Interagency Operations Advisory Group
Optical Link Study Group

Optical Link Study Group
Final Report

5 June 2012

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The OLSG would like to thank the following individuals for their contributions to this analysis: Bjoern Guetlich (DLR Space Administration) and Robert Lange (DLR Space Administration/Tesat) for the TerraSar-X and Alphasat descriptions, Andreas Kaufer (European Southern Observatory, ESO) for the La Silla terminal hosting discussion, and Karl Ulrich Schreiber (Bundesamt fuer Kartographie und Geodaesie, BKG) for the Wetzell laser ranging uplink safety and operations concept discussion.

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Executive Summary

In response to an action assigned at Interagency Operations Advisory Group-14 (IOAG-14), the Optical Link Study Group (OLSG) was established to assess if there is a “business case” for cross support in the space communication domain for optical space communication. The application of optical communication for payload data return has the highest potential for missions with high data rate requirements, with the understanding that the tracking, telemetry, and command (TTC) is to be conducted by a radio frequency (RF) communication system. The motivation for optical space communication systems stems from the expectation that substantially higher (10 times) data rates than RF-based solutions might be feasible with similar onboard terminal burden (mass, volume and power). The OLSG assessed this expectation by defining mission scenarios and corresponding space communication system designs, examining actual or potential onboard terminal realizations, and analyzing associated ground terminal solutions. In the course of this study, the OLSG converged on investigating two wavelengths in its analysis—1550 nm and 1064 nm. The maturity of onboard space terminals that are already realized (e.g., for Earth relay inter-satellite links) or are in preparation as demonstrations (e.g., for Moon-to-Earth links through the Earth atmosphere) now requires that economical ground segment solutions be identified for potential future operational implementations.

The OLSG found that cross support will allow sharing of the cost and usage of the global optical terminal infrastructure needed to serve future missions and will boost missions’ scientific return. Each of the scenarios (Low Earth Orbit [LEO], Moon, Lagrange, Mars Space-to-Earth, and Earth relay) was analyzed to determine ground segment solutions that maximize the data return for the mission. The OLSG found that it is always possible to develop a technical solution for the ground segment; however, the number of ground stations involved would be a substantial cost burden for a single agency. Special attention was given to studying the effects of potential disruptions of optical communications due to weather (clouds, optical turbulence and other atmospherics) and aviation interference. Specifically, the ground segment of the optical space communication system has the following inherent difficulties:

1. An uplink beacon is needed to facilitate the space terminal pointing. Such a beacon has to penetrate navigable airspace and can only be operated with permission from a national civil aviation authority, which might lead to usage constraints. The safety assessment of the laser uplinks follows the definitions of the International Civil Aviation Organization (ICAO), which allow one to compute the Nominal Ocular Hazard Distance (NOHD) beyond which the laser beam is considered eye safe. The 1550 nm wavelength for uplink is favored over 1064 nm, since the maximum permitted exposure level to the human eye is twenty times higher for 1550 nm. It can be shown that due to the narrow beam widths of the beacon uplink, exposure risk to aviation is very small. The technical means to cope with potential air traffic requirements are available and practiced regularly by laser ranging stations and astronomical observatories (laser guide stars). Our analysis shows that systems for the LEO and Earth Relay scenarios can be designed in an eye-safe manner using 1550 nm, but that is not possible for the other scenarios using the assumptions made in

this analysis. However, a more refined design could provide an eye-safe uplink beacon to lunar distances.

2. Optical space communication through the Earth atmosphere is nearly impossible in the presence of most types of clouds. Therefore, the optical communication system solution for a particular mission has to utilize optical ground stations that are geographically diverse, such that there is a high probability of a cloud-free line of site (CFLOS) to a ground station from the spacecraft at any given point in time (e.g., at the same longitude, or at a sufficient number of stations at different longitudes to allow the stored onboard data to be transmitted within the allocated time). The OLSG analyzed the space-Earth mission scenarios for CFLOS and expressed the results in a common metric across the scenarios—percent data transferred (PDT). The analysis indicates ground segment solutions are possible for all scenarios, but require multiple, geographically diverse ground stations in view of the spacecraft. Unfortunately, for locations at high latitudes, e.g., Svalbard, the satellite-based meteorological cloud information was not sufficient to conduct a detailed CFLOS analysis for a LEO scenario with polar stations, similar to that done for the other scenarios. However, the OLSG projected in-situ measurements and derived an approximation of the cloud data, providing a high-confidence result. The concept of predictive near-real-time weather, combined with a more dynamic operations concept including slews of the onboard terminal to a cloud-free station, are considered advantageous for optimization of optical communications. However, the need for ground sites whose clouds are uncorrelated from each other and are simultaneously in view of the user spacecraft leads to a requirement for geographically separated ground sites, and thus a clear case for the advantages of cross support.

The OLSG addressed the investment cost aspect of the scenarios by defining cost estimates for realizable optical terminals. The OLSG also estimated site-specific investment costs (ground communications, infrastructure, etc.) for each ground site required in a particular scenario. By adding these site-specific costs to the terminal cost, the OLSG arrived at an estimated investment cost for each ground terminal site required in a scenario, and calculated the approximate total investment cost for that scenario. Estimated investment costs for each scenario are: 14.4 M€ for LEO, 19.7 M€ for Lunar, 16.9 M€ for L1, 15.3 M€ for L2, and 110.4 M€ for Deep Space (Mars). The estimated investment cost for the Earth Relay Scenario, including a global, redundant, and therefore highly operationally viable constellation of relay spacecraft, is 1,652 M€. Estimates of annual recurring costs are also included for each scenario.

OLSG finds that there is a strong business case for cross support in optical space communications, as identified in a number of scenarios:

- LEO – space terminals are rapidly maturing and a number of terminals are being developed. Ground terminal solutions are technically and economically feasible. The operational implementation for the overall ground cross-support network is feasible in the near term, and should be comprised of one polar and six mid-latitude stations (seven sites required) to allow migration from traditional RF payload data downlinks to optical downlinks. The large number of geographically dispersed ground sites required is a clear case for cross support.

- Lunar/L1/L2 – space flight terminals are currently under development. Ground terminal solutions are technically and economically feasible. The preliminary assessment shows very high potential for cross support. The operational implementation for the overall ground cross support network is feasible in the near term, and in fact will be demonstrated with the upcoming Lunar Laser Communications Demonstration (LLCD) mission, where a three-station network comprised of NASA and ESA ground stations is planned for support of the demonstration mission.
- Deep Space (Mars) – flight terminals are still in the early development phase. Ground terminals will be complex and very expensive. The analysis has demonstrated a high potential exists for cross support, but the overall system solution for deep space is not yet fully mature for operational implementation in the near term.
- Earth relay – space terminal inter-satellite link and feeder link capabilities have been demonstrated, and relay terminals are under development for operational use for ESA's European Data Relay System (EDRS). The analysis has demonstrated that a high potential exists for cross support in both the inter-satellite links and feeder links. While the data relay system could be developed by a single agency, there are advantages to implementing cross support from an economic perspective.

Having established the benefits of cross support, the OLSG recommends:

1. IOP-3 should consider the question of optical link interoperability in addition to RF interoperability, due to the unique challenges related to weather outages/interference. Optical link interoperability will result in even more benefit to space agencies than interoperability for RF communications, as it will boost scientific data return.
2. Encouragement of early demonstrations of cross-support scenarios that will demonstrate the value of cross support in the optical communication domain and confirm the findings of the OLSG.
3. As the ICAO eye-safety calculation assumes a far-field approximation, and does not consider an extended source for the uplink beacons, the OLSG seeks a dialog with ICAO to develop a more refined calculation method for the near field, which will be more appropriate for the scenarios analyzed by the OLSG in this report.
4. Due to the diversity of technical solutions being implemented by the agencies for operational use (EDRS), and numerous technology preparations and demonstrations, the following strategy is proposed (see Figure 1):
    a. That the OLSG continues its work by producing a "Standardization Guidance Addendum" to this report by November 2012, with the aim to define guidance for the standardization process.
    b. That technical assessments of realized optical communication solutions are shared between the agencies, using the CCSDS Optical Communication Special Interest Group (SIG) as a forum for exchange.
    c. That the CCSDS Optical Communication SIG prepares a concept paper and charter for standardization, taking into account recommendations from the Interagency Operations Panel (IOP-3), leading to the formation of a CCSDS Optical Communication Working Group by Spring 2014.

d. That the CCSDS Optical Communication Working Group shall within 3-4 years produce agreed standards based on continued technical assessment for implementation in cross supportable missions in the early 2020s.

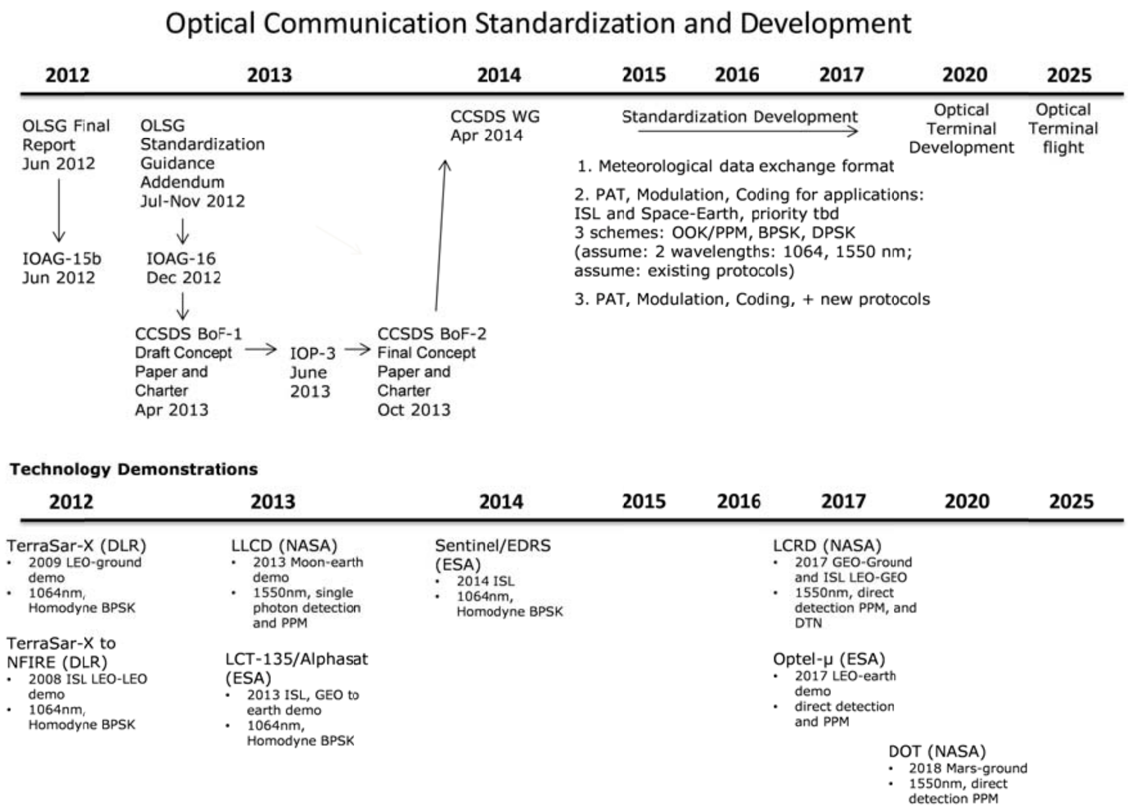


Figure 1: Proposed schedule of optical communication standardization and development.

1 Introduction

1.1 Charter

At its 14th meeting on 2-4 November 2010, the Interagency Operations Advisory Group (IOAG) created an Optical Link Study Group (OLSG) to explore the operational use of optical space communications, with the motivation to try to harmonize optical systems internationally.

The IOAG established the following OLSG Terms of Reference:

- Collect and summarize various agencies' strategic objectives for optical communications.
- Collect information concerning existing or planned systems (flight systems and ground stations): technical characteristics (wavelength, acquisition scheme, etc.), planned utilization, locations of ground stations, locations of Earth relay satellites, contact points. Identify any unique characteristics of each domain (such as extremely weak signal from deep space, global coverage issues, etc.).
- Identify commonalities between various systems and applications. Identify cases where cross support would be beneficial (such as when dealing with cloud obstruction). Identify necessary technical aspects for which coordination is needed to allow interoperation.
- Based on the data collected above, identify proposals for various application options, e.g., Low Earth Orbit (LEO) to Earth, Geostationary Earth Orbit (GEO) to Earth, Moon to Earth, Lagrange Points to Earth, Mars to Earth, Deeper Space to Earth; Space to Space around Earth, Moon, Mars. Identify areas where common standards are possible.
- Identify other approaches for cross support when common standards are not possible.
    - Assess the potential for cooperative missions to have identical wavelengths/systems.
    - Assess the need to exploit different ground terminals/potential to exploit multi-wavelength terminals.

1.2 Motivation

It is believed that optical space communication can significantly increase the mission data return and enable new types of future missions. Due to the inherent issues particular to optical space communication (most prominently the influence of cloud obscuration) requiring the (costly) operation of multiple optical ground stations, **routine** cross support between space agencies will very likely play a much larger role compared to traditional radio frequency (RF) space communication.

1.3 Scope

The scope of this analysis is limited to the optical space communication application of space-Earth payload data downlinks and inter-satellite links (ISL) around the Earth in free space. Also included are optical space-Earth feeder links for Earth relays.

In addition to the optical payload data downlinks, traditional RF links are assumed for basic Telemetry, Tracking, and Command (TTC) service and for radiometric measurements. For this OLSG analysis, an optical (uplink) beacon or communication beam is always assumed as a pointing, acquisition, and tracking (PAT) aid for the onboard optical communication terminal. Although current technology requires use of a beacon, beaconless PAT may be possible in the future.

The following potential applications and features of an optical space communication system are de-scoped from the discussion in this document:

- Use of an optical *uplink* for ranging, time transfer, and data transfer. These implementations are only considered as additional options; e.g., a data uplink channel might be considered as an option for carrying protocol control information as an alternative to the TTC uplink. A high precision ranging and time transfer might be considered for specific missions where these features are considered "enabling."
- Inter-satellite links around the Moon, Mars are not considered.
- High-rate optical uplinks, e.g., for Telecom satellite feeder links, are not considered since they are deemed to belong in the commercial domain.

1.4 Methodology

Following the Terms of Reference provided in the OLSG Charter, the participating agencies identified their objectives for optical communications links and provided information about existing missions, infrastructure, and future plans.

After reviewing the diverse data that was received, the OLSG defined two categories of mission scenarios for analysis: 1) space-to-Earth scenarios, which require transmission of optical signals through the Earth's atmosphere; and 2) relay mission scenarios, which include space-to-space communications from LEO to geostationary relays, as well as communications from the surfaces of the Moon and Mars to orbiting relays.

Within each category all identifiable scenarios for utilization of optical links were tabulated and evaluated for their technical feasibility and potential for meaningful cross support. Because of the need to constrain the number of analyses so the work could be completed within the time allotted, the OLSG selected only those scenarios with the highest potential for cross support for full evaluation. This process resulted in selection of five space-to-Earth scenarios for further analysis: LEO, Lunar orbit, Lagrange points 2 and 1, and deep space. Only one relay mission scenario was selected: LEO to a geostationary relay, which included consideration of relay-to-Earth feeder links via radio frequency and optical means.

The OLSG developed a Basic Concept of Operations, identifying optical system performance characteristics that are applicable to all scenarios, and that affect mission design and space terminal pointing. The Basic Concept of Operations also considers factors such as ground segment geographic constraints, cloud obscuration, laser safety requirements, etc.

Starting from this Basic Concept of Operations, the OLSG analyzed each of the scenarios using a prescribed general format, addressing the end-to-end design of the space communication system, including downlink data rates and volumes. Where possible, an existing or planned reference mission was used. Mass and power estimates were based on developmental or demonstration models and may change due to required “ruggedization” prior to operational use. Link budgets were developed in a standard format, using a prescribed set of candidate ground stations. These links were then analyzed for the impact of local weather effects, such as clouds, on system performance. In this manner, the OLSG assessed the impact of a global, international network of ground stations.

2 Space-Earth Mission Scenarios: Basic Concept of Operations

2.1 *Concept of Operations*

Concepts of operations (ConOps) for optical communication systems include the details of when and how optical communication is used for a specific application. The OLSG analyzed two very different types of high-level scenarios that call for different ConOps. The first scenario class includes links through Earth's atmosphere. The second class also includes links above the atmosphere. The distinguishing characteristic is that for systems with links through the atmosphere, phenomena like clouds may impair the ability to get data through to a specific ground station during a scheduled pass, requiring that alternatives are available. An inherent assumption is that for the foreseeable future, space missions will have RF communication systems and the ConOps can include an approach that is a hybrid of optical and RF communications capabilities. In particular, for applications with optical links through the atmosphere, TTC and critical data functions will most likely be accomplished via the RF links.

2.1.1 Driving Factors in a ConOps

ConOps tend to be specific to each mission or mission class, e.g., LEO or deep space, but in general the most important characteristic is the ability to transfer as much data as possible in some given period, whether orbit-to-orbit, day-to-day, or over the life of the mission. For the typical space science mission, data transfer is usually an asymmetric process in that there is usually more data transferred from the spacecraft (return link) than to the spacecraft (forward link). For human spaceflight missions, the data rates may be more symmetrical.

Other factors that must be considered in the development of the ConOps are:

- Spacecraft considerations
    - Optical system performance characteristics like aperture size, output power, etc.
    - Burden on the host
        - Mass, volume and power utilization of the optical systems
        - Special requirements like demanding stability and pointing capabilities
- Earth station considerations
    - Geographic locations—geographically diverse and weather-diverse stations are desired for high throughput
    - Weather and atmospheric conditions for links through the atmosphere to Earth stations
    - Operational constraints imposed by aviation and laser safety
- Mission considerations
    - Time available on the data source spacecraft, relay spacecraft, or Earth stations for the data transfer function
    - Allowable latency in transferring data, potentially impacting onboard data storage requirements

2.2 Mission ConOps

The basic optical communications ConOps assumes there is a specific amount of data at the source that must be transferred to the sink in a specific amount of time—not unlike a typical RF scenario. The high-level process assumes a scheduled approach where the communications process starts at a specific time, with a link establishment process between the source spacecraft and the sink (ground station or relay satellite). If the link is successfully established, data is transferred during the specified time and then the link is terminated according to plan. If link establishment is not successful or the link cannot be maintained for the required duration, due to clouds or other link impairment, then an alternative process is required. At a minimum, the data not transferred must be stored until it can be transferred later (to another ground station or relay) or deleted.

2.2.1 Line of Sight

The first consideration in link establishment is a line of sight between the source and sink. Line of sight depends upon geometry in all cases and also depends on a cloud-free line of sight (CFLOS) for links through the atmosphere.

2.2.1.1 Geometric Line of Sight

Geometric line of sight is calculated based upon the source spacecraft trajectory, location of the ground station(s), and any local terrain considerations, e.g., mountains, trees, etc.

2.2.1.2 Cloud Free Line of Sight

Space-to-ground optical communications may be impacted by the presence of cloud cover. Typical clouds have optical fades that far exceed three decibels (dB). Therefore, it may not be feasible to include enough link margin in the link budget to prevent a link outage. It should be noted that some cirrus clouds may have optical fades less than three dB when averaged over a very short period of time (e.g., minutes). However, an optical communications link directed through the sky may encounter "knots" or areas within thin cirrus that may far exceed three dB. Therefore, a mitigation strategy ensuring a high likelihood of a CFLOS between a ground station and the spacecraft is needed to maximize the transfer of data and overall availability of the network.

One strategy to address this problem of cloud outages in laser communications involves "ground station diversity," where multiple stations have the potential to receive communications when other sites are cloud-covered or unavailable due to geometric visibility limitations. The availability of a communication link between a spacecraft and a ground station network depends on many factors, including the number and location of the sites in the network and the orbit of the spacecraft, which together determine the elevation angle of the link and the path length of transmission through the atmosphere. For this report, a ground station is considered "available" for communication when it has a CFLOS at an elevation angle to the spacecraft terminal of approximately 20° or more. The network is "available" for communication when at least one of its sites is "available." Typical meteorological patterns cause the cloud cover at stations within a few hundred kilometers of each other to be correlated. Consequently, stations within the network should be placed far enough apart to minimize these correlations, thus maximizing the probability of CFLOS. This requirement may lead to the selection of a station that has a lower CFLOS than sites not selected, but is less correlated with other network sites. The stations also need to be close enough to each other to maintain continuous access with the spacecraft as its position with respect to the ground changes with time.

The Laser Communications Network Optimization Tool[1] (LNOT) combines these factors and considers their interactions to compute the optimal configuration of sites based on a specific mission scenario (e.g., Deep Space to ground), a long-term record of high resolution clouds, and other constraints like minimum elevation angle from the ground to the spacecraft. The cloud database used by LNOT is a state-of-the-art, high-end, and validated cloud analysis that was developed based on geostationary meteorological satellite imagery. This imagery was obtained from the U.S. Geostationary Operational Environmental Satellites (GOES), Europe's Meteosat Second Generation (MSG), and Japan's Multi-functional Transport Satellite (MTSAT) for the period 1995 to the present over the continental United States and Hawaii, and for 2005 to the present over portions of the world where existing NASA and ESA ground sites exist today (e.g., NASA's Deep Space Network [DSN]). To incorporate polar ground sites, one would need to integrate cloud data available from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) sensors and the European Meteorological Operational (MetOp) satellite systems. However, doing so was not possible for this analysis, so clouds at polar sites were characterized by human surface reports. The spatial resolution of all existing cloud data is four km and cloud data is available at temporal resolutions as high as 15 minutes, allowing use of LNOT to analyze different optical communication scenarios such as LEO, Lunar, L1, L2, and Deep Space.

For this report, LNOT is used to compute a metric referred to as the Percent Data Transferred (PDT), which determines the amount of mission data transmitted to a network of ground sites based on the existence of CFLOS to one or more sites, data rates/storage, and data volume. Using the seven years of cloud data (2005-2011) and the position of the satellite, LNOT dynamically tracks the data collected by the satellite, the data stored onboard the satellite, and the data sent to the ground. For each hour in the cloud database, LNOT determines whether there is CFLOS from the satellite to any ground station. It also determines the amount of time during that hour the satellite has access above 20° to any ground station. If a ground site has CFLOS to the satellite, the analysis assumes data is sent at the specified data rate, and the data buffer is reduced by the amount of data sent. If no site has CFLOS to the satellite, the amount of data in the buffer is increased. If the buffer is full, the oldest data is purged, and the amount of data lost is recorded. For each scenario, the number of hours of CFLOS required each day to downlink the mission data is defined as the data volume divided by the data rate, and is reported in units of hours. The PDT is computed at the end of the simulation as the amount of data successfully sent to the ground divided by the amount of data collected by the satellite. The target PDT for the various scenarios considered in the OLSG analysis is 95%, and that criteria is used to determine the number of ground stations required.

2.2.1.3 Predictive Weather

Depending on the scenario, free space optical communications operations can take advantage of cloud prediction at each ground site to maintain CFLOS, and thus maximize

[1] Wojcik, Gary S. et al., *Deep-space to ground laser communications in a cloudy world* (Free-Space Laser Communications V. Edited by Voelz, David G.; Ricklin, Jennifer C., Proceedings of the SPIE, Volume 5892, pp. 17-27, 2005).

availability. Maintenance of CFLOS can be accomplished by knowing whether the line of sight to each ground site is cloud free at a given time, and knowing how many minutes into the future each site is expected to remain cloud free. A study using the *Lasercom Simulator* demonstrated that having local cloud instrumentation at each site and making a simple cloud forecast significantly reduced the amount of time the space laser communications terminal required to re-point and acquire with a new ground station (see Figure 2 below). This figure shows five whole sky imagers (WSI), one for each site in a five-site network. Each site shows the current cloud conditions in the skydome. The black strip in each WSI represents an occulter used to block the Sun. The simulation output shows how the number of slews on the space terminal is reduced with access to cloud data (1249 slews with no cloud data and 291 with access to cloud data). In this particular case, having local cloud data to aid decision making reduced the number of slews by an order of magnitude. In addition, the PDT of the five-site network that had access to local cloud data was higher than that of the network without local cloud information. For deep space applications the amount of lead time required for predicting a site's availability for an optical link will increase, and could be on the order of 20-40 minutes.

