optical ground stations, some shifts of functions and changes in network protocols are needed.

- The scheduling of ground resources will change rapidly, and the ground network operator needs to be able to reschedule without the interaction of the satellite owner.
- The current preprogramming of dump times on the satellites, needs to be replaced or extended with a ground based "clear-to-dump" command that is issued whenever a ground resource is available.
- A protocol that divides on-board "files" into pieces needs to be introduced, where ground can request missing pieces in case of temporary outages due to small clouds
- As the pieces of an on-board "file" may be downloaded at different ground stations, a bit-torrent like protocol could be used to request the packages from different sources and merged at the satellite owners node. The network service provider central node keeps track of where the different pieces are in the network.

There are a number of recent developments that are focusing on protocols for handling links with varying characteristics, often referred to as delay tolerant networks or disruption tolerant networks (DTN) [3].

V. Growth Potential of the OPTEL-μ System

The following sub sections provide an outlook on transmission growth potential of the OPTEL-μ system.

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 DC power is required for the ST.

B. Changing Modulation format

On a long term, the same hardware items used in the current ST could be re-configured electrically to act not as OOK, but as DPSK transmitter. Latter, however, requires higher complexity of the OGT receiver architecture. The current selection of OOK is optimal for low complexity, low maintenance OGS operations in remote control. Once available in industrialized performance, a delta design toward a DPSK transmitter could lead up to a ~2-fold increase of data rate. On ground, the current OGT design allows for a double-mount configuration that can be used in transition phases, when OOK systems are still operational and DPSK systems start to get established.

VI. Conclusion

A modular optical downlink system for direct downlinks from Low Earth Orbit is described that achieves comparable downlink rates to K_a-Band systems. It utilizes a miniature laser communications terminal in space segment with about 45W, 5kg and 5.6ltr to achieve 2.5Gbps data rate. The system operates at downlink communications frequencies around 1550nm in the C-band. An uplink based on LIDAR technology achieves Class 1M laser safety and supports line of sight steering and ARQ. Use cases comprise advantageous point-to-point burst downlinks in eye-in-the-sky scenarios for visual observation, add-on to existing RF equipment, facilitating along-track capacity planning and large volume data transfer. A network of low cost optical ground stations is deployed at preferred locations for large volume downlink reception. For OGS networks of seven stations or more, the aggregated data volume per day reaches volumes known from K_a-Band designs for near-Earth spacecraft. Apart from K_a-Band systems, due to its very low on-board resources footprint, the OPTEL-μ system offers a complementary service to those missions allowing for relaxed timeliness requirements, thereby extending the availability of high rate downlinks also to micro-satellites. Noteworthy, the downlink volume could be further increased with minor modifications of the system. In general optical frequencies provide a significant growth rates with systems announced for 10Gbit/s downlink data rates.

The operational concept for a multi-mission OGS network will differ from traditional RF networks, where the OGS allocation and rescheduling is performed transparent to the network user. Disruption-Tolerant-Network can be a suitable protocol for implementing the data interface to the network.

Appendix A
Acronym List

ARQ	Automated Repeat Request
CDFS-II	Cloud Depiction and Forecast System II
CWDM	Coarse Wavelength Division Multiplex
FoR	Field of Regard
NOHD	Nominal Ocular Hazard Distance
OGS	Optical Ground Station
OGT	Optical Ground Terminal
OOK	On-Off Keying
PPM	Pulse Position Modulation
Rx	Receive
S/C	Spacecraft
ST	Space Terminal
Tx	Transmit

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