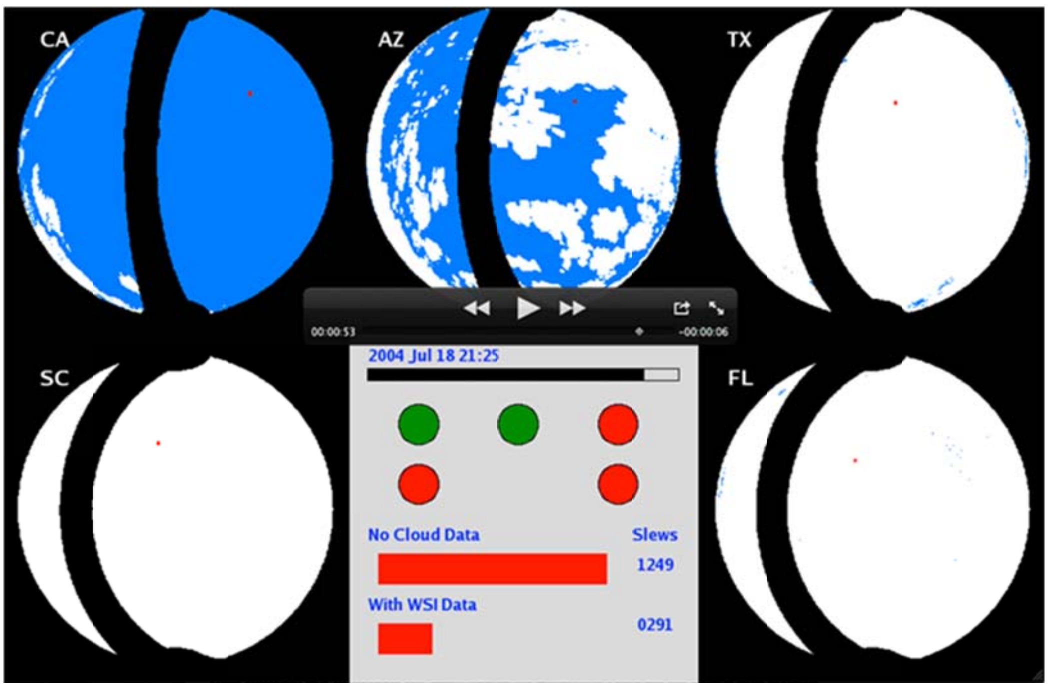


Figure 2: Lasercom Simulator output showing the benefit of local cloud instrumentation on minimizing link handovers and maximizing PDT.

2.2.2 Acquisition

Once line of sight is established, the source and sink terminals must establish two-way links via an acquisition process. The details of this process vary, usually depending upon the round-trip time delay and the beacon beam widths of the two terminals. In the case of short time delays, a closed-loop process can be used, whereby one of the terminals transmits a signal that the other terminal locks onto, and responds that it has locked to close the loop before data is transferred. For long light times (e.g., deep space) it is not realistic to establish a closed loop before data is transferred. In that case, either the sink terminal (e.g., Earth terminal) transmits an uplink beacon signal and the source terminal acquires this signal, or the sink terminal has no beacon and the source terminal relies on other positioning references (e.g., Earth thermal radiations) to point to the counter-terminal. Note that beacon signals used for the acquisition process may be different from those used for communication, and an RF link could potentially be part of the process.

If for any reason the signal is lost later in the operations process (before planned loss of signal), the acquisition process may be restarted. Note that this subsequent acquisition process may not be successful if, for example, clouds have come between the transmitter and receiver or if round-trip light times are large.

2.2.3 Data Transfer

Once the acquisition has occurred, data is transferred. This process assumes some underlying, and presumably standardized, synchronization formats, data framing, and protocols. Assuming data is transferred successfully, an orderly termination of the link occurs. If data transfer is interrupted for any reason, the link may need to be reestablished or the data transferred to another station at a later time.

2.3 Space Link Design

The OLSG developed space link designs, including uplink and downlink budgets, to prove that the communication systems as assumed for the scenarios are realizable. In the most general terms, an optical space communications link will consist of three elements:

1. Uplink and downlink acquisition and tracking beacons
2. A communications uplink
3. A communications downlink

In most of the scenarios studied in this report, the required uplink communications will be provided by an existing RF link. Therefore, optical uplink communications are not studied further in this section of the report.

The optical communications downlink is usually a much more challenging problem than an optical uplink, because high data rates must be achieved by a transmit terminal that is severely constrained in size, mass, and power consumption. Optical communications downlink is discussed in detail in section 2.3.1.

To assist the space terminals in pointing, acquisition and tracking of the ground terminal, the ground terminal may transmit a powerful beacon signal to the space terminal. This uplink beacon gives rise to safety and interference issues, which are addressed in section 2.3.2.

Any downlink beacon emitted by a space terminal beyond LEO distances will be so attenuated by beam spreading losses that neither safety concerns nor interference will typically be an issue, especially since the space terminal will operate at much lower power levels than any ground terminal.

2.3.1 Downlink

The purpose of a communications system is to transfer information from one point to another. This transfer is often achieved by imposing a modulation onto a carrier wave, which is then transmitted to its destination. Well understood advantages of using an optical carrier frequency (instead of RF) in space communications are: the possible increase in modulation bandwidth, the ability to achieve significantly higher transmission and reception antenna gains, and the potential reduction of size, mass, and power consumption impact on a spacecraft.

The ability to acquire signals and transfer data in a way that can realize these benefits depends on the characteristics of the flight and ground optical systems, transmitter and detector photonics, modulation and coding schemes, and any propagation impairments.

The design of a space link must consider all relevant effects in a quantitative manner and establish a link budget which incorporates all relevant contributing factors, in order to reliably predict the performance of the space link.

Using the downlink budget for a lunar mission (Lunar Atmosphere and Dust Environment Explorer, or LADEE) as an example (see Figure 3), the structure and content selected for the downlink budgets presented in this report are explained.

MOON DOWNLINK BUDGET

INPUT PARAMETERS

Range	384.0E+03	km
Elevation	30	deg

TRANSMITTER

Modulation Type	16-PPM	
Tx Wavelength	1.55	μm
Tx Ave Power	0.5	W
Tx Data Rate	622.0E+06	Hz
Tx Aperture Diam	0.1076	m
Tx Angular Diam	3.78	arcsec
Tx Footprint Diam	7.04E+03	m
Tx Optical Transmission	33.0	%
Tx Depointing	0.50	arcsec
Uncoded Slot Rate	5.0E+09	s^{-1}
Uncoded Bits Per Word	2.00	

ATMOSPHERIC LOSSES

Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-1.0	dB

RECEIVER

Rx Aperture Diam	0.40	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	46.3	%
Rx Array Size	4	apertures
Fiber Coupling Loss	-3.57	dB
Required Photons / Pulse	3.74	
Code Rate	0.50	

LINK BUDGET

Tx Ave Power	**26.99**	**dBm**
Tx Photons / Pulse	1.25E+10	
Tx Antenna Gain	106.77	dBi
Tx Transmission Loss	-4.82	dB
Tx Pointing Loss	-0.31	dB
Isotropic Space Loss	-309.86	dB
Atmospheric Loss	-1.44	dB
Rx Antenna Gain	118.18	dBi
Array Gain	6.02	dB
Rx Transmission Loss	-3.34	dB
Rx Pointing Loss	0.00	dB
Rx Fiber Coupling Loss	-3.57	dB
Total Optical Path Loss	**-92.38**	**dB**
Ave Power at Rx Detector	**-65.39**	**dBm**
Photons / Pulse at Rx Detector	**7.26E+00**	
Required Photons / Pulse	3.74	
Link Margin	**2.88**	**dB**

Figure 3: Sample downlink budget for a lunar mission (LADEE).

Table 1 explains the significance of the terms and quantities appearing in the link budget format used throughout this report.

Table 1: Explanation of terms used in the link budget tables.

#	Quantity	Unit	Definition
1	Range	km	Range R [km]. Distance between Tx and Rx
2	Elevation	deg	Elevation ϑ_{RX} [deg] of RX LOS over local horizon
			Transmitter parameters
3	Tx Wavelength	µm	Tx laser wavelength λ [µm]
4	Tx Ave Power	W	Tx laser average power $P_{TX\ ave}$ [W]
5	Tx Data Rate	bps	Tx data rate [bps]
6	Modulation type		In case of Pulse Position Modulation (PPM) modulation, the M-ary PPM order is indicated and no deadtime assumed
7	Uncoded Slot Rate	s^{-1}	In case of PPM modulation, resulting PPM slot rate
8	Uncoded Bits Per Word		In case of PPM modulation, uncoded bits transmitted per PPM symbol
9	Tx Aperture Diam	m	Tx telescope aperture diameter D_{TX} [m]
10	Tx Angular Diam	arcsec	Tx beam diffraction limited $1/e^2$ angular diameter $\alpha_{TX} = 4\lambda/\pi D_{TX}$ [arcsec]
11	Tx Footprint Diam	m	Tx beam $1/e^2$ footprint diameter $D_{fp} = R\times4\lambda/\pi D_{TX}$ [m] at range R
12	Tx Optical Transmission	%	Optical transmission T_{TX} [%] of Tx telescope, including aperture obscuration
13	Tx Depointing	arcsec	Tx telescope angular pointing error δ_{TX} [arcsec]
			Parameters describing atmospheric effects
14	Atm Zenith Transmittance	%	Atmospheric transmittance T_{ATM} [%] at the Tx wavelength, including dust and aerosol absorption
15	Relative Airmass		Relative airmass M at elevation ϑ_{RX}

#	Quantity	Unit	Definition
			calculated by the Pickering model
16	Atm Transmission Along LOS	%	Atmospheric transmission $T = e^{M \ln T_{ATM}}$ along the communications line of sight (LOS). Cloud effects are assumed to be binary and are not included.
17	Scintillation Loss	dB	Assumed characteristic scintillation loss due to atmospheric turbulence L_{SCINT} [dB]
		Receiver parameters	
18	Rx Aperture Diam	m	Rx telescope aperture diameter D_{RX} [m]
19	Rx FOV	arcsec	RX telescope field of view diameter $\alpha_{RX\ fov}$ [arcsec]
20	Rx Depointing	arcsec	Rx telescope angular pointing error δ_{TX} [arcsec]
21	Rx Optical Transmission	%	Optical transmission T_{RX} [%] of RX telescope, including aperture obscuration
22	Rx Array Size	apertures	Number of Rx telescopes N_{array} in case of array at the receiver
23	Fiber Coupling Loss	dB	Loss due to coupling into fiber at the receiver
24	Required Photons / Pulse		Detector sensitivity at the assumed data rate, including quantum efficiency and sky noise background as a function of the Sun-Earth-Probe angle
25	Code Rate		Non-redundant proportion of the data stream when forward-error-correction is employed
		Link budget	
26	Tx Ave Power	dBm	Tx laser average power $P_{TX\ ave}$ [dBm]
27	Tx Photons / Pulse		Number of photons per laser pulse $N_{TX\ pulse} = E_{pulse}/(hc/\lambda)$
28	Tx Antenna Gain	dBi	Tx telescope gain $G_{TX} = 20\times\log_{10} \pi D_{TX}/\lambda$ [dBi]
29	Tx Transmission Loss	dB	Tx telescope optical transmission losses $L_{TX\ opt}$ [dB] due to internal absorption and scattering
30	Tx Pointing Loss	dB	Tx telescope depointing loss $L_{TX\ pt}$ = -

#	Quantity	Unit	Definition
			$10\times\log_{10}(2J_1(m_{TX})/m_{TX})^2$ [dB]
31	Isotropic Space Loss	dB	Isotropic free-space path loss over link range $L_{FS\ ISO} = 20\times\log_{10} 4\pi R/\lambda$ [dB]
32	Atmospheric Loss	dB	Atmospheric loss $L_{ATM} = 10\times\log_{10}T_{ATM} + L_{SCINT}$ [dB]
33	Rx Antenna Gain	dBi	Rx telescope gain $G_{RX} = 20\times\log_{10} \pi D_{RX}/\lambda$ [dBi]
34	Array Gain	dB	Array gain $G_{array} = 10\times\log_{10} N_{array}$ [dB]
35	Rx Transmission Loss	dB	Rx telescope optical transmission losses $L_{RX\ opt}$ [dB] due to internal absorption and scattering
36	Rx Pointing Loss	dB	Rx telescope pointing loss: Diffraction beam pattern $L_{RX\ pt} = -10\times\log_{10}(2J_1(m_{RX})/m_{RX})^2$ convoluted with sensor FOV (tophat function)
37	Total Optical Path Loss	dB	Sum of losses and gains described above L_{OPT} [dB]
38	Ave Power at Rx Detector	dBm	Average TX power incident on RX detector $P_{RX\ ave} = P_{TX\ ave} - L_{OPT}$ [dBm]
39	Photons / Pulse at Rx Detector		Photons per pulse incident on RX detector $N_{RX\ pulse} = N_{TX\ pulse}\times10^{-0.1\times L_{OPT}}$
40	Link Margin	dB	Difference between the detector sensitivity and the actual number of photons

As optical communication downlinks are intermittently interrupted, the use of data return acknowledgement and retransmission protocols, such as Delay Tolerant Networking (DTN), help improve the data return. Such protocols cope with atmospheric disturbances to the downlink and additionally prevent the loss of data during the redirection of the downlink to a second ground telescope if the first should be obscured by clouds. Data acknowledgment requires sending information back to the spacecraft either through an optical uplink, or alternatively through an RF uplink. Since the data rates on optical communication links will typically be higher than those of RF links, research should be conducted on the best data return acknowledgement and retransmission protocols for use with optical links. The scenario analyses implicitly assume a data acknowledgement and retransmission protocol in the computation of the PDT.

2.3.2 Uplink (Beacon)

2.3.2.1 Uplink Budget

In the scenarios considered, the optical communications ground terminal is required to transmit a powerful laser beacon as a pointing and tracking aid to allow the space terminal to track the position of the ground terminal with the necessary accuracy. The beacon power ranges between 500 mW (LEO) and 5 kW (Mars).

To successfully conclude the acquisition procedure, the uplink beacon must reach the aperture at the space terminal with sufficient irradiance, even under stressing atmospheric conditions. Therefore, the performance of the link can be evaluated in terms of irradiance margin.

A design of such uplink/beacon transmission may include the following considerations reflected in the corresponding link budget calculations:

1. To mitigate the effect of atmospheric turbulence leading to significant irradiance fluctuations/fading at the space terminal, the beacon would be transmitted as an incoherent superposition of several beams emitted from corresponding separate sub-apertures from mutually incoherent sources.
2. Given the characteristics of the local atmospheric turbulence at any given time—which is conveniently parameterized by the Fried parameter r_0 (the spatial scale over which the phase perturbations can be considered as negligible)—the most suitable (sub-)aperture size of the transmitters would be chosen to be equal to this parameter (r_0). Since r_0 varies with time (of day) and local conditions (good sites have a large r_0 over longer periods), a transmitter design would account for the local statistically worst case. At sites considered adequate for optical communications, r_0 ranges from several cm to few tens of cm.
3. The mutually incoherent sub-apertures should be spaced by a distance larger than r_0 in order to experience statistically independent turbulence effects and reduce the overall signal fading at target. When a single telescope is used for uplink and downlink, the spacing of the transmitting sub-apertures is taken such that they fit into the receiving telescope's aperture as their envelope. Other configurations may consider use of a separate uplink and downlink ground terminal. Our scenarios correspond to an implementation where the incoherent beams of smaller diameter beams are emitted through the main telescope. For our considerations, the actual design is irrelevant.
4. For the following eye-safety calculations, which also consider near-field propagation, each sub-beam is taken to be Gaussian with its beam waist equal to the sub-aperture size.

Figure 4 is an example uplink beacon budget for a lunar mission. Most of the terms and quantities appearing in the uplink budget are the same as in the downlink case, and are explained in Table 1. Table 2 describes the additional terms.

MOON UPLINK BUDGET

INPUT PARAMETERS		
Slant Range	384.0E+03	km
Elevation	30	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	10.0	W
Tx Array Size	4	apertures
Tx Aperture Diam	0.15	m
Tx Angular Diam	2.71	arcsec
Tx Footprint Diam	5.05E+03	m
Tx Optical Transmission	46.3	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-1.5	dB
RECEIVER		
Rx Aperture Diam	0.11	m
Rx FOV	5.00	arcsec
Rx Depointing	3.50	arcsec
Rx Optical Transmission	33.0	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	63.0E-09	W/m^2

LINK BUDGET		
Tx Ave Power	**40.00**	**dBm**
Tx Antenna Gain	109.66	dBi
Tx Array Gain	6.02	dBi
Tx Transmission Loss	-3.34	dB
Tx Pointing Loss	-1.56	dB
EIRP	**120.78**	**dBW**
Isotropic Space Loss	-309.86	dB
Atmospheric Loss	-1.94	dB
Irradiance at rx aperture	**412.6E-09**	**W/m^2**
Rx Antenna Gain	106.77	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-4.81	dB
Rx Pointing Loss	-1.24	dB
Total Optical Path Loss	**-100.32**	**dB**
Ave Power at Rx Detector	**-60.32**	**dBm**
Req. Irradiance at rx aperture	63.0E-09	W/m^2
Link Margin (Irradiance)	**8.16**	**dB**

Figure 4: Sample uplink beacon budget for a lunar mission (LADEE).

Table 2: Explanation of terms used in the uplink beacon budget tables.

#	Quantity	Unit	Definition
1	Tx Array Size	apertures	Number of Tx apertures N_{array}
2	Req. Irradiance at the rx aperture	W/m^2	Irradiance required at the receiver aperture in order to successfully complete the acquisition procedure
3	EIRP	dBW	Equivalent isotropically radiated power $EIRP = (G_{TX}P_{TXave}G_{array})/(L_{TXopt}L_{TXpt})$
4	Irradiance at receiver aperture	W/m^2	Irradiance including atmosphere and scintillation loss $I_{RX} = (EIRP/L_{ATM})/(4\pi R^2)$
5	Link Margin (Irradiance)	dB	Difference between required and actual irradiance at the receiver aperture

2.3.2.2 Laser Safety

Given use of 1064 nm and 1550 nm wavelengths, the International Civil Aviation Organization (ICAO) requires that biological safety be taken into account when using lasers. The determination for biological safety as stated by ICAO is the maximum permissible exposure (MPE) threshold. The MPE is a function of wavelength, exposure time and the nature of the exposure (intrabeam, diffuse reflection, eye or skin). MPE values are determined from biological studies and are published in laser safety standards for regional, national (such as the American National Standards Institute standard Z136.1) and international (such as International Electrotechnical Commission standard 60825-1) use. The MPE specifically for eye exposure is based on the total energy or power collected by the human eye. The MPE threshold is set at 0.1 W/cm^2 for continuous (> 10 sec) exposure and 1 J/cm^2 for transient (< 10 sec) exposure. Applying this principle to optical communications systems using either the 1064 nm or 1550 nm wavelengths, eye safety constraints must be taken into account using the threshold calculations for both uplink and downlink. In each scenario, it was determined that the downlink signal is eye safe. However, safety measures must be instituted for uplink scenarios that exceed the MPE thresholds.

Table 3 presents a “worst case” analysis of laser safety for each scenario for both wavelengths, where the transmit optics are assumed to have full transmission and no scintillation loss is assumed. (These assumptions are conservative as they lead to greater power densities when considering eye hazards.)

Table 3: Laser safety calculation for the uplink beacon beams at 1550 nm and 1064 nm.

NOTE: A single radiating aperture has been considered for each scenario. For the beacon lasers, the maximum permissible exposure (MPE) limits of the continuous wave operation mode apply. The NOHD slant range distance computed according to the ICAO’s formulation is reported in line 9. A modified formulation, which includes the field distribution in near field, leads to the NOHD slant ranges reported in line 10. Finally, line 11 shows the irradiance values at the transmitting aperture in case of Gaussian beams. The scenarios which prove to be eye-safe at the aperture are highlighted in green.

	Inputs	LEO	LEO	MOON	MOON	L1	L1	L2	L2	MARS	MARS	GEO relay	GEO relay
1	Mode of operations	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW
2	Power [W]	0.125	0.125	10	10	70	70	50	50	555.56	555.56	2.5	2.5
3	**Wavelength [nm]**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**
4	Number of apertures	4	4	4	4	8	8	8	8	9	9	4	4
5	Aperture diameter [m]	0.05	0.05	0.15	0.15	0.15	0.15	0.15	0.15	0.07	0.07	0.15	0.15
6	Beam divergence, 1/e points [mrad]	2.79E-02	1.92E-02	9.30E-03	6.39E-03	9.30E-03	6.39E-03	9.30E-03	6.39E-03	1.99E-02	1.37E-02	9.30E-03	6.39E-03
7	Tx efficiency	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	**MPE [W/cm^2]**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**
	ICAO Formulation												
9	**NOHD slant range [m]**	451	2,940	12,111	78,900	32,042	208,749	27,080	176,425	42,125	274,439	6,055	39,450
	Formulation including near field												
10	**NOHD slant range [m]**	0	2,290	4,094	77,161	29,957	208,165	24,574	175,707	42,068	274,517	0	35,798
	Irradiance at Aperture (Gauss)												
11	**[W/cm^2]**	0.0127	0.0127	0.1132	0.1132	0.7922	0.7922	0.5659	0.5659	28.8716	28.8716	0.0283	0.0283

The power density at the exit of the aperture is shown in line 11 of Table 3, indicating that the LEO and GEO Relay uplinks are safe at all distances. The Nominal Ocular Hazard Distance (NOHD) is the distance from the aperture at which the laser beam power density falls below the MPE. In line 9 of the table, the NOHD is calculated based on the method specified by the ICAO. This calculation, however, makes a far-field assumption that is not accurate for all of the scenarios of interest. A more refined calculation including near-field effects (following methods outlined in the ANSI standard Z136.1) is illustrated in line 10 and shows the LEO and GEO Relay uplinks are eye-safe using 1550 nm. The Lunar scenario could also be designed to be eye-safe with minor modifications to the scenario assumptions, thus avoiding a requirement for a laser safety system. All other scenarios (under the current assumptions) will require a laser safety system.

Laser uplinks from Earth are traditionally protected by local onsite occupational health and safety standards, coordination with air traffic control authorities, and automated airspace monitoring. While onsite occupational health and safety measures vary by region, control measures to ensure coordination with air traffic control authorities have been identified in the Manual on Laser Emitters and Flight Safety published by ICAO. To protect the safety of aircraft against the hazardous effects of laser emitters, protected zones should be established around the affected airspace within the laser-beam free flight zone (up to 600 meters above ground), critical flight zone (up to 3,050 meters), and sensitive flight zone (above 3,050 meters). Within the laser-beam free flight zone, the intensity of laser light is restricted to a level that is unlikely to cause any visual disruption, where irradiance is not to exceed 50nW/cm^2 unless some form of mitigation is applied. Within the critical flight zone, irradiance is not to exceed 5 µW/cm^2 and within the sensitive flight zone, it is not to exceed 100 µW/cm^2. According to ICAO, these restrictions refer to visible laser beams only. But in all navigable airspace, the irradiance level of any laser beam, visible or invisible, is expected to be less than or equal to the MPE, unless the prior permission has been obtained by the proper authority. Physical, procedural, and automated control measures established to ensure that aircraft operations will not be exposed to levels of illumination greater than the maximum acceptable irradiance level should meet one or more of the operator control measures:

- Ability to physically block the laser beam to prevent light from being directed into protected airspace
- Ability to adjust the laser beam divergence and output power or pulse energy emitted through the system aperture to meet exposure levels
- Redirection of beam in a specific area
- Manual operation of a shutter or beam-termination system, used in conjunction with airspace observers
- Scanning the laser beam to reduce the level of illumination
- Automated system designed to detect aircraft and terminate or redirect the beam or shutter the system

2.3.2.3 Interference and Backscattering

A further concern to be dealt with by optical ground communications terminals located in close proximity to astronomical telescopes is the issue of optical interference. The uplink beacon always suffers some losses from Mie scattering and scattering by dust and water droplets or ice crystals suspended in the air. An astronomical telescope pointing in the direction of the beacon will image the beacon as a line emanating from the ground terminal and extending to the position of the space terminal (see Figure 5).

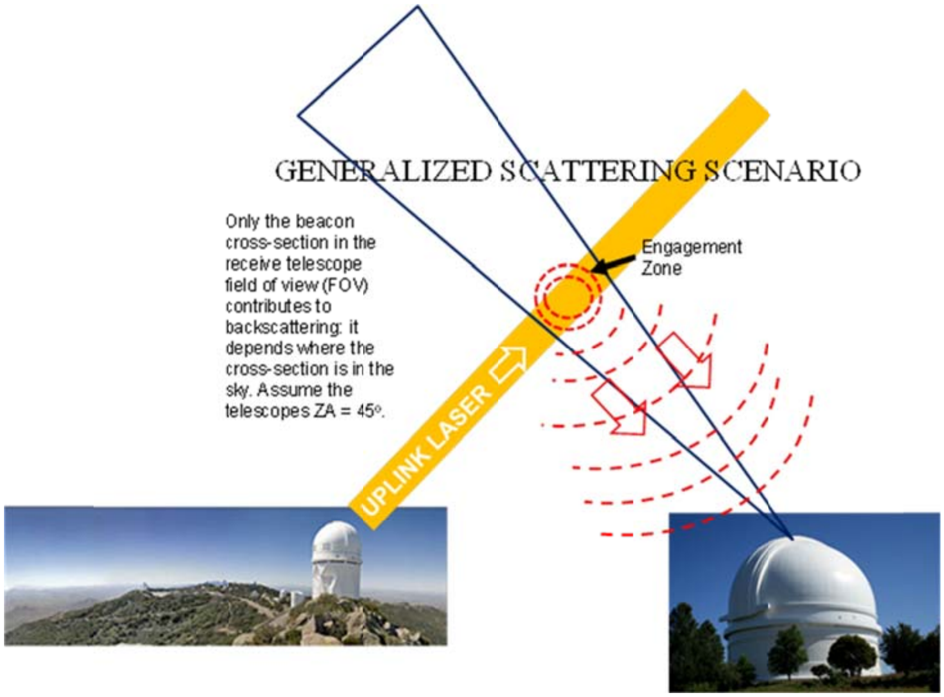


Figure 5: Scattering Scenario

Though the angular field of view of an astronomical telescope is small (typically a fraction of a degree), depending on atmospheric conditions and the beacon power and wavelength, the irradiance levels from the scattered beacon may be unacceptably high, and interfere with the astronomical observations. It may therefore be necessary to mitigate the unwanted irradiance either by installing a narrow-band notch filter in the astronomical telescope or by coordinating the astronomic observations and the ground terminal's communications schedule.

The uplink beacon must not interfere with the observations of astrophysics missions. During the site selection and survey process to identify most suitable sites for installing the uplink beacon and uplink data laser source, the site managers will be consulted to determine if any interference may occur at all with ongoing observations. If so, either approaches will be considered to mitigate the situation, or alternative sites will be identified. High power guide star uplink lasers are now commonplace at most major observatories for adaptive optics. In general, the interference issues have been worked out for these lasers, and there is high confidence level that the same could be done for laser communications uplink lasers. Table 4 provides calculations of expected uplink scattering at 1550 nm (transmissions at 1064 nm will yield similar results).

Table 4: Estimated Uplink Laser Scattered Flux from Uplink Beacon (Rayleigh scattering calculated at 1550 nm)

Mission Type	Average Uplink Power (W)	Mean Irradiance (W/m^2) at telescope due to scattered uplink laser. Engagement zone is 1 km away	Mean Irradiance (W/m^2) at telescope due to scattered uplink laser. Engagement zone is 3-km away
LEO	0.5	1 E-14	2.5 E-15
GEO	10	0.2 E-12	0.45 E-13
Lunar	40	0.8 E-12	1.8 E-12
L1	560	1.1 E-11	0.9 E-13
L2	400	8 E-12	0.9 E-13
Mars	5000	0.8 E-10	2 E-11

Furthermore, the uplink beacon must not interfere with the observations of astrophysics missions in space that employ highly sensitive science instruments (imaging/spectroscopy) observing in the visible and far infrared. Such missions are likely to be located in the L2 region, and care will have to be taken to ensure that the uplink beacon does not interfere (including scattering and diffraction on the satellite itself) with science observations. In most cases this issue can be mitigated by choosing the beacon wavelength and incorporating corresponding filtering in the instruments. However, in extreme cases this issue could become an impediment to beacon-aided pointing, leading to a corresponding data rate reduction due to pointing/jitter loss. On the other hand, as long as science observations and optical data downlink are not simultaneous, much of the interference issue will be avoided.

2.3.3 Modulation and Detection

An important factor in the system and link design is the choice of modulation and detection. Examples include:

- On-Off Keying (OOK) with non-coherent detection
- Serially Concatenated Pulse Position Modulation (SCPPM) with non-coherent photon counting detection
- Binary Phase Shift Keying (BPSK) with coherent/homodyne detection
- Differential Phase Shift Keying (DPSK) with differentially coherent detection

2.3.4 Operating With Small Sun Angles

Another major area of concern for optical communications is the need to operate very close to the Sun. An optical communications terminal attempting to communicate with a terminal in Earth orbit may find it impossible to acquire when the terminal in space is directly in front of the Sun; however, with the right modulation and coding, it is possible to maintain communications with a previously-acquired terminal passing in front of the Sun.

This process can be particularly difficult for a deep space optical communications system, because of the very low photon flux, the relatively large apertures (which are harder to protect from heating), and the modulation generally proposed. Such circumstances are easily envisioned when considering the outer planets; for example, from Pluto, the Earth is always very close to the Sun. The OLSG evaluated this problem for a Mars scenario, where there is an optical communications terminal in orbit around Mars and an optical communications terminal at Earth. Figure 6 illustrates what is happening during solar conjunction in this scenario. SEP is the Sun-Earth-Probe angle, while SPE is the Sun-Probe-Earth angle. Small SEP angles interfere with the Earth terminal's ability to acquire and track the laser communication signal. Small SPE angles interfere with the Mars terminal's ability to acquire and track the uplink beacon laser from Earth. During solar opposition, small SPE angles also affect the Mars terminal, as the Earth is again very close to the Sun.

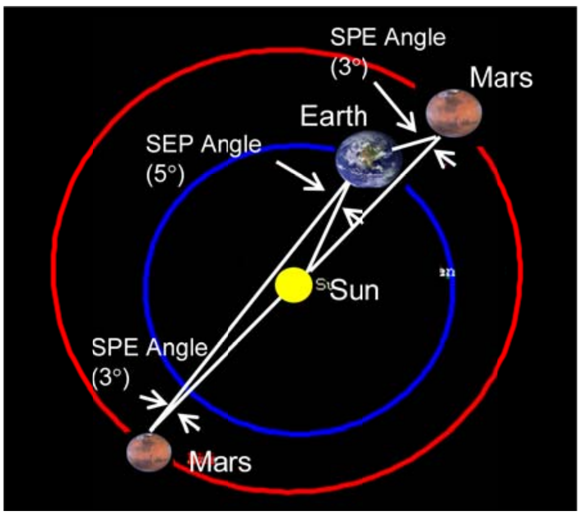


Figure 6: Sun-Earth-Probe and Sun-Probe-Earth angles.

Each day there is a time of sunrise, Mars rise, sunset, and Mars set. Most of the time, both the Sun and Mars will be in the sky simultaneously. From an optical communication systems engineering perspective, a critical design driver is the fact that Mars is simultaneously at its farthest distance and at its smallest SEP angle. The communication outages that arise when either the Earth or Mars is too close to the Sun have been evaluated for various SPE angles (and the corresponding SEP angles during solar conjunction) and are shown in Table 5. The objective of ground terminal design will be to minimize the number of outage days. For example, the Lunar Laser Communications Demonstration (LLCD) will operate with an SPE of two degrees.

Table 5: Communication Outages vs. SPE

SPE Angle (Degrees)	SEP Angle (Degrees)	Outage (Days per Martian year)
2	2.8	23
4	5.7	49
6	8.6	75
8	11.4	100
10	14.3	126
15	21.9	190
20	28	255

2.4 ConOps Basic Elements in Any Optical Communications Scenario

The ConOps can be broken down into individual components related to the basic elements in the optical communications scenario:

- Space terminal (direct communication to ground stations)
- Ground terminal
- Space Relay Terminal (inter-satellite links)
- Missions Operations Center

A ConOps must also include the capability to monitor weather and atmospheric conditions. Laser safety issues should be taken into account as well (see Section 2.3.2.2). Note that the scenario analyses examined in Sections 3 and 4 are based upon realistically implementable systems.

2.4.1 Space Terminal

When receiving, the space optical communications terminal must be stable and pointed to within a fraction of a beamwidth, where beamwidths can be on the order of 30 microradians for a 5 cm diameter terminal or 7 microradians for a 22 cm diameter terminal (for reference, a 3 m diameter dish at 32 GHz has a beamwidth of approximately 3.1 milliradians); provide a collector large enough to capture adequate power to support signal acquisition, uplink data rate, and ranging; couple this light onto low-noise, efficient detectors while trying to minimize the coupled background light—potentially while having to operate at very small SPE angles; perform synchronization, demodulation, and decoding of the received waveform; and pass any data on to the spacecraft.

When transmitting, the primary functions of the space optical communications terminal are: to efficiently generate optical power that can have data modulated onto it; transmit this optical power through efficient optics; and stabilize and aim the very narrow beam at the opposite terminal (e.g., ground station on Earth), despite platform vibrations, motions, and distortions. In some cases where the round trip light time is large, the transmitter may be required to have a point-ahead (PA) offset relative to the uplink beam as shown in Figure 7. In both transmit and receive modes, there may be both a coarse and fine pointing capability.

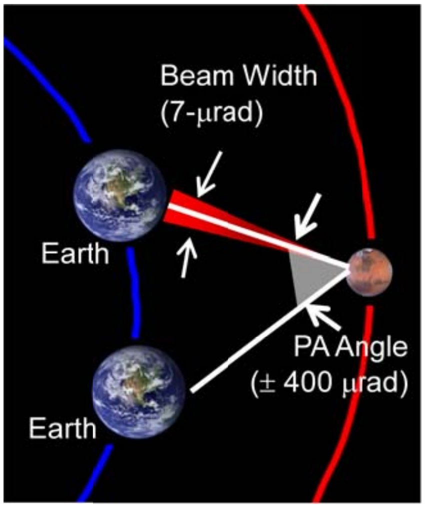


Figure 7: Point ahead angle example.

2.4.1.1 Space Terminal Cost Estimate

It is assumed that the space terminals will be mission-specific; each agency will bear the cost of providing the space terminal for its missions; therefore, costing the space terminal is not included in this analysis.

2.4.2 Ground Terminal

An Earth ground terminal must provide three functions: transmit an uplink beacon beam so that the user space terminal points to the correct location on the Earth, receive the communications signal from the user space terminal, and transmit a signal to the user space terminal.

The receiver must include a collector large enough to capture adequate power to support the data rate; couple this light onto low-noise, efficient detectors while trying to minimize the coupled background light; and perform synchronization, demodulation, and decoding of the received waveform.

The uplink beacon, transmitted from the vicinity of the receive terminal, must provide a pointing reference to establish the user space terminal beam pointing direction. Turbulence effects dominate the laser power required for a ground-based beacon. Turbulence spreads the beam, reducing mean irradiance at the terminal in space, and causes fluctuations in the instantaneous received power.

2.4.2.1 Ground Terminal Cost Estimate Process

An estimate of the cost of the ground terminals is included for each scenario. The basic contributions to the cost estimate are:

- Terminal costs

  - Basic telescope structure(s)—optics, mount, control system, building, etc.
  - Electronics and electro-optics—detectors, lasers, modulator and demodulator, encoder and decoder, monitor and control, etc.
- Weather and atmospheric monitoring
- Aviation safety system
- Site facilities investment costs, including building and power
- Wide area communication investment costs, including ground communication
- Recurring costs, such as terminal operating costs, and continuous ground communication costs

It should be noted that savings can be achieved by placing the optical communication terminal at an existing space agency facility where support infrastructure exists and/or using existing astronomical telescopes that may be surplus. Terrestrial fiber can be a major driver in the overall cost estimation of an optical ground station, contingent upon remoteness of site location. For each scenario, an adequate number of ground terminals were selected in order to achieve a minimum 95% PDT to meet the basic requirements set forth by the concept of operations. Costs were calculated independently for each site for each scenario; therefore, if a site were to be used as a terminal location for more than one scenario, certain costs (such as wide area communication investment costs) would not be incurred for each additional scenario. Specific criteria, such as the aviation safety system as well as the weather and atmospheric monitoring system, were normalized for the purpose of this estimate. Other factors that are contingent on scenario and location, such as terminal size, wide area investment costs, and site facilities investment costs, were scaled based on existing cost of ground terminals worldwide.

2.4.3 Space Relay Terminal

In the case of a space-based relay satellite supporting other user spacecraft in orbit, the relay satellite needs to support an inter-satellite optical communications link and a feeder link to the ground. For the inter-satellite link with user space terminals on other spacecraft, the relay satellite needs to have a space terminal that provides the same basic functions as the ground terminal described in Section 2.4.2.

The feeder link between the relay satellite and Earth can be either an optical or RF link. If the relay satellite has an optical feeder link, the satellite needs to have a space terminal that operates like the space terminal already described above in Section 2.4.1. However, the space-based relay satellite does not necessarily need to have two different types of optical communications terminals. In fact, with enough onboard memory, it may be possible to have a single optical communications terminal support both the inter-satellite link and the feeder link (store and forward). For real-time relay operations, however, there have to be at least two optical communications terminals: one to support the inter-satellite link and one to support the feeder link.

2.4.4 Mission Operations Center

The Mission Operations Center coordinates all optical communications activities. The mission operations for the spacecraft and the optical communications systems are intimately intertwined. Commands for the user space optical communications terminal are assumed to be sent via an RF uplink. There are two paths for getting engineering data (health and status) from the user space terminal—optical or RF.

2.4.5 *Weather and Atmospheric Monitoring Equipment*

The weather and atmospheric conditions play a significant role in optical communications link availability and quality and it is necessary to automatically monitor these parameters at the Earth stations for real-time and historical analysis and link handover decision making.

- Weather: Weather information is gathered locally by standard meteorological packages that monitor temperature, humidity, barometric pressure, and wind speed and direction.
- Clouds: A thermal infrared cloud camera is used to monitor the extent of cloud coverage, in addition to the satellite data discussed in the CFLOS discussion (Section 2.2.1.2) above. These sensors indicate not only whether there are clouds or no clouds at very high temporal resolution, but also the sky temperature and emission.
- Daytime Sky Radiance: A sun photometer provides this measurement.
- Atmospheric Loss: During the day, a sun photometer is also used to measure atmospheric loss. At night, a calibrated photometric system that tracks stars of stable emission, e.g., Polaris, can be used.
- Clear Air Optical Turbulence: A Differential Image Motion Monitor (DIMM) is the predominant method of measuring seeing. During the night this instrument tracks stars and during the day, the Sun.

2.4.5.1 Ground Station Weather Instrumentation

Various types of cloud instrumentation have been proposed to support operational free space optical communications. This instrumentation would be used to perform link handover decisions in the event that multiple sites have simultaneous visibility to the space terminal. These instruments include both day/night visible and long-wave infrared cameras (see Figure 8). Such instrumentation can provide quantitative depiction of clouds throughout the skydome with time resolutions on the order of a minute. These high resolution images of clouds can be used to support very near-term predictions of cloud cover in the line of sight to the space terminal. If longer-term cloud forecasts are required, use of imagery from meteorological satellites may be desirable. In any case, more research on placing these instruments into operations should be conducted.

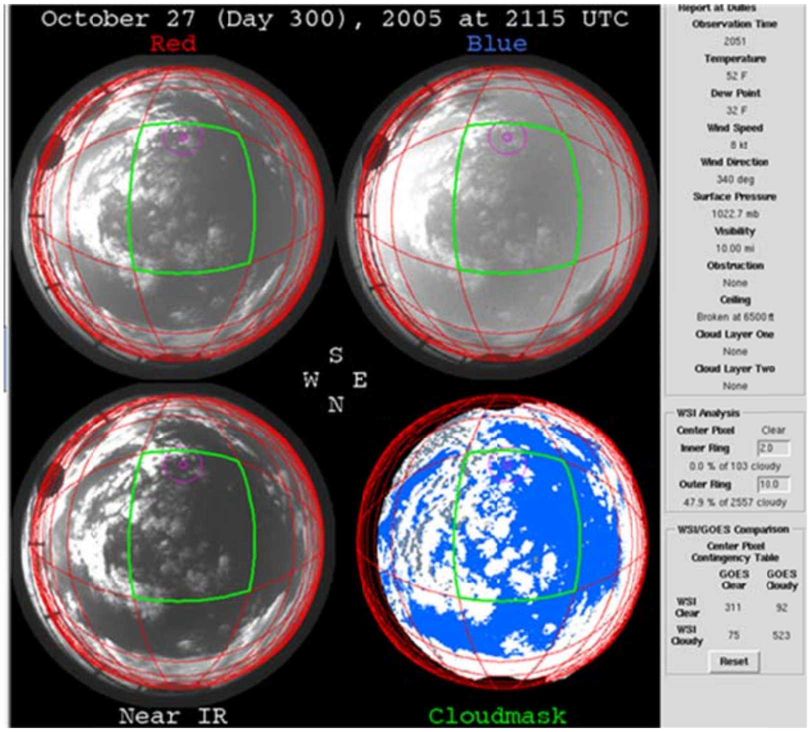


Figure 8: Example of a Whole Sky Imager (WSI) that could be used to support link handover decisions for a free space optical communications network.

2.4.5.2 Deutsches Zentrum für Luft- und Raumfahrt (DLR) implementation

At DLR-Institut für Kommunikation und Navigation (IKN), cloud monitoring is performed with the CloudCam, which uses a camera in the middle infrared (MIR) and a hyperbolic mirror. The CloudCam captures the cloud situation during night and day. The device dimension is 600x600x1300 mm³ (LxWxH).

Clouds are detectable by their radiation in the thermal spectrum. Because this radiation differs from clear sky emission, cloud cover can be imaged regardless of sunlight conditions. Processing of recorded images allows real-time assessment of the cloud situation and the calculation of long-term statistics.

2.4.5.3 NASA Jet Propulsion Laboratory (JPL) Implementation

NASA JPL is currently monitoring the atmospheric channel at two sites, Goldstone Deep Space Communications Complex (GDSCC) and Table Mountain Facility (TMF), both located in California. Characteristics of the equipment deployed at these two sites are briefly described below.

2.4.5.3.1 Table Mountain Facility, CA

TMF is located in the San Gabriel Mountains (California) and is bordered on the north by the Mojave Desert. TMF altitude is 2200 m above sea level. To monitor the atmospheric channel at TMF the following instrumentation are deployed in situ.

- Sun-Photometer—The Sun-Photometer monitors daytime atmospheric transmission and daytime sky-radiance at a set of wavelengths between 340 nm to 1640 nm. Data are collected every 15 minutes. Every hour the system transmits the stored data to a geo-satellite, which relays the data to the ground. The system is completely autonomous. Data from the sun photometer provide an instantaneous characterization of the atmospheric transmittance and sky-radiance, and are archived to provide statistical representation of the channel itself.

- Sun-Scintillometer –Daytime atmospheric turbulence is monitored by a Sun-scintillometer (or Seykora-scintillometer), which consists of a large area detector monitoring the instantaneous variation of the Sun irradiance due to clear air turbulence.
- Cloud Camera—Cloud coverage is monitored by a large field-of-view imaging system, consisting of a camera sensitive in the thermal infrared range (8-13 μm), which provides daytime and nighttime observations. This system was specifically designed using Commercial off-the Shelf (COTS) components. The cloud camera is housed in a weatherproof enclosure to guarantee continuous observation of the sky. The system provides radiometrically calibrated images of the sky at an (resettable) interval of 5 minutes. The instrument also provides information about the presence of thin and cirrus clouds. The system has a field of view of 60 degrees and stores sky images with an interval of five minutes.
- DIMM--Nighttime turbulence is monitored by a DIMM. The DIMM consists of a telescope that tracks and images the double images of a star on a charge-coupled device (CCD) camera. Astronomical seeing is derived from measurements of the rms of the centroid motions of the double images of the star (see Figure 9).

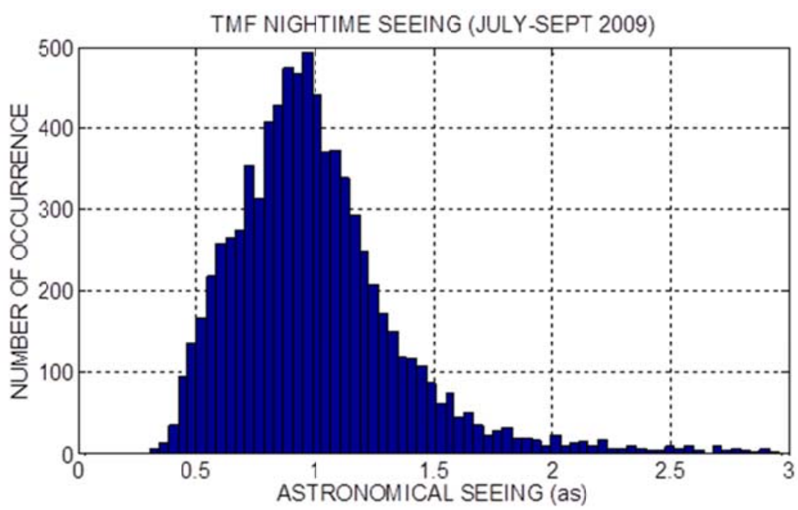


Figure 9: Histogram of astronomical seeing at Table Mountain Facility, CA. The data is from measurements by a DIMM during the period July-Sept, 2009.

- Weather Station—The weather station continuously monitors atmospheric pressure, temperature, humidity, average wind speed, and wind gust speed. Data are collected every five minutes and archived.

2.4.5.3.2 Goldstone Deep Space Communications Complex, CA.

NASA JPL has been monitoring the atmospheric channel at the GDSCC, which is one of the three communications complexes of NASA’s Deep Space Network. Goldstone is located in the Mojave Desert at an altitude of 1100 m above sea level. Monitoring of the atmospheric channel at GDSCC is performed in similar fashion to that at TMF, deploying the following instrumentation.

- Sun-Photometer—similar to TMF
- Sun-Scintillometer—similar to TMF
- Cloud Camera—Similar to TMF, but includes a second generation of thermal infrared imager with a field of view of 110 degrees
- Weather Station—similar to TMF
- Nighttime Seeing Monitor—Nighttime atmospheric turbulence is monitored by a nighttime seeing monitor. The instrument consists of a simple imaging system that is continuously monitoring the star Polaris. The astronomical seeing is derived from measurements of the centroid motion of the single image of Polaris in the focal plane detected by a CCD. This process provides similar measurements to those of the DIMM, but the measurements are not as accurate.
- Boundary Layer Scintillometer (BLS)—The atmospheric turbulence at the ground layer is measured using a BLS. The instrument consists of a Light-Emitting Diode (LED) transmitter and a receiver spaced by few hundred meters. The structure coefficient of the refractive index (Cn2) is monitored by this instrument during the entire day at an interval of five minutes (see Figure 10). The periodical minima in Figure 10 correspond to times before sunset and after dawn.

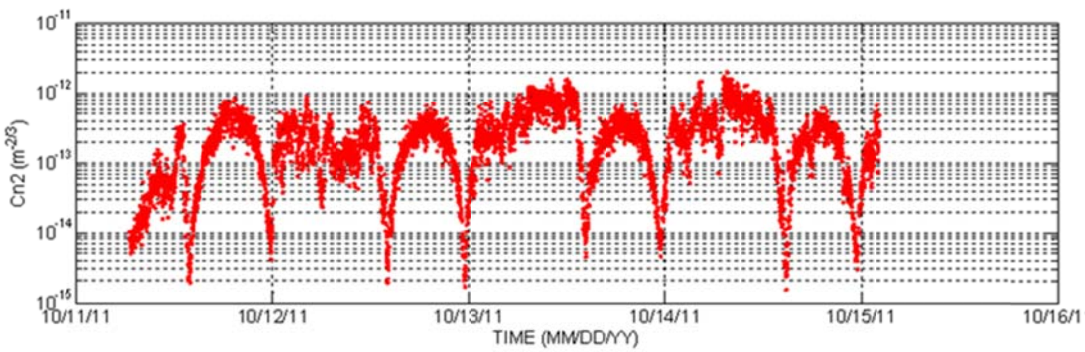


Figure 10: Measurements of the ground layer structure coefficient of the refractive index at Goldstone (time is in UTC).

- Particle monitor—A particle counter monitors the aerosol concentration in the atmosphere. Aerosol concentration at Goldstone is composed essentially of dust. Dust concentration is responsible for variation of atmospheric transmittance and radiance, while dust contamination can affect the performances of a telescope due to the scattering of the direct sunlight. The particle counter provides measurements of the concentration of dust in the atmosphere for different particle sizes (from 0.3 to 10 μm). Measurements are provided every five minutes.

3 Space-Earth Mission Scenarios

The mission scenarios for Space-Earth optical communication described below are considered realistic examples that could serve as a starting point for actual mission designs. The mission scenario descriptions include a concept of operations, a space terminal description and a ground terminal description, a CFLOS analysis, and a link budget, followed by costing information for the ground terminal and a business case. The space and ground terminal descriptions may include one or more implementation examples, which for the purpose of this document are only intended to show existing realizations or potential future solutions rather than an optimized design.

3.1 Low Earth Orbit (LEO) Scenario

3.1.1 Concept of Operations

3.1.1.1 Basic ConOps

LEO satellites have an altitude of 160–2,000 km and are typically in a circular orbit.

The main application of optical communications in low-Earth orbit is the data return from remote-sensing missions. Because of the increasing resolution of onboard sensors, new Earth-observation (EO) satellites continuously generate data with a limit set by the maximum data rates of RF downlinks. Table 6 shows the properties of some recent EO satellites. The onboard storage capacity in terms of data acquisition time varies from one hour for Envisat, to more than one day for the Soil Moisture and Ocean Salinity (SMOS) mission.

Table 6: Properties of some recent Earth-observation satellites.

	generated payload data	On-board data storage	TM link	Downlink Data rate	Data Relay via GEO	Orbit
ERS-2	94 Gbit/day	6.5 Gbit	2 Mbit/s	15 Mbit/s up to 105 Mbit/s	n.a.	Sun sync (785 km)
ENVISAT	4 Tbit/day	160 Gbit		2x 100 Mbit/s	2x 100 Mbit/s	Sun sync (790 km)
CRYOSAT-2	320 Gbit/day	256 Gbit	8 kbit/s	100 Mbit/s	n.a.	92° inclin. (730 km)
METOP	300 Gbit/day	24 Gbit	4 Mbit/s	3.5 Mbit/s up to 70 Mbit/s	n.a.	Sun sync (~800 km)
SMOS	15 Gbit/day	2x 20 Gbit	722 kbit/s	16.8 Mbit/s	n.a.	Sun sync (~700 km)
TerrSAR-X	1.2 Tbit/day	390 Gbit	n.a.	300 Mbit/s	n.a.	Sun sync (514 km)
TanDEM-X	1.2 Tbit/day	n.a.	n.a.	300 Mbit/s	n.a.	Sun sync (514 km)

Figure 11 shows the elevation of a satellite above the horizon as a function of time. Satellite overflights with four maximum elevations (10°, 30°, 50° and 80°) are considered. With communication links possible only above 20° elevation, the average communication time per contact is about five minutes.

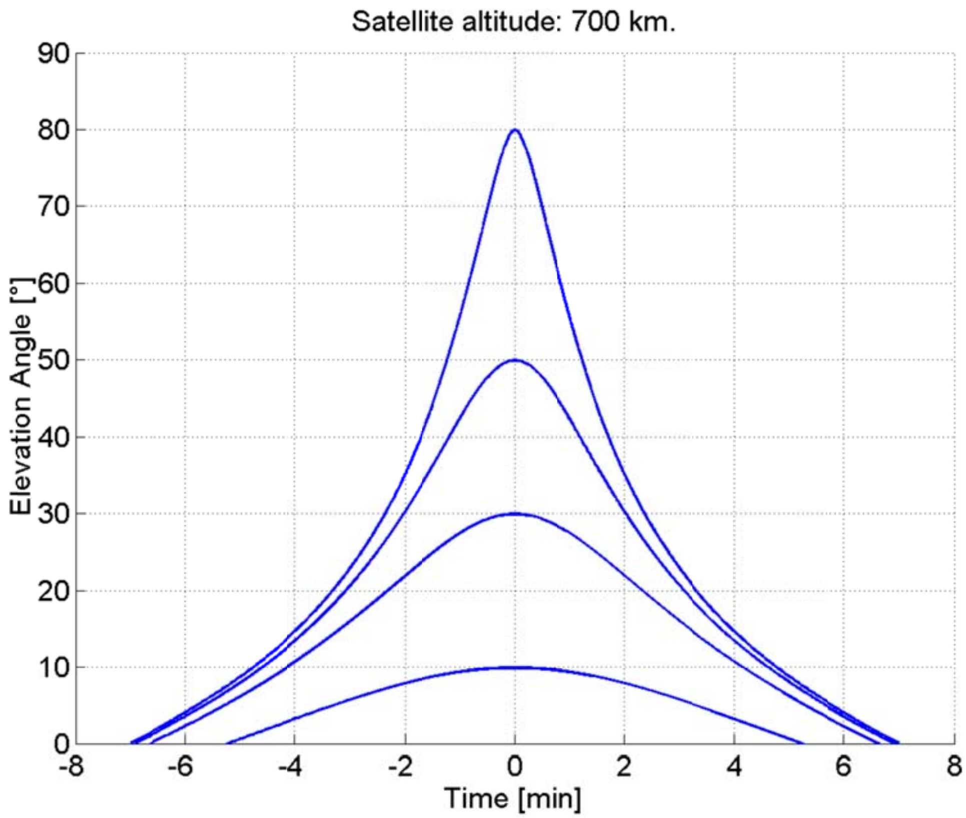


Figure 11: Elevation angle versus time for satellite overflights with various maximum elevations.

Figure 12 shows the average contact time per day between a polar satellite (700 km altitude) and a ground station as a function of the ground station latitude. This contact time is orbit-limited, which means that unavailable contacts due to clouds are not taken into account. Several minimum elevations above which communication is possible are considered. Assuming a minimum elevation of 20° for communication, a ground station at a pole has an average orbit-limited contact time around 6,000 s (= 1hour, 40 minutes) per day, whereas a ground station at the equator has an average orbit-limited contact time around 600 s (= 10 minutes) per day.

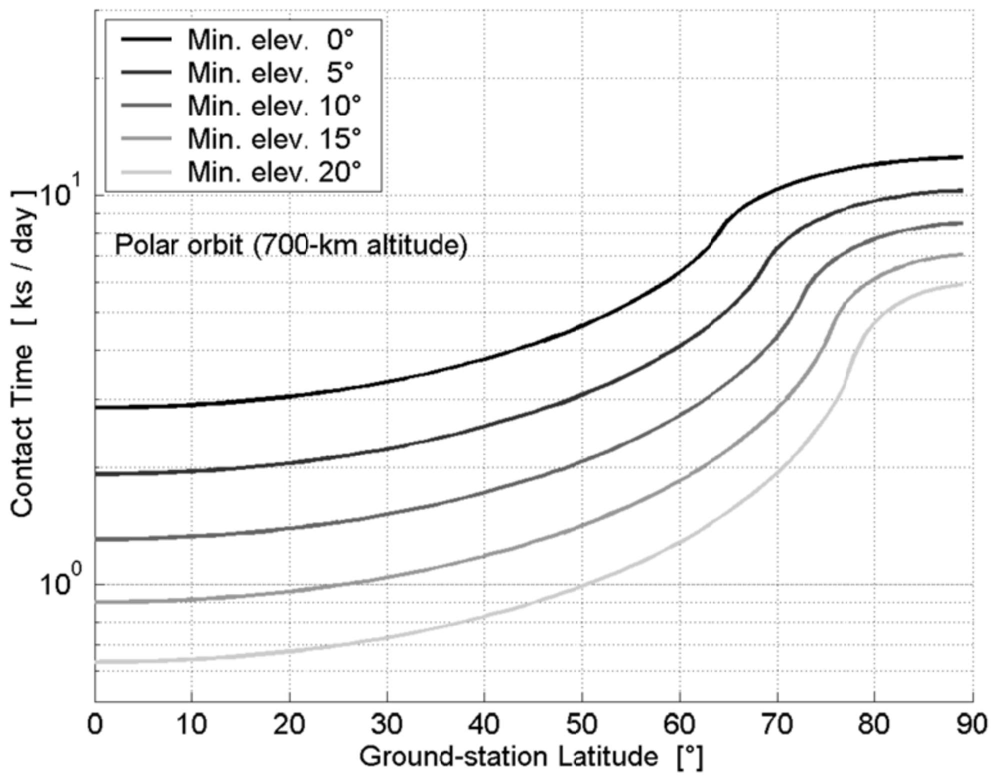


Figure 12: Orbit-limited contact time per day as a function of the ground station latitude for a polar-orbit satellite.

The probability that the Optical Ground Station (OGS) finds the satellite above a certain elevation also demonstrates the importance of communication at low elevations. For a polar-orbiting satellite (700 km altitude), Figure 13 shows the probability distribution of the satellite elevation for different OGS latitudes. For OGS latitudes between 0° and 70°, the elevation distribution does not vary much.

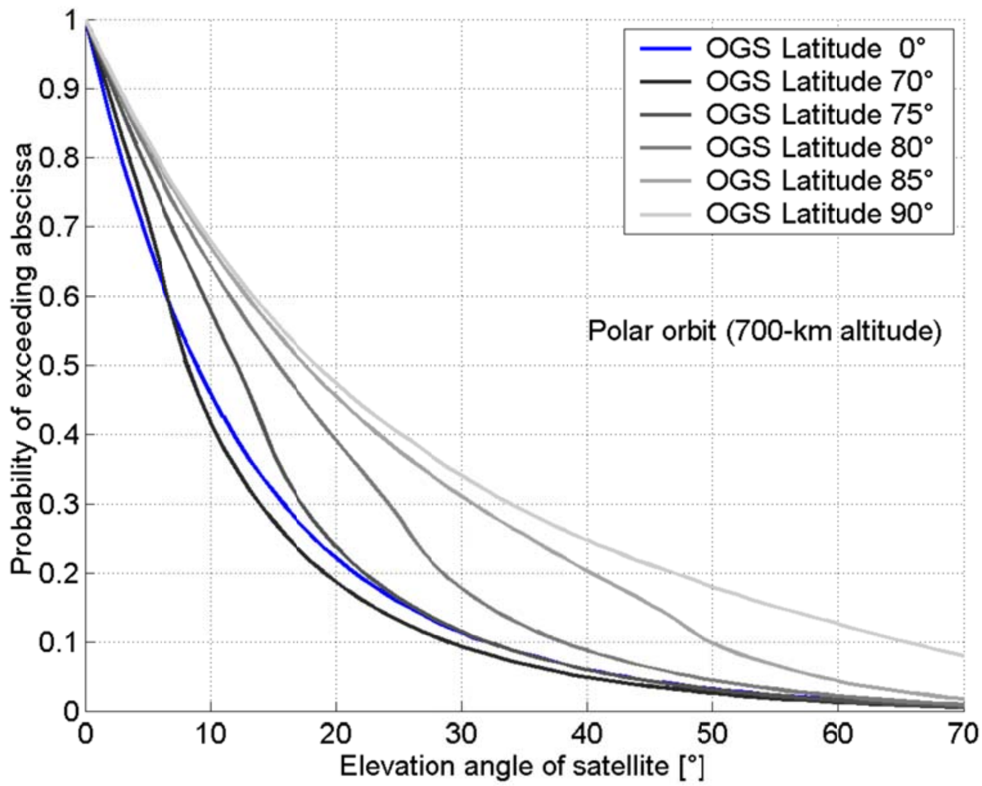


Figure 13: Probability distribution of the satellite elevation (assuming the satellite is above the OGS horizon).

On the other hand, communication at lower elevations is challenging due to

- Longer propagation distance
- Stronger atmospheric attenuation
- Stronger wavefront distortions and scintillation
- Higher cloud probability
- Larger Doppler shift

LEO downlinks are not affected much by background light. High-data-rate receivers are generally less sensitive to background light than low-data-rate receivers. The reason is simply that at higher data rates the bit periods are shorter, and therefore less background light is collected per bit. Additionally, most of the background light can be removed at the receiver by using an optical filter of narrow bandwidth (a few nanometers) and by maintaining a small field of view (angular filtering). Background light can challenge the ground receiver when the Sun is behind the satellite. However the angular extent of the Sun relative to the hemisphere is about 10^{-5}. Thus, the probability of having the Sun behind the satellite is small, at least much smaller than the probability of cloud cover. By monitoring the background light level, the receiver can be switched off momentarily (during OGS-satellite-Sun alignments) if necessary.

Several modulations can be used: OOK; DPSK; 2-PSK (2-Phase Shift Keying); and *M*-ary Pulse Position Modulation (*M*-PPM, where *M* is the number of possible symbols) with low *M*.

Because the contact time per satellite overflight is short (~ 5 minutes) and can be momentarily disrupted by clouds, the link acquisition procedure should be fast. As illustrated in Figure 14, the simplest way for the satellite to acquire the direction to the OGS is for the OGS to emit a wide powerful beacon towards the satellite. The beacon divergence should be large enough to cover the uncertainty cone of the satellite position. With a satellite position error of less than 1 km, a beacon divergence around 5 mrad should be sufficient. Because the uplink beacon is open-loop controlled in this case, there is no hand-shaking required.

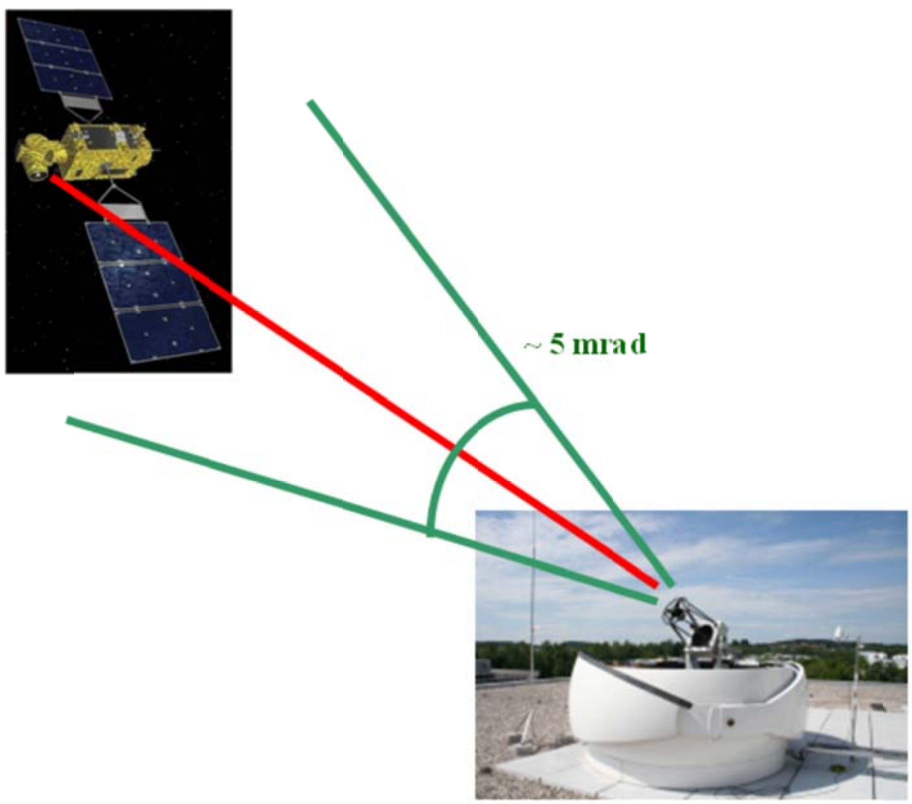


Figure 14: Illustration of a large beacon beam (divergence ~ 5 mrad) emitted by an OGS and a narrow communication beam emitted by the satellite.

3.1.1.2 Scenario ConOps

The scenario chosen for a more thorough analysis is based on the following assumptions:

- The satellite has a polar orbit at 700 km altitude.
- Data are generated onboard at a rate of 12 Tbit/day (a factor 10 times more than what the current TerrSAR-X satellite generates, see Table 6).
- Onboard memory can store data generated during three orbits (4.5 hours), which amounts to approx. 2.3 Tbit. Data are expected to be dumped at least once every three orbital revolutions with a high probability (e.g., 95%).

- The data rate is 10 Gb/s.
- Data are transmitted only above 20° elevation.
- An example set of nine globally located ground terminals may provide optical communications to the satellite

From these assumptions we deduce:

- The average amount of data dumped per contact is 3 Tbit (= 5 min x 10 Gb/s).
- With 15 orbits/day, the satellite shall dump, on average, 800 Gbit per orbit (= [12 Tbit/day]/[15 orbits/day]) with a high probability. Thus, 80s (= [800 Gb/orbit]/[10 Gb/s]) of contact time per orbit is required.

Table 7 summarizes the ConOps parameters for the LEO Scenario.

Table 7: LEO Scenario Concept of Operations Parameters

LEO Scenario			
Onboard Data Collection Rate	**Onboard Storage Capacity**	**Hours of CFLOS Required per Day**	**Data Rate used for Link Budget**
12 Tb/day	2.3 Tb	0.3	10 Gbps

3.1.2 Space Terminal

In this section, five different concepts for LEO flight terminals are presented: DLR-IKN's Optical Space Infrared Downlink System (OSIRIS), the DLR/Tesat Laser Communication Terminal (LCT), the Optel-μ terminal, NASA JPL's 10-Gb/s terminal, and the Small Optical Transponder (SOTA) from Japan's National Institution of Information and Communication Technology (NICT).

The space terminal must provide the functions described in the ConOps:

- Optical head
- Communication system
- PAT system
- Onboard storage

The electro-optics box includes lasers, laser amplifiers, encoder and modulator, data formatting and spacecraft electrical interfaces. For most LEO satellites, the laser terminal should possess its own coarse pointing assembly (CPA), which typically takes the form of a periscope. Additionally, a fine pointing assembly (FPA) and optical tracking sensor should both operate with an angular error that is much smaller than the downlink beam divergence. A point-ahead angle (PAA) around 50 μrad should be implemented.

3.1.2.1 Space Terminal Potential Implementation

3.1.2.1.1 OSIRIS (from DLR-IKN)

DLR-IKN is developing an experimental laser terminal called OSIRIS for compact LEO satellites. The pointing will be accomplished by the attitude control system of the satellite bus. Because it has no CPA, the system mass is less than 1 kg.

OSIRIS includes a laser diode driven by an electronic circuit that receives TTC data from the satellite bus. The emitted light is guided in a single-mode fiber and emitted from a collimator. The wavelength used is 1550 nm and standard fiber-optic components are used. The laser unit is shown in Figure 15.

Figure 15: Space-qualified directly modulated laser diode.

This technology allows data rates up to 200 Mbit/s and a mean optical output power of approximately 20 dBm. The power consumption is typically 8 W.

A prototype of a directly modulated laser diode has been built and space qualification tests have been carried out successfully. These tests included thermal/vacuum cycling, as well as vibration and pyroshock tests. The electronic and laser units are shown in Figure 16.

For applications demanding higher data rates or transmit powers, a different approach can be followed. The use of optical amplifiers (Erbium Doped Fiber Amplifiers or EDFAs), as used in commercial fiber optic transmission systems, allows data rates up to 2.5 Gbit/s and optical output powers up to 5 W.

Figure 16: Laser Source using an optical amplifier.

The achievable data rate depends on the size of the ground receiver and on the downlink beam divergence. The beam divergence is determined by the accuracy of the satellite's attitude and orbit control system. Most modern satellites have the capability to do "target-pointing" maneuvers. The system can easily be adapted to satellites with worse target-pointing capability to the disadvantage of data rate.

3.1.2.1.2 DLR/Tesat LCT

DLR space administration, together with its contractor Tesat-Spacecom, developed and implemented two identical LCT demonstrators on the TerraSAR-X (Germany) (see Figure 17) and NFIRE (U.S.) satellites in LEO. While the main purpose of the effort was to demonstrate maturity of inter-satellite links, space-to-ground links were a second focus of investigation. Further details on the LCT development and the inter-satellite link capability can be found in Section 4 on the relay mission scenarios, which also discusses the operational application of homodyne BPSK in context of the European Data Relay System (EDRS) and the GEO-to-Earth scenario investigated with the second generation of the Tesat LCTs. Both LCTs (TerraSAR-X and NFIRE) have been designed for LEO-to-LEO inter-satellite link operation at a data rate of 5.6 Gbps. The space-to-ground link campaign, which followed after the LEO-to-LEO inter-satellite link verification, has impressively demonstrated the feasibility of extending the inter-satellite link capability of the LCTs to the space-to-ground link scenario. First LEO-to-ground links and then also duplex LEO-to-ground, ground-to-LEO links at a data rate of 5.625 Gbps using 1.064 µm homodyne BPSK have successfully been realized without means of scintillation mitigation such as adaptive optics.

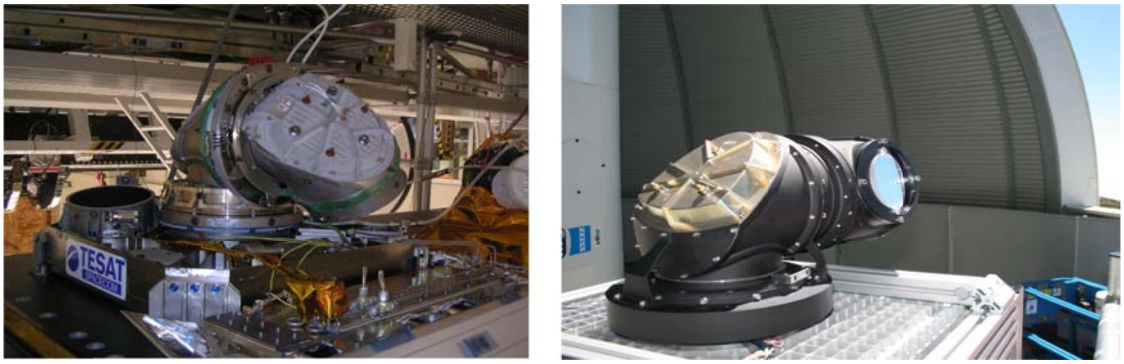


Figure 17: Left: LCT on TerraSAR-X. Right: Image from the test campaign to test the LEO-to-ground link performance.

With ground stations at Hawaii (Haleakala) and Tenerife (Observatorio del Teide) LEO-to-ground and ground-to-LEO links have been established to and from the Tesat LCT on the NFIRE satellite. For LEO-to-ground links, a 60 mm telescope aperture on the ground is sufficiently large to collect enough photons to establish the wide band data link. This aperture is also sufficiently small to ensure that the optical phase across the aperture is not distorted by the atmosphere (in high altitude atmospheric layers). Table 8 shows the performance parameters of the ground station for LEO-to-Ground duplex links.

Table 8: Key parameters of the Tesat ground LCT for LEO-to-Ground communication

Link	LEO-to-Ground duplex communication
Data Rate	5.625 Gbps
Link Distance	1.000 km
Optical Transmit Power	0.7 W
Bit Error Rate	Error free but burst errors for the downlink $< 10^{-5}$ for the uplink
Ground Station Telescope Diameter	60 mm

As for the TerraSAR-X-to-NFIRE inter-satellite link, bit errors are measured for the NFIRE-to-ground (Figure 18) and ground-to NFIRE links (Figure 19).

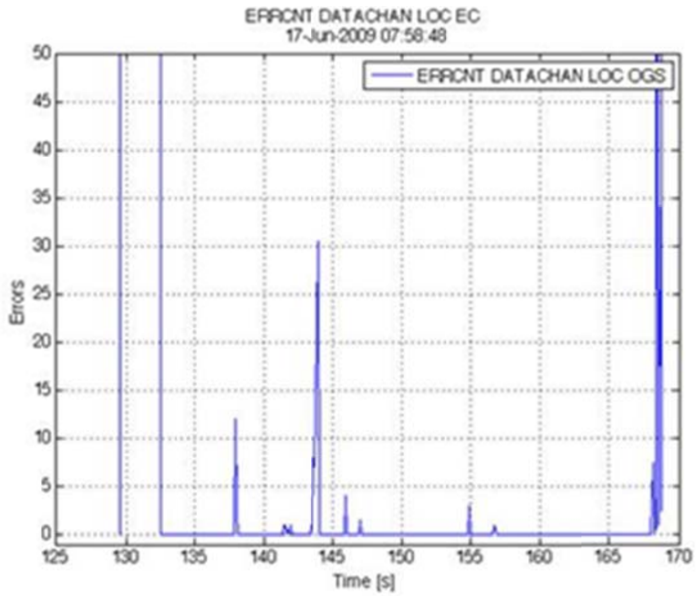


Figure 18: Bit errors measured for the LEO-to-Ground link in one of the 25 data channels of 225 Mbps.

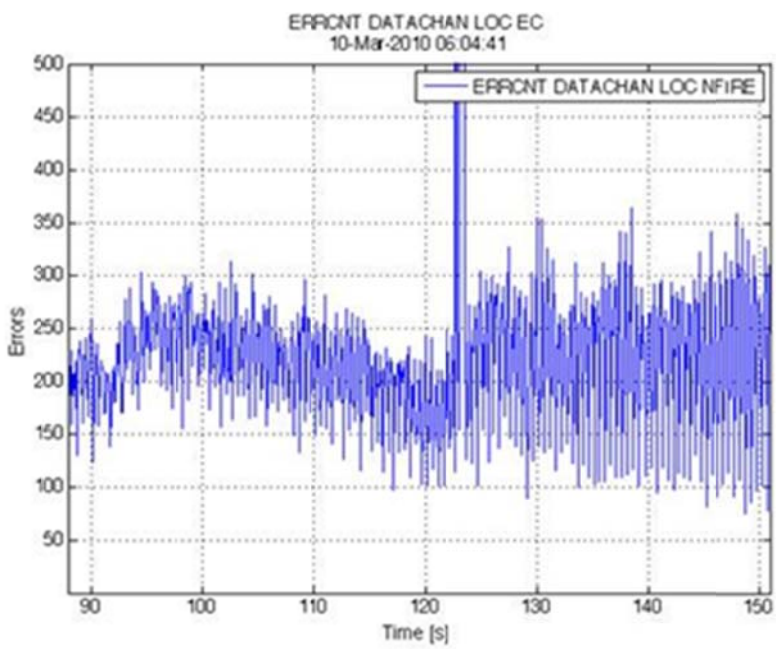


Figure 19: Bit errors measured for the Ground-to-LEO link in one of the 25 data channels of 225 Mbps.

For LEO-to-ground communication, minor burst errors occur separated by error-free time intervals, but the bit error rate for the ground-to-LEO link increases to below 10^{-5}. Since the beam disturbance by the atmosphere is more severe from ground-to-space than it is from space-to-ground, it is expected that the bit error rate for the uplink will greater than that of the downlink. Both results—the LEO-to-ground link and the ground-to-LEO link—are achieved without use of any code. These results clearly demonstrate that in spite of its phase-sensitive detection, homodyne BPSK is a well suited modulation scheme for duplex space-to-ground links.

3.1.2.1.3 Optel-μ Terminal (from RUAG)

RUAG Switzerland is developing under ESA contract a terminal for small LEO Earth Observation satellites at altitudes ranging between 400 km to 900 km. A modular design is envisaged for the Optel-μ space terminal to facilitate its accommodation on different platforms. Key features of the space terminal include:

- Mass, power, volume: 45 W average, 5.0 kg, 5.6 l
- Downlink Rate : 2 channels simultaneous 2x1.25 Gbps, OOK (raw data rate), BER $< 10^{-9}$ (up to 1000 km link distance), internal buffer size 100 Gbytes (flash memory)
- Communications wavelength band: 1520 nm…1570 nm
- Optical downlink beacon at 808 nm
- Uplink beacon: Laser Safety Class 1 M, 1030 nm/1064 nm, 16-PPM ARQ
- Sun exclusion angle: ±10°

The physical implementation of the Optel-μ space terminal is described in Table 9.

Table 9: Physical Implementation of the Optel-μ space terminal

Optical Head Unit (OHU) 1 module outside spacecraft (S/C)	8.5 W, 2.5 kg, 2.8 l
Laser Unit (LU) 2 modules inside S/C	13 W, 1.2 kg, 1.3 l
Electronics Unit (EU) 1 module inside S/C	22.4 W, 1.3 kg, 1.4 l

Key interface requirements of the Optel-μ space terminal are listed in Table 10.

Table 10: Key Interface Requirements of the Optel-µ space terminal

Data rate to S/C mass memory (MM)	150 Mbps each for 2xSpaceWire Interface
BER to MM	10^{-12} (10^{-14} with higher level error detection)
Possible protocols to MM	RMPA, PacketWire (LVDS)
Allowed platform jitter	< 10 µrad radial between 1 and 500 Hz
Allowed max. angular speed during S/C attitude manoeuvres	3°/s per S/C axis
Allowed max. acceleration during S/C attitude manoeuvres	1.5°/s^2 per S/C axis
Power bus	24 VDC up to 36 VDC, unregulated

The Environmental constraints and lifetime of the Optel-µ space terminal are described in Table 11.

Table 11: Environmental Constraints and Lifetime of the Optel-µ Space Terminal

Overall random vibration level	27.1 g_{rms}
Non-operating temperature range	-40°C to +60°C (for OHU) -40°C to +50°C (for LU and EU)
Operating temperature range	-40°C to +60°C (for OHU) -30°C to +30°C (for LU and EU)
Radiation level (5 years)	22 krad (2mm Al-equivalent shielding)
Design lifetime	5 years
Extended lifetime	7 years

3.1.2.1.4 10-Gb/s LEO Terminal (from NASA JPL)

The NASA JPL team has developed a prototype compact laser communications transceiver with significantly reduced complexity (and therefore low cost) for downlinking data at 10 Gb/s from Earth-orbiting spacecraft. Emphasis is on downlink; the optical uplink data rate is modest (due to existing and adequate RF uplink capability). The design can be implemented using flight-grade parts. Mass and volume reduction is favored over power-consumption reduction. The design and development approach of the flight transceiver involves:

1. A high-bandwidth coarse wavelength division multiplexed (CWDM) (4 x 2.5 Gb/s or 10-Gb/s data-rate) downlink transmitter
2. Simplified optical system assembly:
    a. Single transmit and receive aperture of 5 cm diameter
    b. A COTS master-oscillator power amplifier (MOPA) laser transmitter generating ~0.5 W of output power per wavelength channel (i.e. a cumulative power of 2 W exiting the aperture)
    c. The transmit downlink wavelengths fall within the standard C-band (1530-1560 nm) telecom grid of EDFA fiber amplifiers. The received uplink beacon wavelength is at 1568 nm
    d. A simple and highly compact, low-jitter two-axis gimbal
    e. Indium gallium arsenide (InGaAs) quadrant PIN detector for acquisition and tracking
    f. Fast steering mirror to remove residual pointing disturbances from gimbal so that a ~ 30 µrad laser beam can be transmitted
    g. Data buffering, power conditioning, clock, electrical (e.g., data) interfaces with spacecraft, and spacecraft's command and data handling (C&DH), and attitude control systems (ACS)
3. Use of components for which flight qualified versions are commercially available. An example is use of Telecordia-qualified fiberoptic communication components, including active components (lasers, amplifiers, photodetectors that except for vacuum and radiation meet most of the qualifications required for space)
4. Use of forward-error-correction codes and deep interleaving to minimize atmospheric turbulence-induced losses on the downlink beam
5. Shift of the burden to the ground by relying on optical receivers retrofitted to 1 m diameter ground telescopes.
    a. Applying CWDM allows utilization of larger active-area photo-detectors at the ground station, thereby minimizing link degradation due to atmospheric turbulence blurring effects on the received beam on the ground

The terminal is illustrated in Figure 20, and Figure 21 shows an optical-head prototype. Target mass and power consumption for the flight data transmitter system is less than 10 kg and approximately 60 W for the 400 km orbit (900 km slant range), and 15 kg and 120 W for the 2000 km orbit (6000 km slant range). The higher mass and power for the latter are the result of employing a higher power lasers only.

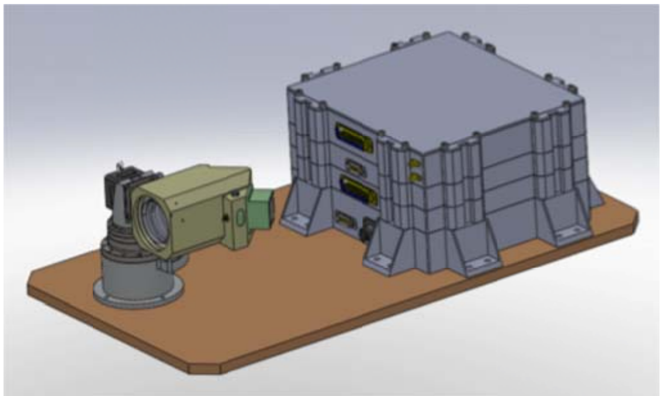


Figure 20: Schematic diagram of the terminal consisting of the optical head on a 2-axis gimbal (left) and an electronics/laser box (right).

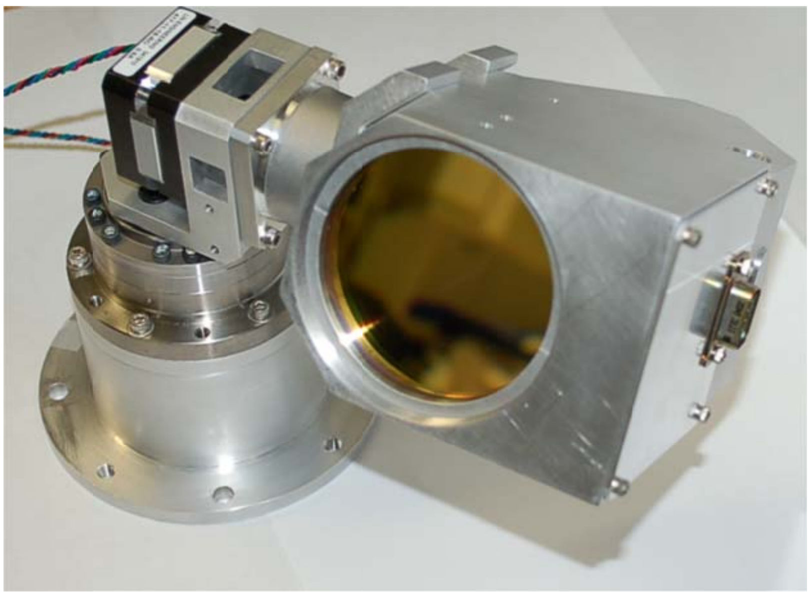
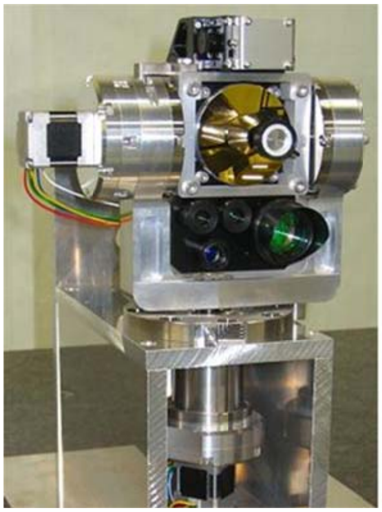


Figure 21: The optical-head prototype for laboratory and in-the-field (communications from an airplane) testing.

3.1.2.1.5 Small Optical Transponder (SOTA) (from NICT)

Japan's NICT is developing a laser communication terminal for small LEO satellites. The prime contractor is NEC Corporation, Japan. The terminal (see Figure 22) is called SOTA. SOTA has a two-axial gimbal system for coarse tracking and a fast steering mirror for fine tracking. The mass is 6.2 kg including both the optical part and the electric part.



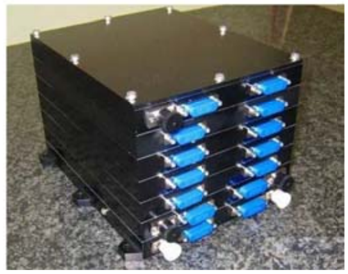


Figure 22: Small Optical Transponder (SOTA).

SOTA emits three wavelengths of 1.5µm, 0.98µm, and 0.8µm, respectively. The key parameters are listed in Table 12.

Table 12: Key parameters of the SOTA laser communication terminal

Mass	6.2 kg (including both the optical part and the electric part)			
Power	Tx1	Tx1 + Rx	Tx2, 3, 4	Tx 2, 3, 4 + Rx
	28.1 W	39.5 W	32.5 W	37.3 W
Gimbal Range	Az: > ±50 deg, El: -22 deg ~ + 78 deg			
Link range	1,000 km			
Wavelength	Tx1: 976 nm			
	Tx2 and Tx3: 800 nm-band			
	Tx4: 1550 nm			
	Rx: 1064 nm, Acquisition/Tracking: 1064 nm and 1550 nm			
Data Rate	1 Mbps or 10 Mbps (selectable)			

3.1.3 Ground Terminal

The ground terminal transmits a beacon and receives the data beam. It monitors local atmospheric conditions and provides interfaces to ground communications systems (Wide Area Network, or WAN, etc.) and the mission operations function. Because the uplink beacons can be designed to be eye-safe, safety measures such as aircraft detection are not necessary.

Because high data rates (e.g. 10 Gb/s) require small detectors and hence small fields of view, a fine optical tracking mechanism for the received beam shall be implemented to improve the receiver performance.

A dome shall protect the ground terminal from the environment (including condensation on the optics) and it shall open in such a way that the telescope has a hemispherical view to the sky.

To avoid the need for human presence at the station, a remote-operation system shall be implemented. For example, satellite orbit data shall be loaded to the mount control software prior to each link.

The ground terminal shall be connected to the terrestrial network with enough capacity. Because the optical downlink scenario has no real-time requirement, the data dumped during a satellite overflight (~ 3 Tbit) can be transferred to the operator over a longer time (e.g., 10 hours). So a data rate of 100 Mb/s between the ground station and the terrestrial network may be sufficient.

3.1.3.1 Ground Terminal Potential Implementation

Several existing ground stations have already performed LEO downlinks. During the Optical Inter-Orbit Communications Engineering Test Satellite (OICETS) downlinks in 2006 and 2009, following OGSs were involved:

- NICT-OGS (Tokyo), NICT
- OGS-OP (Oberpfaffenhofen), DLR
- Optical Communications. Telescope Laboratory (OCTL) (California), JPL
- Tenerife OGS (Tenerife), ESA

See section 7.1 (Annex) for a description of these ground stations.

As shown in Figure 23, DLR's OGS deployed two beacon beams to be seen by the OICETS satellite.

Figure 23: DLR's OGS at Oberpfaffenhofen during a laser link with the OICETS satellite at nighttime (2009). The two infrared uplink beacons can be seen.

Furthermore, under contract with ESA, RUAG Switzerland is developing an optical ground station (OGS) to support small LEO Earth Observation satellites. Emphasis is placed on cost efficiency, since a network at favorable weather conditions is required to achieve the targeted availability. The key features of the ESA/RUAG optical ground terminal are:

- Aperture size: 0.6 m
- Zenith angle range: < 70°
- Ground elevation limit with respect to local horizon: 20° (start acquisition)

3.1.4 CFLOS Analysis

LNOT was used to determine the performance of a LEO Scenario using the specifications described above for 2005-2011. The CFLOS analysis for the LEO Scenario is similar to that for the other scenarios for most candidate sites. However, as was discussed in Section 2.2.1.2, the cloud database used by LNOT was developed using geostationary meteorological satellites. Geostationary satellites provide excellent coverage of tropical and mid-latitude regions, but do a poor job in high-latitude regions because of the oblique look angles. Since LEO satellites have significantly more geometric access time to high latitude stations, it is important to consider high-latitude sites for a LEO optical communications system. Therefore, in the absence of satellite-derived 15-minute cloud data for high-latitude sites, a cloud analysis was developed from surface observations for three sites: Svalbard, Norway; Fairbanks, Alaska; and McMurdo Station, Antarctica. Cloud reports providing the skydome cloud amount are available every 3-6 hours for each of these sites. These data were analyzed for their temporal statistics. Their statistical correlations were computed based on the time of year and time of day. These parameters were used to interpolate between the 3-6 hour cloud observations to create a cloud database with one-hour resolution, which could be used by LNOT similar to the cloud data for the non-polar regions. The resulting one-hour cloud database has the same statistical properties (e.g. temporal correlations, average cloud amount) as the original coarser cloud data from surface observations.

A list of 16 candidate sites for LEO ground stations was created from NASA, ESA, and JAXA sites, astronomical observatories, and International Laser Ranging Service (ILRS) sites:

- Canberra DSN Complex (Australia)
- Madrid DSN Complex (Spain)
- Table Mountain Facility (California, USA) (NASA)
- Goddard Space Flight Center (GSFC) (Maryland, USA) (NASA)
- White Sands Complex (WSC) (New Mexico, USA) (NASA)
- Tenerife Observatory, Canary Islands (ESA)
- JAXA Earth Observation Center (Japan)
- Hartebeesthoek, South Africa (ILRS)
- Matera, Italy (ILRS)
- Mt. Haleakala, Hawaii, USA (ILRS)
- McDonald Observatory (Texas, USA) (ILRS)
- New Norcia (Australia)
- La Silla Observatory (Chile) (ESO)
- Guam Ground Station (NASA)
- Svalbard Ground Station (Norway)
- Fairbanks Ground Station (Alaska, USA)

McMurdo Station in Antarctica was included in initial analysis. However, it was later determined that terrestrial fiber links from McMurdo were insufficient to support the LEO

Scenario, and McMurdo was removed from consideration. The final list includes two polar sites (Svalbard at 78.9 N latitude and Fairbanks at 64.8 N latitude) and 14 non-polar sites.

The LEO Scenario requires data to be dumped at least once every three orbital revolutions with a high probability (e.g. 95%) as described Section 3.1.1.2. LNOT was used to compute the PDT for this scenario, and to determine how many ground stations might be required to achieve 95% PDT. The PDT was computed for the LEO Scenario using a process similar to that of the other scenarios, as follows. Using the seven years of cloud data and the position of the satellite, LNOT dynamically tracks the data collected (in Gb), the data stored onboard the satellite, and the data sent to the ground. For each hour in the cloud database, LNOT determines whether there is CFLOS from the satellite to any ground station. It also determines the amount of time during that hour the LEO satellite has access above 20° to any ground station. In the LEO Scenario, this geometric access time is measured in minutes, not hours. If a site has CFLOS to the satellite, data is sent at the specified data rate (10 Gb/s), and the data buffer is reduced by the amount of data sent. The amount of data sent when the line-of-sight (LOS) is cloud-free is equal to the product of the number of minutes of geometric access greater than 20° and the data rate. For example, if there are four minutes of cloud-free access to a station during an orbital revolution, the satellite can send 2.4 Tb of data (10 Gb/s × 240 seconds) to that ground station. If no site has CFLOS to the satellite during the current hour of data processing, the amount of data in the onboard buffer is increased by 500 Gb (12Tb per day divided by 24 hours) to simulate another hour of data collection. If the onboard buffer is full, the oldest data is purged, and the amount of data lost is recorded. The PDT is computed at the end of the simulation as the amount of data successfully sent to the ground divided by the amount of data collected by the satellite.

The LEO Scenario differs from the other scenarios in that sites gain and lose access to the satellite very quickly. A site in the mid-latitudes typically has a LOS above 20° to a LEO satellite such as Aqua for a few minutes per satellite pass. Polar sites have somewhat more contact time per orbit, as well as more orbits with access above 20° per day. Therefore, a high-latitude site has the potential to provide great value to a network of LEO ground stations. Taken collectively, the seven example sites shown in Figure 24 below provide an average of about 125 minutes per day of contact above 20° to the LEO satellite. However, geometric access is only part of the calculation. To successfully transmit data at optical wavelengths, the satellite must have cloud-free access to the ground station. When the effects of clouds are included, this time is reduced to an average of about 60 minutes of cloud-free access per day. The entire volume of data collected in a day (12 Tb) can be sent to the ground in 20 minutes of cloud-free access time. However, the satellite can only store data from three orbits (~4.5 hours of data), and therefore must transfer data to the ground at least once every three orbits to avoid exceeding the storage limit and losing data. Therefore, while the entire amount of data stored onboard the satellite can be transferred in less than five minutes (duration of a typical LEO contact), data will be lost when no site has CFLOS on three successive LEO orbits. With the seven sites in this scenario, the LEO satellite always has access above 20° to one or more sites at least once every three orbits. However, there are times when clouds obscure the LOS during the LEO passes, resulting in lost data.

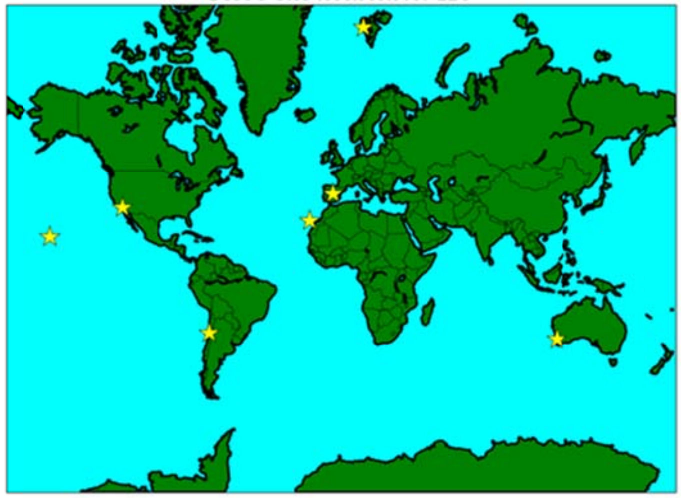


Figure 24: Optimal seven-site network configuration for the LEO Scenario.

The top performing LEO ground station networks were identified by exhaustively computing the performance of all the possible combinations of the 16 candidate sites for networks consisting of 3-15 sites. These PDT calculations were performed for combinations of non-polar sites only, as well as mixed polar and non-polar networks. This analysis indicates a seven-site network nearly achieves the objective of 95% PDT using both polar and non-polar sites, with a PDT of 94.8% for the top network (Figure 24). In fact, a seven-site network of only non-polar sites produces a similar PDT of 94.4%, despite having only about two-thirds the amount of geometric access time as the best seven-site network that includes Svalbard. While Svalbard provides very good geometric access to the LEO satellite, the cloud analysis indicates it is a very cloudy site, which negates much of its geometric benefit. Conversely, several of the non-polar sites only provide a few minute of geometric access per day, but have a very high probability of being cloud-free. Fairbanks rarely shows up in the top networks. It is located at a relatively high latitude, but at 64.8°, its geometric access time is significantly less than Svalbard at 78.9°. Additionally, Fairbanks is very cloudy, leading to the conclusion that it is not a very attractive high-latitude site for an optical ground station. McMurdo Station, with performance statistics similar to Svalbard, is an attractive site, but it was removed from final consideration due to the limitations of its terrestrial communications.

Figure 25 shows the cumulative distribution of the monthly PDT for the top seven-site network of ground stations for this scenario. The PDT is greater than 88% for all months during 2005-2011, and the overall PDT for this LEO Scenario is 94.8%. Figure 26 shows the cumulative distribution of the amount of data transferred daily from LEO to the seven-site ground station network. The data indicate that at least 10 Tb of data is sent to the ground on 90% of the days during 2005-2011. This analysis indicates that a globally distributed set of ground stations can be used to receive very large amounts of data from a LEO satellite, making cross support very attractive. High-latitude sites such as Svalbard increase PDT slightly when compared to strictly non-polar networks, but are not necessary to achieve high performance from a LEO mission.

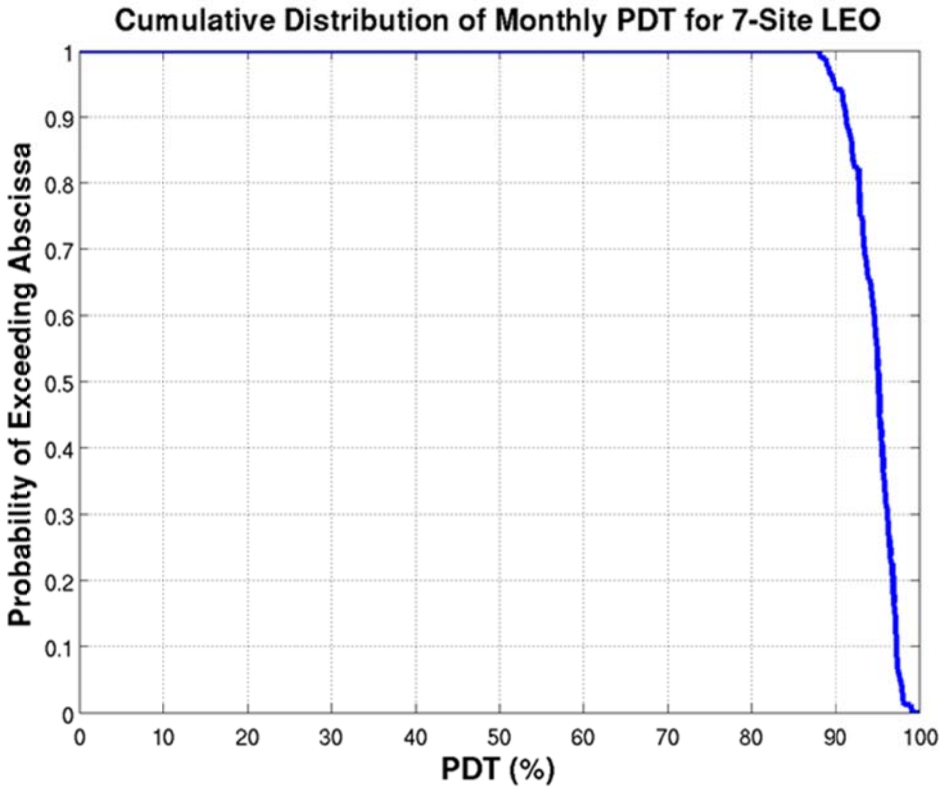


Figure 25: The cumulative distribution of the monthly PDT for the period 2005-2010 for the optimal seven site network.

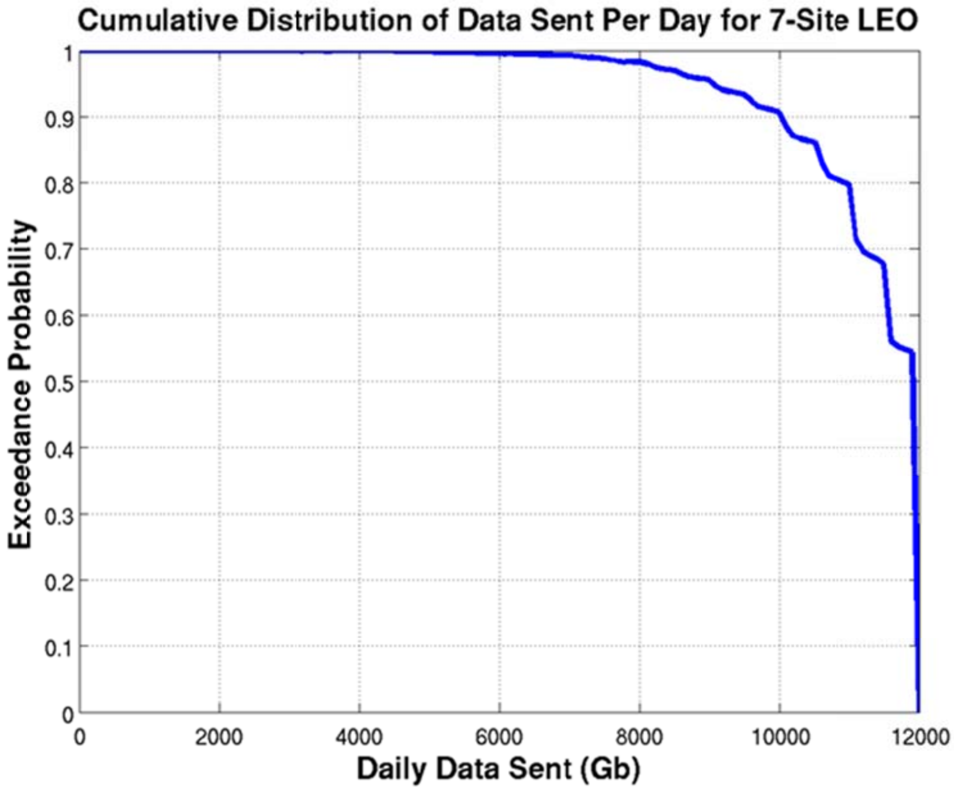


Figure 26: The cumulative distribution of the amount of data successfully sent to the ground by the LEO satellite for the seven site network of ground stations.

3.1.5 Link Budget

3.1.5.1 Downlink Budget

An example link budget for an elevation of 20° is shown in Figure 27. With Tx- and Rx-aperture diameters of 5 and 50 cm respectively, the calculated link margin is about 4 dB. The scintillation loss (estimated to be -2 dB) can be mitigated by channel coding.

LEO DOWNLINK BUDGET

INPUT PARAMETERS		
Range	1.30E+03	km
Elevation	20	deg
TRANSMITTER		
Modulation Type	OOK	
Tx Wavelength	1.55	μm
Tx Ave Power	0.5	W
Tx Data Rate	10.0E+09	Hz
Tx Aperture Diam	0.05	m
Tx Angular Diam	8.14	arcsec
Tx Footprint Diam	5.13E+01	m
Tx Optical Transmission	50.0	%
Tx Depointing	0.40	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-2.0	dB
RECEIVER		
Rx Aperture Diam	0.50	m
Rx FOV	5.00	arcsec
Rx Depointing	1.00	arcsec
Rx Optical Transmission	50.0	%
Rx Array Size	1	apertures
Code Rate	1.00	

LINK BUDGET		
Tx Ave Power	**26.99**	**dBm**
Tx Antenna Gain	100.12	dBi
Tx Transmission Loss	-3.01	dB
Tx Pointing Loss	-0.04	dB
EIRP	94.05	dBW
Isotropic Space Loss	-260.46	dB
Atmospheric Loss	-2.65	dB
Irradiance at g/s	1.20E-04	W/m^2
Rx system	117.11	
Rx Antenna Gain	120.12	dBi
Array Gain	0.00	dB
Rx Transmission Loss	-3.01	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-48.93**	**dB**
Ave Power at Rx Detector	**-21.94**	**dBm**
Required Power	-26.00	dBm
Link Margin	**4.06**	**dB**

Figure 27: Example downlink budget for the LEO Scenario.

3.1.5.2 Uplink Budget

A sample uplink beacon budget for the LEO scenario is reported in Figure 28. The transmitter consists of four 5 cm apertures, which provide a beam divergence of about 40 µrad (8.14 arcsec). The average power per aperture is 0.125 W, for a total transmitted power of 0.5 W. In the calculation, the scintillation loss (or turbulence loss) is computed as the Strehl ratio[2] and accounts for spread loss and beam wandering, under the assumptions of a seeing of 2 arcsec (Fried parameter r_0 of 5 cm, at zenith, at a wavelength of 500 nm). The irradiance required at the receiver aperture is based on the acquisition procedure of LLCD. The link budget shows that the average transmitted power could be reduced by about 26 dB, which corresponds to 0.3 mW per aperture.

[2] L. C. Andrews, R. L. Phillips, R. J. Sasiela, R. R. Parenti, *Strehl ratio and scintillation theory for uplink Gaussian beam waves: beam wander effects* (Opt. Eng. 45[7], 2006).

LEO UPLINK BUDGET

INPUT PARAMETERS		
Range	1.3E+03	km
Elevation	20	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	0.13	W
Tx Array Size	4	apertures
Tx Aperture Diam	0.05	m
Tx Angular Diam	8.14	arcsec
Tx Footprint Diam	51.31	m
Tx Optical Transmission	45.0	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-2.3	dB
RECEIVER		
Rx Aperture Diam	0.05	m
Rx FOV	5.00	arcsec
Rx Depointing	0.40	arcsec
Rx Optical Transmission	50.0	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	63.0E-09	W/m^2

LINK BUDGET		
Tx Ave Power	**20.97**	**dBm**
Tx Antenna Gain	100.12	dBi
Tx Array Gain	6.02	dBi
Tx Transmission Loss	-3.47	dB
Tx Pointing Loss	-0.17	dB
EIRP	**93.47**	**dBW**
Isotropic Space Loss	-260.46	dB
Atmospheric Loss	-2.90	dB
Irradiance at rx aperture	**5.37E-05**	**W/m^2**
Rx Antenna Gain	100.12	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-3.01	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-63.75**	**dB**
Ave Power at Rx Detector	**-42.78**	**dBm**
Req. Irradiance at rx aperture	63.0E-9	W/m^2
Link Margin (Irradiance)	**29.30**	**dB**

Figure 28: Example uplink budget for the LEO Scenario.

3.1.6 Ground Station Cost

Table 13 provides a cost estimation of the optical ground stations for the LEO Scenario.

Table 13: Ground station costs for the LEO Scenario (k€).

LEO Scenario Ground Station Costs in k€	**Halea-kala**	**La Silla**	**TMF**	**Tenerife**	**Madrid**	**Svalbard**	**New Norcia**	**Total**
Initial Station Investment Costs:								
Terminal (telescope, dome, and electronics)	481	481	481	481	481	481	481	
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	750	780	780	780	780	390	390	
Wide Area Communication Investment Costs (ground comm)	157	1,560	471	0	0	0	0	
Weather and Atmospheric monitoring	250	250	250	250	250	250	250	
Aviation Safety System	350	350	350	350	350	350	350	
Subtotal Initial Station Investment Costs	**1,988**	**3,421**	**2,332**	**1,861**	**1,861**	**1,471**	**1,471**	**14,405**
Recurring Operating Costs:								
Site and Terminal Operating Costs	390	780	390	390	390	390	390	
Communication Operating Costs	390	390	390	390	390	390	390	
Subtotal Recurring Operating Costs	**780**	**1,170**	**780**	**780**	**780**	**780**	**780**	**5,850**

3.1.7 Business Case

The LEO Scenario enables a high potential for cross support. The CFLOS analysis shows that ground stations spread over the world are necessary to obtain a high percentage of data transfer. The ground stations of such a network shall be provided by several space agencies.

3.2 Highly Elliptical Earth Orbit (HEO) Scenario

The HEO Scenario is not elaborated as it is considered similar to the Lunar Scenario with shorter distances.

3.3 Geostationary Earth Orbit (GEO) Scenario

This scenario is discussed in section 4.1.1.2.3 Earth Relay Optical Feeder Link and section 4.2 Telecom Mission Optical Feeder Uplink.

3.4 Lunar Scenario

3.4.1 Concept of Operations

3.4.1.1 Basic Concept of Operations

The Lunar Scenario refers to a system providing optical communications from a lunar orbiting satellite to a ground station on the Earth's surface. This scenario is of particular interest since the NASA LLCD is currently in preparation for a 2013 launch. Much of this scenario description is drawn from LLCD experience, as well as extrapolation to potential future lunar missions. The space terminal of LLCD is called the Lunar Lasercomm Space Terminal (LLST) and the dedicated ground terminal is called the Lunar Lasercomm Ground Terminal (LLGT).

The first criterion for a free space optical link is geometric line of site from the spacecraft to a ground terminal. As with other scenarios, the optical link quality is affected by the ground station elevation angle, with lower elevations reducing the link capabilities. For all lunar orbiting spacecraft, the first obvious requirement is line of sight to the Moon itself; thus, lunar elevation angles will be consistent for all missions in this scenario analysis. Orbit-specific information further refines the scenario, though this information will vary from mission to mission.

LLCD will be launched on LADEE. This science mission will fly a relatively low altitude (250 km) retrograde lunar orbit. Due to the specific orbit, the satellite regularly passes behind the Moon and loses contact with the ground station. For LADEE, the passes with geometric line of sight vary between 40 and 80 minutes in duration. Lunar polar orbits that do not pass behind the Moon (from perspective of the ground site) would have more continuous geometric access when the Moon is in the sky.

Under current plans, LLCD will be able to communicate with two ground stations. One—the LLGT—is a transportable terminal currently slated to be located on Mount Haleakala, on Maui, Hawaii. The second ground site is the OCTL, located on Table Mountain, California; this site is referred to as the Lunar Lasercomm OCTL Terminal (LLOT).

The geometry from LADEE to the two ground sites illustrates several general features of lunar missions. These features are particularly relevant for interoperability, as multiple ground sites would be a major benefit of interoperability. While California and Hawaii are not at the same longitude, the fact that they are in the same hemisphere means that the Moon is visible simultaneously to both sites much of the time. Consider Figure 29, which shows the access times to the LLST from the two ground sites over a one-month period beginning July 1, 2013. Access is plotted at the given elevation angle. From the figure, one can see the overall lunar geometry varying over the course of the month, governing the general pattern of the elevation angle to both sites. The Haleakala site, however, has consistently higher elevation angles than the Table Mountain site, because the latitude of the two ground sites differs, with higher elevation angles occurring nearer the equator.

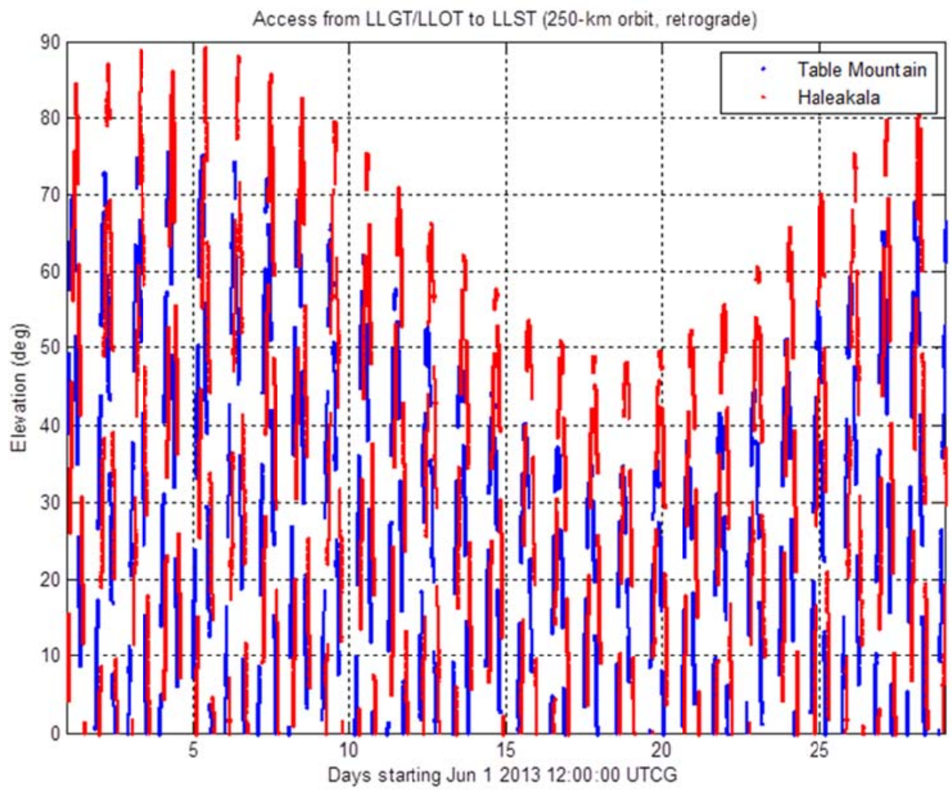


Figure 29: Access from LLGT/LLOT to LLST.

One can also see the similarity in time of the accesses from the two ground sites. Since the two sites are in the same hemisphere, the Moon (and hence the LLST) is often visible to both sites when one has access. This feature is apparent in Figure 30, which shows the access over a single 24-hour period (from June 1-2, 2013). For most of the illustrated passes, the link can be made to either site; however, though the Haleakala site has the largest maximum elevation angle, it does not always have the higher elevation angle for each pass.

Figure 31 summarizes the overlap of access from the two sites. Figure 31 shows that over the course of a month, most of the passes have access to either site, with only a few passes having access to only one or the other. During days 6 and 7, however, only the Haleakala site has access to any pass, due to the elevation angle restrictions placed upon the OCTL site. On those days, the lunar geometry never rises above the minimum elevation angle, meaning that OCTL has no access to LLST.

Figure 31 also shows that the two ground sites do not provide access diversity in terms of independent passes. The two ground sites do, however, provide significant weather diversity. Thus, in passes where both sites have geometric access, the probability of cloud free line of sight to at least one of the sites improves the probability of communicating during that pass. The CFLOS analysis is quantified in section 3.4.4.

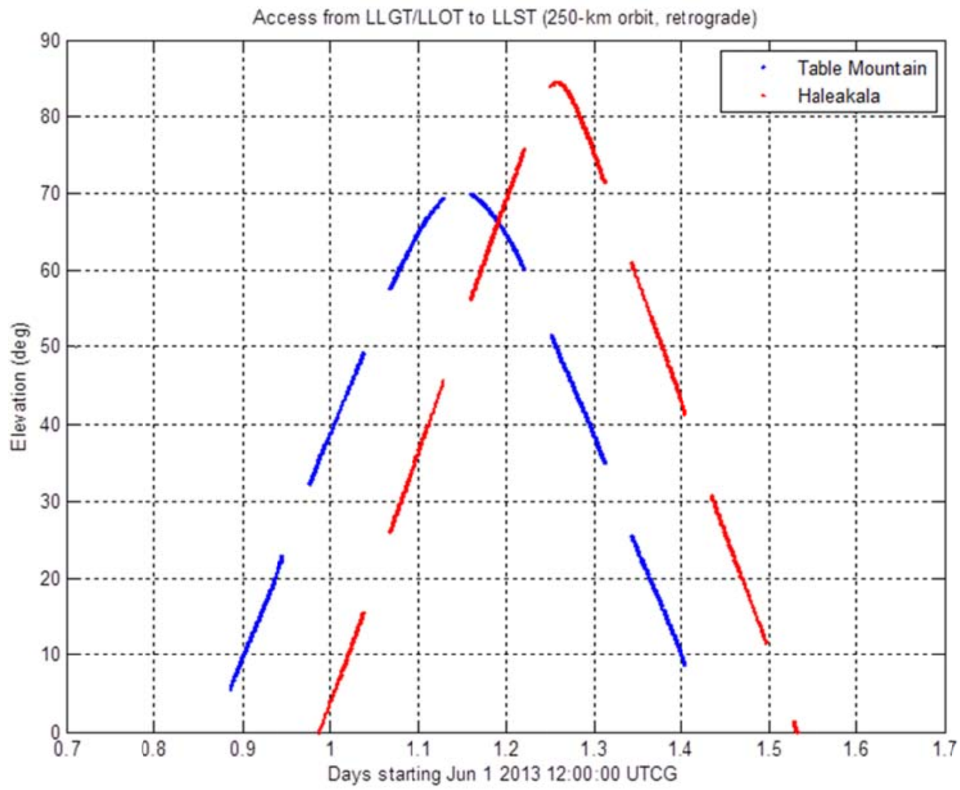


Figure 30: LLGT/LLOT access to LLST June 1-2, 2013.

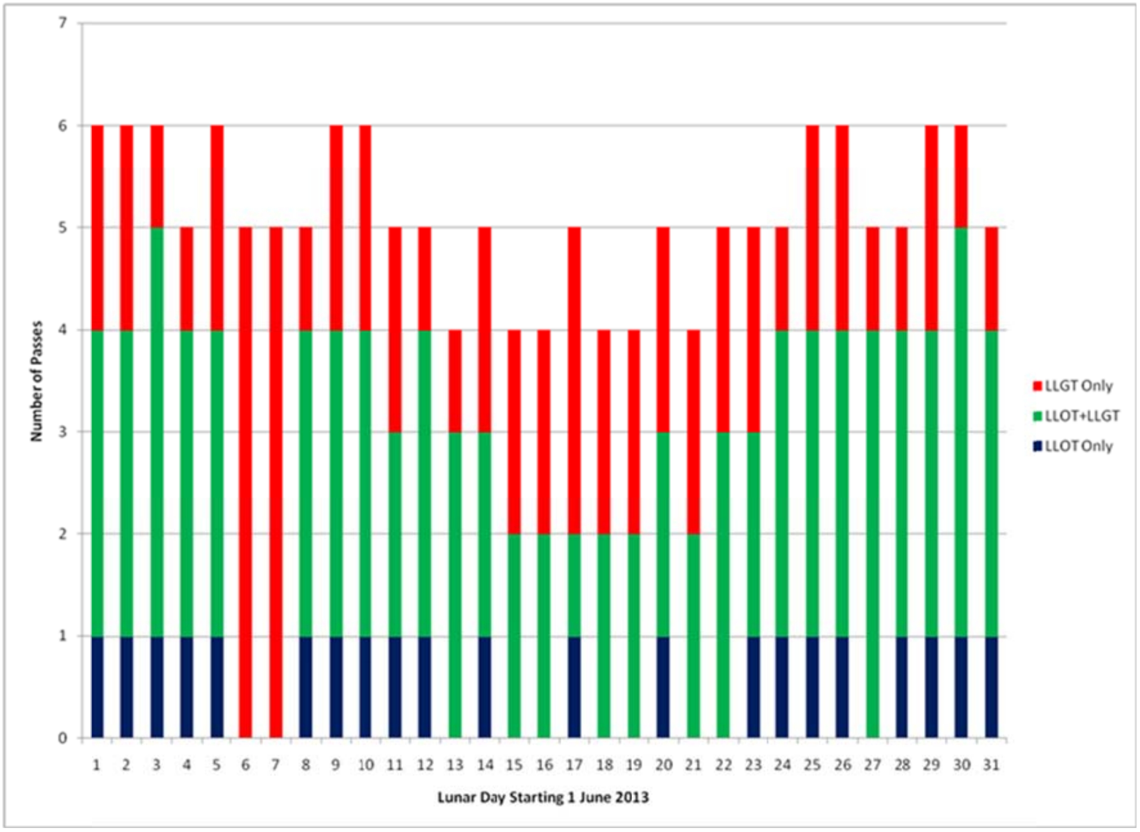


Figure 31: Number of passes with access from LLGT and/or LLOT to LLST.

While the California and Hawaii ground sites are the locations planned for LLCD, one can consider the hypothetical scenario of ground sites at Haleakala and Tenerife (a potential benefit of interoperability). Figure 32 shows that the two sites have a similar elevation angle variance, though the maximum elevation at Haleakala is approximately 10 degrees higher. The two sites also have nearly complementary access times. Since the two sites are nearly 180 degrees separated in longitude, there is almost no overlap in the passes with access between the sites (see Figure 33). The total number of passes with geometric access for this hypothetical lunar mission is nearly double compared to that of a similar mission that uses only one ground site. It should be noted, however, that these two ground sites do not provide weather diversity within a single pass, as the passes have distinct geometric accesses. Thus, lack of CFLOS at one site could not immediately be remedied by the other site. On the other hand, when one site is unavailable due to clouds, the delay until the alternate site has geometric access is unlikely to result in a loss of data unless the data storage is completely filled.

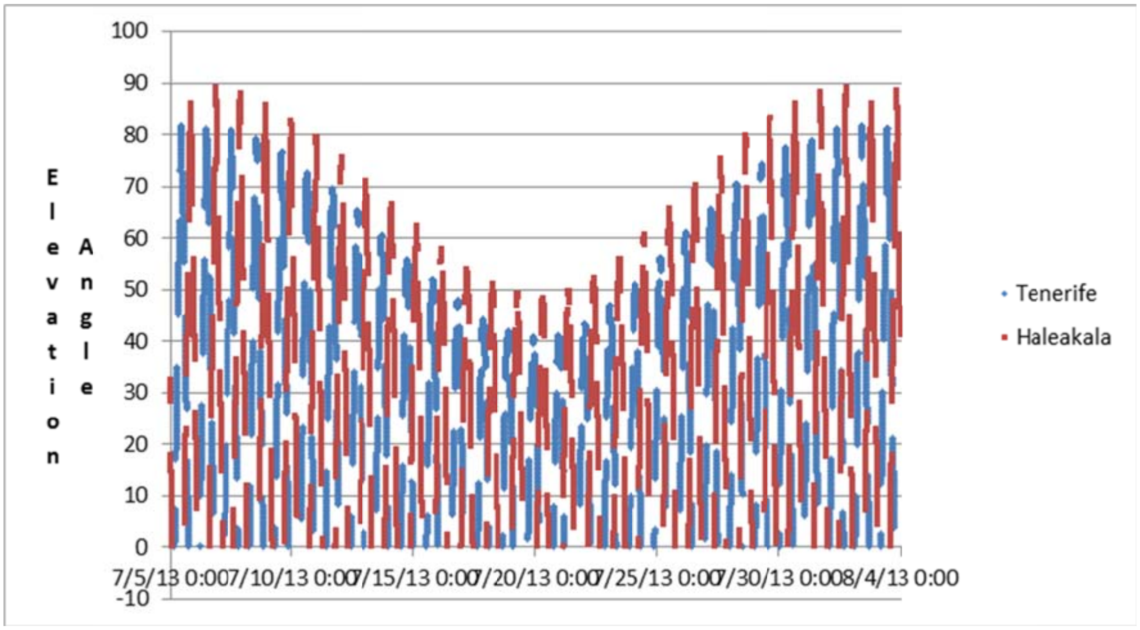


Figure 32: Geometric Access from LLST to hypothetical ground terminals at Haleakala and Tenerife (from July 5 – August 4, 2013).

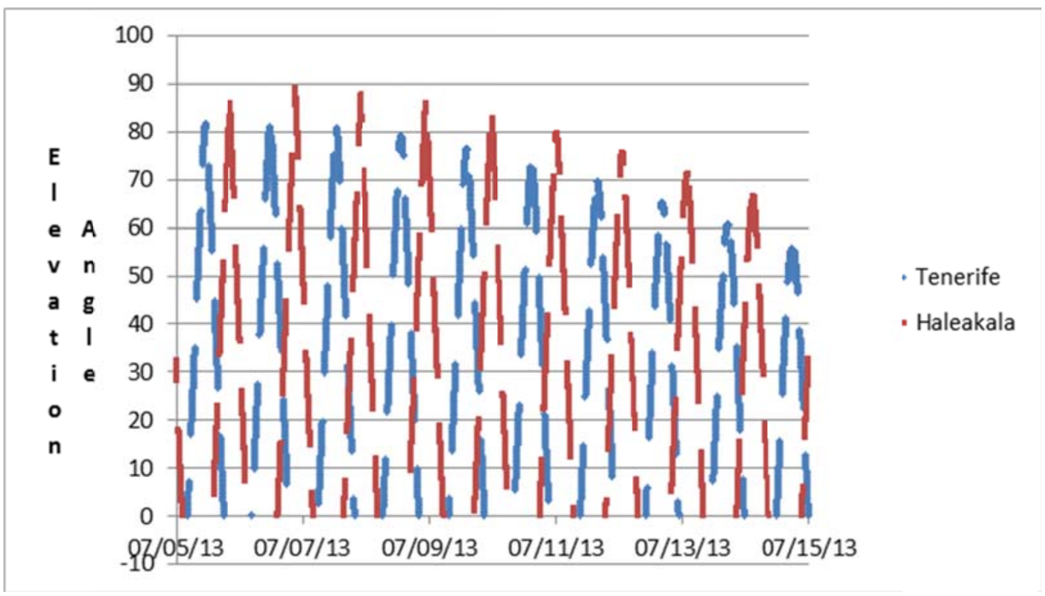


Figure 33: Geometric Access from LLST to hypothetical ground terminals at Haleakala and Tenerife (from July 5 – 15, 2013).

3.4.1.2 Scenario Concept of Operations

As with other scenarios, the primary purpose of the optical communications link is to transmit science data. Thus, the goal is the delivery of large data volumes with minimal loss of data. Low latency for downlink data is not a driving scenario requirement. An uplink beam must provide functionality for pointing, acquisition and tracking. In addition, the uplink beam may (as it will for LLCD) provide a data stream, but the uplink data rate is likely to be much lower than the downlink data rate. Because of the uncertain availability of the optical uplink, primary spacecraft commanding should be performed with an RF link.

Acquisition is to be performed on a pre-scheduled basis, with both the spacecraft and the ground station employing open-loop pointing toward each other. In the case of LLCD, the ground station scans the uncertainty region, while the LLST points in a fixed direction. Upon receiving light from the LLGT, the LLST then transmits its beam in response, thus the LLGT is initiating the acquisition procedure.

LLCD has a variable data rate on the uplink and on the downlink. The data rate used can be varied, depending upon the link conditions. While the link distance remains relatively constant (varying by approximately 1 dB due to lunar geometry), elevation angles, atmospheric conditions, and background light (mainly from the lunar surface as illuminated by the Sun) can lead to more challenging communications environments. Data rate reductions can allow for successful communication under such challenging circumstances.

LLCD will not demonstrate data storage and buffering, but future lunar missions are likely to require such buffering. In that scenario, the ConOps would need to establish the expected data buffering and download data rate appropriately, given the available ground stations and the corresponding CFLOS availability. For the CFLOS analysis in section 3.4.4, the following assumptions are made about potential data volume. The data rate is assumed to be 622 Mbps (matching the LLCD maximum data rate). The data volume generated is 5.72 Tbits/day. This number corresponds to ten times the data volume generated by the Lunar Reconnaissance Orbiter (LRO). The data storage (i.e., buffering) capability is 1.3 days, or 7.4 Tbits. The minimum elevation angle for establishing a communications link is assumed to be 20 degrees. Table 14 summarizes the ConOps parameters for the Lunar Scenario.

Table 14: Lunar Scenario Concept of Operations Parameters

Lunar Scenario			
Onboard Data Collection Rate	**Onboard Storage Capacity**	**Hours of CFLOS Required per Day**	**Data Rate used for Link Budget**
5.72 Tb/day	7.4 Tb	2.55	622 Mbps

3.4.2 Space Terminal

The space terminal must provide the functions described in the ConOps. The optical communication space terminal consists of an optical head, controller electronics and modem, plus all of the interfaces with the spacecraft. This hardware must implement the uplink and downlink communications beams, as well as the pointing, acquisition, and tracking functions.

3.4.2.1 Space Terminal Potential Implementation

The LLST is comprised of an optical assembly, controller electronics, and the optical modem. The combined payload is approximately 30 kg in mass and draws between 50-140 Watts of power. The optical assembly contains a 10.8 centimeter telescope mounted on an inertially stabilized, two-axis gimbal. LLCD communicates using pulse position modulation (PPM) for both the uplink and the downlink. The downlink transmitter operates at a maximum data rate of 622 Mbps and implements 16-PPM. The downlink data rate is variable, however, enabling the ability to close the link at lower data rates in more challenging atmospheric conditions. The average optical power transmitted is 0.5 W, generated with an EDFA. The uplink receiver utilizes optically pre-amplified direct detection, and demodulates 4-PPM at a maximum rate of 20 Mbps, with rate fallback modes for challenging atmospheric conditions. Both the uplink and downlink are encoded with a high-efficiency, serially concatenated convolutional code. The encoding and decoding electronics, as well as the electronics for the other modem functions, are performed using field-programmable gate array (FPGA) digital logic.

3.4.3 Ground Terminal

The ground terminal must provide the functions described in the ConOps, including the generation and transmission of the uplink signal, reception, demodulation and decoding of the downlink signal, and the generation of the uplink beacon (if a beacon is included in the ConOps). In addition, the ground terminal also includes the capability to store and/or distribute the downlinked data. The ground terminal must include optical assemblies to perform the transmit and receive functions; controller functionality to do pointing, acquisition, and tracking; a modem to generate the optical transmit signal and process the digital receive signal; and data routing and/or storage functionality to both generate the uplink data and process the downlink data.

3.4.3.1 Ground Terminal Potential Implementation

The LLGT consists of an array of four 15-cm transmit telescopes and four 40-cm receive telescopes. The array concept provides atmospheric diversity for both the uplink and downlink, reducing the impact of atmospheric turbulence. Furthermore, the array concept represents a scalable architecture, where additional telescopes can be integrated to provide more link capability. All eight telescopes are mounted on a single azimuth and elevation gimbal. For the transmit direction, each aperture radiates 10 W of average optical power at four slightly separated wavelengths to allow for non-coherent combing at the LLST with minimal penalty. The receiver performs direct detection using an array of single photon detectors. These detectors are superconducting nano-wire single photon detectors (SNSPD) that require cryogenic cooling, but have been shown to have high detection efficiency and can operate at a very high data rate. Single photon detecting technology is a key technology driver for highly sensitive optical links, and has been identified by NASA as a powerful technology that will enable long distance optical links.

3.4.4 CFLOS Analysis

LNOT was used to run a scenario using the assumptions defined in the Lunar Scenario ConOps in Section 3.4.1.2. To show the value of interoperability between the United States and European assets, two sets of site configurations were evaluated. The first set consisted of a Haleakala (NASA) and Tenerife OGS (ESA) configuration, and the second was a four-site network containing Haleakala (NASA), Table Mountain Facility (NASA), Tenerife (ESA) and Hartebeesthoek, South Africa (ESA). As indicated in the concept of operations above, a site was considered available for communication when the lunar probe was at least 20 degrees above the horizon and a CFLOS existed. Using the scenario assumptions in Section 3.4.1.2, Table 15 below shows the mean PDT for the period 2005-2010. The mean PDT for both Haleakala and Tenerife individually exceed 80%. As a two-site network, the PDT is approximately 97.4%. This increase is due to a combination of cloud de-correlation and the geographic separation between the two sites in terms of the total visibility time to the Moon. When TMF and Hartebeesthoek are added to the two-site network, the PDT increases to approximately 99.6%. The meteorological diversity between these sites is responsible for the high performance, almost guaranteeing that at least one site is available. Figure 34 shows the Cumulative Distribution Function (CDF) of the monthly PDT for individual sites, as well as the two- and four-site configurations. Haleakala and Tenerife are the best performers individually, and the four-site network produces only a low probability of PDT less than 95%. The Lunar Scenario is an excellent example of where cross support can enhance performance of optical communications.

Table 15: PDT (%) for Lunar Scenario for the 2005-2010 period.

Haleakala (NASA)	Table Mountain Facility (NASA)	Hartebeesthoek (ESA)	Tenerife OGS (ESA)	Haleakala + Tenerife OGS	Haleakala + Tenerife OGS + TMF + Hartebeesthoek
81.0%	68.6%	64.7%	84.4%	97.4%	99.6%

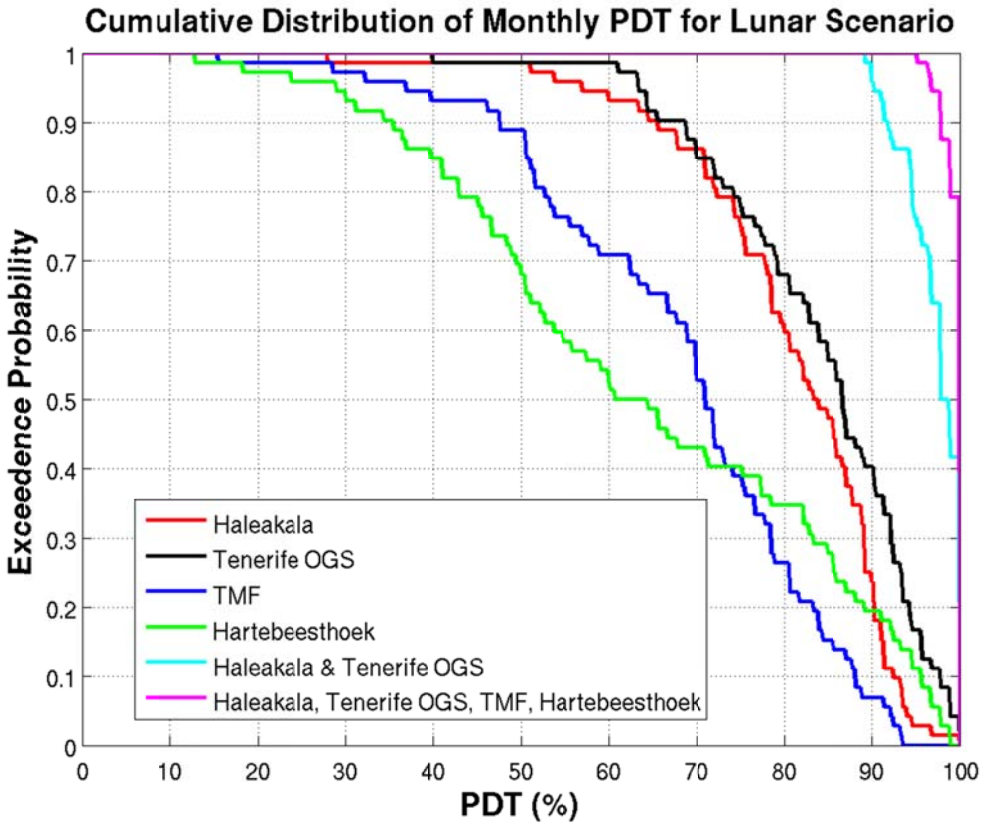


Figure 34: CDF of PDT for the four individual sites and the two- and four-site networks for the Lunar Scenario.

3.4.5 Link Budget

3.4.5.1 Downlink Budget

Figure 35 presents a sample link budget for the 622 Mbps downlink to be demonstrated by LLCD. The maximum data rate is achievable under the best conditions, including a benign atmosphere, a moderate elevation angle, and minimal background light.

MOON DOWNLINK BUDGET

INPUT PARAMETERS

Range	384.0E+03	km
Elevation	30	deg
TRANSMITTER		
Modulation Type	16-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	0.5	W
Tx Data Rate	622.0E+06	Hz
Tx Aperture Diam	0.1076	m
Tx Angular Diam	3.78	arcsec
Tx Footprint Diam	7.04E+03	m
Tx Optical Transmission	33.0	%
Tx Depointing	0.50	arcsec
Uncoded Slot Rate	5.0E+09	s^{-1}
Uncoded Bits Per Word	2.00	
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-1.0	dB
RECEIVER		
Rx Aperture Diam	0.40	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	46.3	%
Rx Array Size	4	apertures
Fiber Coupling Loss	-3.57	dB
Required Photons / Pulse	3.74	
Code Rate	0.50	

LINK BUDGET

Tx Ave Power	**26.99**	**dBm**
Tx Photons / Pulse	1.25E+10	
Tx Antenna Gain	106.77	dBi
Tx Transmission Loss	-4.82	dB
Tx Pointing Loss	-0.31	dB
Isotropic Space Loss	-309.86	dB
Atmospheric Loss	-1.44	dB
Rx Antenna Gain	118.18	dBi
Array Gain	6.02	dB
Rx Transmission Loss	-3.34	dB
Rx Pointing Loss	0.00	dB
Rx Fiber Coupling Loss	-3.57	dB
Total Optical Path Loss	**-92.38**	**dB**
Ave Power at Rx Detector	**-65.39**	**dBm**
Photons / Pulse at Rx Detector	**7.26E+00**	
Required Photons / Pulse	3.74	
Link Margin	**2.88**	**dB**

Figure 35: Example downlink budget for the Lunar Scenario.

3.4.5.2 Uplink Budget

Figure 36 presents a sample uplink budget for a lunar mission. The irradiance required at the receiver aperture is based on the acquisition procedure of LLCD. The calculation shows a good margin on the beacon link.

MOON UPLINK BUDGET

INPUT PARAMETERS

Slant Range	384.0E+03	km
Elevation	30	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	10.0	W
Tx Array Size	4	apertures
Tx Aperture Diam	0.15	m
Tx Angular Diam	2.71	arcsec
Tx Footprint Diam	5.05E+03	m
Tx Optical Transmission	46.3	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-1.5	dB
RECEIVER		
Rx Aperture Diam	0.11	m
Rx FOV	5.00	arcsec
Rx Depointing	3.50	arcsec
Rx Optical Transmission	33.0	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	63.0E-09	W/m^2

LINK BUDGET

Tx Ave Power	**40.00**	**dBm**
Tx Antenna Gain	109.66	dBi
Tx Array Gain	6.02	dBi
Tx Transmission Loss	-3.34	dB
Tx Pointing Loss	-1.56	dB
EIRP	**120.78**	**dBW**
Isotropic Space Loss	-309.86	dB
Atmospheric Loss	-1.94	dB
Irradiance at rx aperture	**412.6E-09**	**W/m^2**
Rx Antenna Gain	106.77	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-4.81	dB
Rx Pointing Loss	-1.24	dB
Total Optical Path Loss	**-100.32**	**dB**
Ave Power at Rx Detector	**-60.32**	**dBm**
Req. Irradiance at rx aperture	63.0E-09	W/m^2
Link Margin (Irradiance)	**8.16**	**dB**

Figure 36: Example uplink budget for the Lunar Scenario

3.4.6 Ground Station Cost

Table 16 provides a cost estimation of the optical ground stations for the Lunar Scenario.

Table 16: Ground Station costs for the Lunar Scenario (k€).

Lunar Scenario Ground Station Cost in k€	Haleakala	Tenerife	Total
Initial Station Investment Costs:			
Terminal (telescope, dome, and electronics)	7,632	7,632	
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	1,560	1,560	
Wide Area Communication Investment Costs (ground comm)	157	0	
Weather and Atmospheric monitoring	250	250	
Aviation Safety System	350	350	
Subtotal Initial Station Investment Costs	**9,949**	**9,792**	**19,741**
Recurring Operating Costs:			
Site and Terminal Operating Costs	1,168	1,168	
Communication Operating Costs	390	390	
Subtotal Recurring Operating Costs	**1,558**	**1,558**	**3,116**

3.4.7 Business Case

As with other scenarios, a major benefit of interoperability is ground station diversity. As described above, ground station diversity provides both access diversity (i.e., geometric line of site) as well as weather diversity. Due to the lunar geometries, ground stations with large longitudinal separations have complementary access to the spacecraft, thus increasing the total time for potential communications. In addition, use of ground stations at similar longitudes, but with uncorrelated weather, increases the possibility that times with geometric access have CFLOS, thus enabling communications. For this reason, optical communications from the Moon would be significantly enhanced with multiple, interoperable ground sites spread around the globe.

3.5 L2 Scenario

3.5.1 Concept of Operations

3.5.1.1 Basic Concept of Operations

The optical communication link in the L2 Scenario is used primarily for high-rate data downlinking. In the L2 Scenario, there will be an optical uplink for PAT in the ground terminal, with the potential added feature of uplinking data, but the optical uplink will not be used for spacecraft commanding.

The OLSG adopted the Euclid mission as the model case for the L2 Scenario, as Euclid is a real future ESA mission. In addition, the Euclid concept of operations fortuitously resembles what is deemed rather suitable for optical downlink of science data. Euclid's daily ConOps calls for science observations for 21 hours, followed by a "burst-mode" downlink of the acquired data during the remaining three hours.

3.5.1.2 Scenario Concept of Operations

The following assumptions were adopted for the L2 Scenario analysis:

- Downlink data rate: 700 Mbps (a 10-fold increase over the planned RF downlink for Euclid)
- The entire 3 hours are taken as necessary to downlink 100% of one day's mission data; the latter therefore assumed to be 7.5 TB
- Onboard storage capacity: corresponding to 3 days of science observations, (thus equal to 22.5 TB)

The ConOps of several ground stations is assumed in the analysis as follows:

- The stations are scheduled one week in advance, based on long-term meteorological statistics and forecast
- A nominal and potential alternate stand-by station(s) are defined
- Weather (cloud measurement) is monitored at all stations to provide short-term (on time scales of an hour) CFLOS forecast
- Based on the above predictions, a controlled station handover to the (most suitable) stand-by station is initiated (e.g., via the RF TC link)

The mission relies on close cooperation between optical station operations and spacecraft operations.

Table 17 summarizes the ConOps parameters for the L2 Scenario.

Table 17: L2 Scenario Concept of Operations Parameters

L2 Scenario			
Onboard Data Collection Rate	**Onboard Storage Capacity**	**Hours of CFLOS Required per Day**	**Data Rate used for Link Budget**
7.5 Tb/day	22.5 Tb	3	700 Mbps

3.5.2 Space Terminal

An optical communication system from the Lagrange orbit (L2) to Earth was studied and partially bread-boarded by RUAG Space (Switzerland) in 2007. The purpose of the study was to identify potential of state-of-the-art laser and detector technology and to implement (for the first time in Europe) pulse position modulation. The laser transmitter in L2 assumed a seed laser at a wavelength of 1064 nm, followed by a modulator and a 1-Watt Ytterbium doped fiber amplifier. The transmitter had a 10 cm telescope diameter and the receiver was ESA's optical ground station (Tenerife OGS) with a 1-meter telescope diameter and an avalanche photo-detector (APD) as receiver.

The system was tested in a 150 km inter-island experiment between a hut located on the island of La Palma and the Tenerife OGS. The test simulated a link from the Lagrange point L2 by scaling down the transmitter diameter and the link distance. As both parameters (the transmitter diameter and the link distance) scale with the square in a link budget calculation, both were reduced by the same factor. The transmitter diameter was scaled down from 10 cm to 10 micrometers (which roughly corresponds to the mode field diameter of the single mode output fiber of the laser amplifier) and the link distance from 1.5 million km to 150 km. In this way the link budget from L2 was maintained in the inter-island experiment, but the transmitter pointing was considerably relaxed.

However, the experiment had to cover a 150 km horizontal link through the atmosphere with the worst possible turbulence conditions. Nevertheless, by using forward error correction and convolution coding, a data rate of 10 Mbps was demonstrated. Atmospheric turbulence on a link from the Lagrange point L2 is considerably lower, thus enabling far higher data rates.

The projected data rate of 700 Mbps is achievable in a link scenario from the Lagrange point L2 back to Earth by increasing the transmitter telescope diameter from 100 mm to 135 mm, the transmitter power from 1 Watt to 5 Watts, and the receiver telescope diameter from 1 m to 2.5 m. A laser communication terminal with these parameters is under development by Tesat Spacecom for the EDRS system, although with a different modulation technology. Astronomical research requires large apertures and 2.5 meter class telescopes can be relatively easy booked for laser communication purposes (e.g., Isaac Newton Telescope on La Palma).

3.5.2.1 Space Terminal Potential Implementation

The onboard implementation of an LCT from the Lagrange point (L2) could be based upon the NASA LLCD design or upon the Tesat LCT design for EDRS. The conceptual terminal would use pulse position modulation, a wavelength of 1550 nm and a data rate of 700 Mbps. It would track a modulated optical beacon signal from the Earth-based receiver terminal at 1550 nm. Onboard vibration isolation would be performed by high-speed tip/tilt tracking of the beacon signal. Solar radiance blocking would be performed by a band-pass filter at 1550 nm.

The onboard LCT would have the following technical parameters:

Aperture diameter:	135 mm
Transmit wavelength:	1550 nm
Transmit modulation:	16-PPM
Transmit data rate:	700 Mbps
Transmit power:	5 Watts
Receive beacon wavelength:	1550 nm
Mass with hemispherical pointing capability:	50 kg
Mass without hemispherical pointing capability:	30 kg
Power consumption:	90 Watts (max.)
Footprint:	60 x 60 cm

Due to the heritage from the in-orbit demonstrations onboard the TerraSAR-X and NFIRE satellite and the developments for EDRS, many individual LCT components have already reached a high TRL level:

- LCT structure, telescope and hemispherical pointing mechanism: TRL 8
- Seed laser, modulator and power amplifier: TRL 8

- High-speed tip/tilt tracking and point ahead mechanisms: TRL 9
- PPM modulation system: TRL 4
- Synchronous beacon tracking: TRL 7

3.5.3 Ground Terminal

The L2 Scenario ground segment was assumed to consist of three ground terminals

1. at the Izana Observatory at Teide on the Canary Island of Tenerife,
2. on Ascension Island,
3. at Hartebeesthoek (South Africa)

The analysis considered the use of a single station, as well as a combination of two sites, always including Tenerife (Tenerife + Ascension Island/Tenerife + Hartebeesthoek).

3.5.3.1 Ground Terminal Potential Implementation

For optical communications from L2, a 1 m class telescope (as indicated in the link budget) is deemed suitable. It is taken as the baseline in the following, although a “truly” deep space 8-10 m class optical ground station can of course also serve to communicate with an L2 mission, if available. The ground segment would thus consist of 1 m class telescopes in three different areas (as mentioned above). Laser communication from the Lagrange orbit L2 is the ideal scenario in terms of background radiation (noise), as operations are only performed at night.

The baseline optical ground terminal is based on the following concept, where the estimated TRLs are given in [brackets]—the latter really depending on the details of the implementation:

- All-reflective telescope with 1 m clear aperture with sufficient optical quality (need not be diffraction limited) with tip-tilt control of received beam. Adaptive optics, while beneficial, are not required. [TRL 9]
- Equatorial fork mount that can be traded off against altitude-azimuth or azimuth-azimuth mounts. The former’s advantage of having no image rotation is a non-issue for this application; however, its tracking singularity is at the pole (North or South, depending on the location’s hemisphere) rather than at the local zenith, which is still an advantage in favor of an equatorial mount, even if it is slightly more costly. [TRL 9]
- Telescope housing – preferably a calotte-type dome for best protection, and appropriate control (linked to, among others, the environmental monitoring system) [TRL 9]
- Optics coated to accommodate multiple wavelengths of interest, incorporating narrow-band spectral filtering against sky background and stray light, as well as uplink and receive beam separation. [TRL 7]
- 400 W laser beacon system at 1.5 µm [TRL 7]
- Incoherent beacon emission from 4-8 sub-apertures (as defined by the spider of the secondary mirror) of the main telescope. The individual transmit beacon beams are divergent to meet the pointing requirements towards L2. All transmit beams are intensity modulated in the kHz frequency range [TRL 7]

- Cryo-cooled (approx. 150 K) short-wave infrared (SWIR) HgCdTe avalanche photodiodes (APD) (small, few-pixel array) with future upgrade to single photon-counting detectors (e.g., super-conducting nano-wire technology) [TRL 3-5]
- Receiver signal-chain using M-ary PPM (M=2,4,16,32,…) (de-)modulation and appropriate decoding and DTN implementation [TRL 7]
- Environmental/weather monitoring system with spatially resolved real-time cloud cover forecast on short time scales (hours) [TRL 5]

Initial pointing, acquisition, and tracking is performed entirely in the optical domain relatively easily, given that satellites around L2 are Sun-illuminated and plainly visible with a 1 m class telescope and commercial high-performance CCD cameras. First, the (wide-enough) beacon is pointed to the acquired satellite position (with suitable point-ahead, if necessary, from flight dynamics data), followed by the acquisition of the downlink beam. Then, closed-loop tracking of the downlink beam can be performed using position information from the small communications receiver array.

3.5.4 CFLOS Analysis

The L2 Scenario was the first mission scenario analyzed by the OLSG, and the analysis methodology has evolved using the following specific assumptions:

1. Simulations considered only those opportunities (i.e., days) where there is a contiguous 3-hour period of CFLOS to downlink one day’s science data from the buffer. Thus, no partial credit is given (data is sent or lost in entire day increments), and each day without at least one *contiguous* 3-hour CFLOS window equals one day’s data loss. This situation corresponds to the most penalizing (and unrealistic) assumption.
2. Simulations considered the single largest contiguous period of CFLOS, even if it is less than 3 hours (however only with 1-hour granularity, since that is the temporal resolution of available cloud data). Partial credit is given if even a fraction (i.e., 1/3, 2/3 or all) of a day’s data can be downlinked within the corresponding CFLOS window (1, 2 or 3 hours wide). This situation also corresponds to a somewhat penalizing assumption, since only one window is considered, even if it is followed by another window after a short interruption (the hourly granularity poses a fundamental limitation in our simulations).
3. Simulations considered the aggregate hours of all available CFLOS windows in a day until all of the stored data could be downlinked. As an illustrative case, the entire buffer (after 3 consecutive days without a downlink possibility) could be downlinked completely if 9 hours of accumulated CFLOS (still only with hourly granularity, i.e., data downlinked in increments not smaller than 1/3 day) were available on the fourth day.

Note that while the optical data rate advantage is to be substantiated by realistic link budget calculations, the former does not enter into the CFLOS analysis as an absolute value. The analysis is sufficiently defined by the requirement that one day’s mission data can be downlinked in three hours.

Based on the L2 Scenario described above, LNOT was used to determine the PDT for several site configurations based on a six-year period from 2005-2010. The calculation method for

PDT accumulated the total CFLOS during each day, ensuring a minimum elevation angle of 20° was met to assess performance. Since the satellite has three days of onboard storage, the maximum performance for this scenario required at least nine hours of combined (between sites) CFLOS every three days. Since ground sites visible to L2 orbit are only visible at night, the PDT is expected to be quite high relative to daytime, when more clouds are typically observed. The overall PDT was computed for three locations, including the Tenerife OGS; Ascension Island; and Hartebeesthoek, S. Africa (see Figure 37 and Table 18 below). The Tenerife OGS has the best performance, since it is both very clear at night and it sits 2.3 km above mean sea-level. However, when combined with an additional site, the effects of geographic diversity become quite noticeable, increasing the PDT to greater than 99%. Using two sites in different hemispheres mitigates not only the weather, but also variability within the L2 orbit that produces different elevation angles throughout the mission.

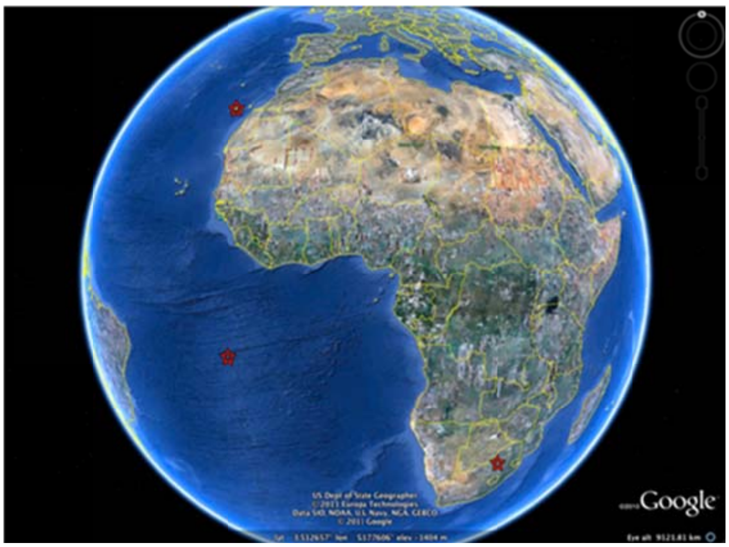


Figure 37: Location of ground sites in the L2 Scenario.

Table 18: PDT (%) for L2 Scenario over the 2005-2010 period.

Tenerife OGS	Ascension Is.	Hartebeesthoek	Tenerife OGS + Ascension Is.	Tenerife OGS + Hartebeesthoek
96.3%	89.6%	85.2%	99.8%	99.9%

Figure 38 shows the cumulative distribution of the monthly PDT for each site and the combinations of sites. For single sites, there is a small probability that the PDT for a given month could drop below 50%. However, when two sites are used, that probability is greatly reduced. In fact, the Tenerife OGS + Hartebeesthoek combination rarely produces a PDT less than 100%. The results of this scenario suggest there is a credible business case for interoperability between the space agencies.

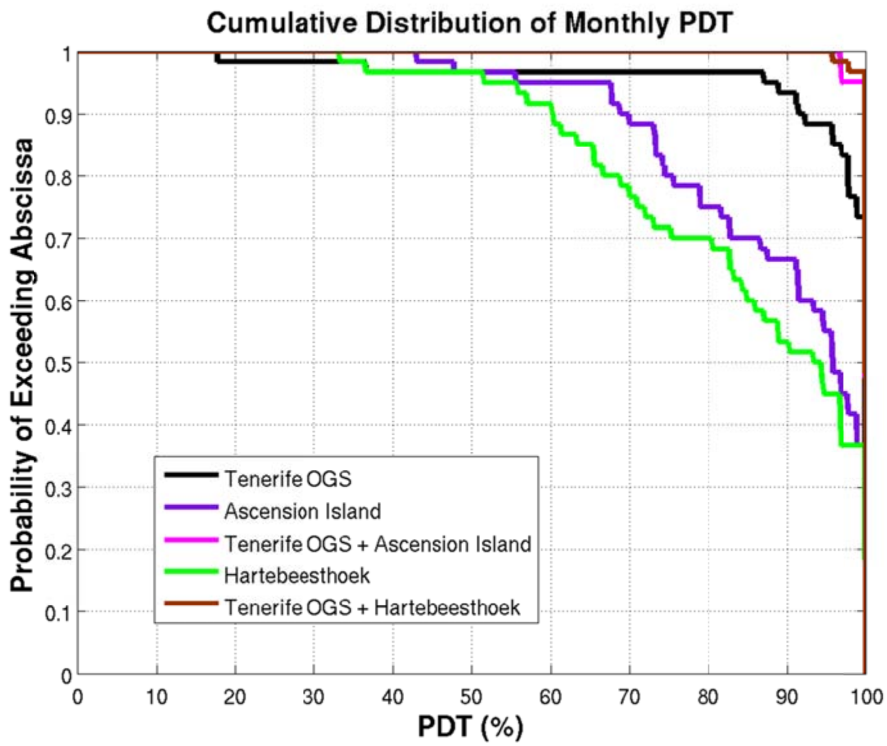


Figure 38: The cumulative distribution of the monthly PDT for the period 2005-2010 for the L2 Scenario.

3.5.5 Link Budget

3.5.5.1 Downlink Budget

For any orbit around L2, the SEP is always greater than 150 degrees, and therefore will never pose a problem. Figure 39 depicts a sample L2 downlink budget, which shows that a data rate of 700 Mbps is achievable with a 1 m telescope on the ground.

L2 DOWNLINK BUDGET

INPUT PARAMETERS

Slant Range	2.0E+06	km
Elevation	20	deg
TRANSMITTER		
Modulation Type	16-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	5.0	W
Tx Data Rate	700.0E+06	Hz
Tx Aperture Diam	0.135	m
Tx Angular Diam	3.02	arcsec
Tx Footprint Diam	2.92E+04	m
Tx Optical Transmission	35.0	%
Tx Depointing	0.20	arcsec
Uncoded Slot Rate	5.6E+09	s^{-1}
Uncoded Bits Per Word	2.00	
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-1.0	dB
RECEIVER		
Rx Aperture Diam	1.00	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	35.0	%
Rx Array Size	1	apertures
Required Photons / Pulse	3.33	
Code Rate	0.50	

LINK BUDGET

Tx Ave Power	**36.99**	**dBm**
Tx Photons / Pulse	1.11E+11	
Tx Antenna Gain	108.74	dBi
Tx Transmission Loss	-4.56	dB
Tx Pointing Loss	-0.08	dB
Isotropic Space Loss	-324.20	dB
Atmospheric Loss	-1.65	dB
Rx Antenna Gain	126.14	dBi
Array Gain	0.00	dB
Rx Transmission Loss	-4.56	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-100.16**	**dB**
Ave Power at Rx Detector	**-63.17**	**dBm**
Photons / Pulse at Rx Detector	**10.74**	
Required Photons / Pulse	3.33	
Link Margin	**5.09**	**dB**

Figure 39: Example downlink budget for the L2 Scenario

3.5.5.2 Uplink Budget

Figure 40 presents a sample uplink budget for the L2 scenario. The transmitter consists of eight 15 cm apertures, with an average power of 50 W each. The single apertures are assumed equal to the ones implemented in the ground terminal of the Lunar Scenario. In addition, the irradiance required at the receiver aperture is based on the acquisition procedure of LLCD.

L2 UPLINK BUDGET

INPUT PARAMETERS		
Slant Range	2.0E+06	km
Elevation	20	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	50.0	W
Tx Array Size	8	apertures
Tx Aperture Diam	0.15	m
Tx Angular Diam	2.71	arcsec
Tx Footprint Diam	2.63E+04	m
Tx Optical Transmission	45.0	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-1.5	dB
RECEIVER		
Rx Aperture Diam	0.14	m
Rx FOV	5.00	arcsec
Rx Depointing	0.20	arcsec
Rx Optical Transmission	35.0	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	63.0E-09	W/m^2

LINK BUDGET		
Tx Ave Power	**46.99**	**dBm**
Tx Antenna Gain	109.66	dBi
Tx Array Gain	9.03	dBi
Tx Transmission Loss	-3.47	dB
Tx Pointing Loss	-1.56	dB
EIRP	**130.65**	**dBW**
Isotropic Space Loss	-324.20	dB
Atmospheric Loss	-2.15	dB
Irradiance at rx aperture	**141.1E-09**	**W/m^2**
Rx Antenna Gain	108.74	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-4.56	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-108.50**	**dB**
Ave Power at Rx Detector	**-61.51**	**dBm**
Req. Irradiance at rx aperture	63.0E-09	W/m^2
Link Margin (Irradiance)	**3.50**	**dB**

Figure 40: Example uplink budget for the L2 Scenario.

3.5.6 Ground Station Cost

Table 19 provides a cost estimation of the optical ground stations for the L2 Scenario.

Table 19: Ground station costs for the L2 Scenario (k€).

L2 Scenario Ground Station Costs in k€	Tenerife	Hartebeest-hoek	Total
Initial Station Investment Costs:			
Terminal (telescope, dome, and electronics)	5,452	5,452	
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	1,560	393	
Wide Area Communication Investment Costs (ground comm)	0	1242	
Weather and Atmospheric monitoring	250	250	
Aviation Safety System	350	350	
Subtotal Initial Station Investment Costs	**7,612**	**7,687**	**15,299**
Recurring Operating Costs:			
Site and Terminal Operating Costs	1,168	1,168	
Communication Operating Costs	390	390	
Subtotal Recurring Operating Costs	***1,558***	***1,558***	***3,116***

3.5.7 Business Case

Analysis of the L2 Scenario indicates that cross support would be beneficial 1) because of the need to maximize contact time via geographical diversity so that continuity of data is maintained, and 2) to enable use of meteorologically diverse ground stations.

3.6 *L1 Scenario*

The L1 case study used the orbit of the existing Solar and Heliospheric Observatory (SOHO) mission, along with the operations concept inspired by Euclid's "burst-mode" downlink model (again, this concept resembles what is deemed well adapted for optical downlink of science data).

In contrast to L2, communications to L1 imply daytime operations, inferring cloudier conditions than at night. In addition, the angular separation of the LOS from the Sun (SEP angle) must also be considered (by signal-to-noise ratio [SNR] considerations in the link budget).

3.6.1 Concept of Operations

3.6.1.1 Basic ConOps

The same underlying assumptions were made as in the L2 Scenario – see section 3.5.1.1

3.6.1.2 Scenario ConOps

The same methodologies were applied as in the L2 Scenario – see section 3.5.1.2.

3.6.2 Space Terminal

The L1 space terminal will be very similar to that of the L2 Scenario (see section 3.5.2); however, the SPE constraints do not apply. This factor is taken into account in the associated link budget.

3.6.2.1 Space Terminal Potential Implementation

The space terminal for L1 is similar to that for the L2 scenario (see section 3.5.2.1).

3.6.3 Ground Terminal

As for the L2 Scenario, the ground segment was assumed to consist of three ground terminals:

a) at the Izana Observatory at Teide on the Canary Island of Tenerife
b) on Ascension Island
c) at Hartebeesthoek (South Africa)

The performance analysis considered the use of a single station, as well as a combination of two sites, always including Tenerife (Tenerife + Ascension Island/Tenerife + Hartebeesthoek).

3.6.3.1 Ground Terminal Potential Implementation

As for the L2 case, use of a 1 m class optical ground station is foreseen. The L1 baseline implementation is virtually identical to that for L2, however, major additional considerations emanate from operations at small SEP angles:

- A carefully designed baffle-system and a closely matched dome (calotte-type has a clear advantage over other designs)
- A heat transport and management system for the telescope tube (baffles in particular), as well as suitable air-conditioning system for the telescope housing inside the dome
- Optics with carefully designed (reflective) spectral filtering as early as possible in the optical path—ideally at the telescope entrance pupil. The latter is rather difficult and costly given the aperture size. Instead, a corresponding coating of the dome window of a fully encapsulated calotte dome is foreseen as a “first stage” filter.

The above issues clearly do not favor the use of unnecessarily large “deep space” ground terminals for L1, where the associated difficulties steeply increase with telescope aperture.

Given that our application does not call for high-resolution imaging, thermal effects on optical quality (such as telescope seeing, thermal gradients, etc.) are relaxed as compared to those for scientific solar telescopes. The mere fact that the latter exist with apertures well exceeding 1 m (the largest in Europe being the 1m Swedish Solar Telescope at Roque de los Muchachos on the Canary Island of La Palma) provides proof of existing solutions to all issues listed above.

3.6.4 CFLOS Analysis

The L1 Scenario is very similar to that of the L2 described above, except that communications only occur when the probe is in the daytime sky. LNOT was again used to compute the PDT for the same sites. Table 20 shows the results of this scenario. PDT ranges from approximately 80% at Ascension Island, to over 92% at the Tenerife OGS. These results are somewhat lower than for the L2 Scenario due to the increased frequency of disruptive clouds during daytime. The combinations of the Tenerife OGS with Ascension Island or

Hartebeesthoek, however, mitigate the impacts of clouds at any one location and thus produce PDT values near 99%.

Table 20: PDT (%) for L1 Scenario over the 2005-2010 period.

Tenerife OGS	Ascension Is.	Hartebeesthoek	Tenerife OGS + Ascension Is.	Tenerife OGS + Hartebeesthoek
92.2%	79.9%	85.2%	98.9%	98.5%

The cumulative distributions of the monthly PDT are shown in Figure 41. The results are similar to those for L2; however, the monthly values of PDT are slightly lower due to the increase in cloud cover observed at these sites during daytime.

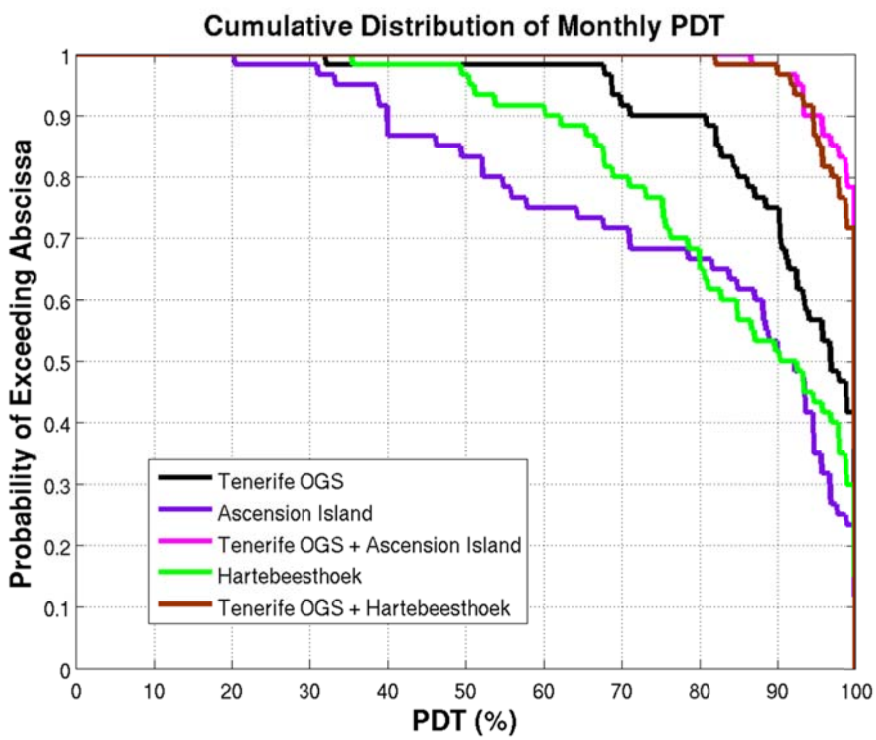


Figure 41: Cumulative distributions of the monthly PDT for the L1 Scenario.

3.6.5 Link Budget

3.6.5.1 Downlink Budget

As mentioned above, the major challenging difference between the L1 scenario and the L2 scenario is that daytime operations are necessary for L1, and the corresponding SEP angle must be taken into account. In addition, daytime operations imply cloudier conditions. Figure 42 shows the downlink budget for the L1 scenario. The differences between the L1 and L2 scenarios have been taken into account in the calculation by increasing the scintillation loss by 1.5 dB with respect to the L2 scenario.

L1 DOWNLINK BUDGET

INPUT PARAMETERS		
Slant Range	2.00E+06	km
Elevation	20	deg
TRANSMITTER		
Modulation Type	16-PPM	
Tx Wavelength	1.55	μm
Tx Ave Power	5.0	W
Tx Data Rate	700.0E+06	Hz
Tx Aperture Diam	0.135	m
Tx Angular Diam	3.02	arcsec
Tx Footprint Diam	2.92E+04	m
Tx Optical Transmission	35.0	%
Tx Depointing	0.20	arcsec
Uncoded Slot Rate	5.6E+09	s^{-1}
Uncoded Bits Per Word	2.00	
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-2.5	dB
RECEIVER		
Rx Aperture Diam	1.00	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	35.0	%
Rx Array Size	1	apertures
Required Photons / Pulse	3.33	
Code Rate	0.50	

LINK BUDGET		
Tx Ave Power	**36.99**	**dBm**
Tx Photons / Pulse	1.11E+11	
Tx Antenna Gain	108.74	dBi
Tx Transmission Loss	-4.56	dB
Tx Pointing Loss	-0.08	dB
Isotropic Space Loss	-324.20	dB
Atmospheric Loss	-3.15	dB
Rx Antenna Gain	126.14	dBi
Array Gain	0.00	dB
Rx Transmission Loss	-4.56	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-101.66**	**dB**
Ave Power at Rx Detector	**-64.67**	**dBm**
Photons / Pulse at Rx Detector	**7.61**	
Required Photons / Pulse	3.33	
Link Margin	**3.59**	**dB**

Figure 42: Example downlink budget for the L1 Scenario.

3.6.5.2 Uplink Budget

Figure 43 presents a sample uplink budget for the L1 scenario. Similarly to the L2 case, the transmitter consists of eight 15 cm apertures, equal to the ones implemented in the ground terminal of the Lunar Scenario, and the required irradiance at the receiver is based on the acquisition procedure of LLCD. Due to daytime operations and the consequent increase of the scintillation loss, the average transmitted power per aperture is 70 W instead of 50W, as in the L2 case.

L1 UPLINK BUDGET

INPUT PARAMETERS		
Slant Range	2.0E+06	km
Elevation	20	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	70.0	W
Tx Array Size	8	apertures
Tx Aperture Diam	0.15	m
Tx Angular Diam	2.71	arcsec
Tx Footprint Diam	2.63E+04	m
Tx Optical Transmission	45.0	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-3.0	dB
RECEIVER		
Rx Aperture Diam	0.14	m
Rx FOV	5.00	arcsec
Rx Depointing	0.20	arcsec
Rx Optical Transmission	35.0	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	63.0E-09	W/m^2

LINK BUDGET		
Tx Ave Power	**48.45**	**dBm**
Tx Antenna Gain	109.66	dBi
Tx Array Gain	9.03	dBi
Tx Transmission Loss	-3.47	dB
Tx Pointing Loss	-1.56	dB
EIRP	**132.12**	**dBW**
Isotropic Space Loss	-324.20	dB
Atmospheric Loss	-3.65	dB
Irradiance at rx aperture	**1.40E-07**	**W/m^2**
Rx Antenna Gain	108.74	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-4.56	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-110.00**	**dB**
Ave Power at Rx Detector	**-61.54**	**dBm**
Req. Irradiance at rx aperture	63.0E-09	W/m^2
Link Margin (Irradiance)	**3.46**	**dB**

Figure 43: Example uplink budget for the L1 Scenario.

3.6.6 Ground Station Cost

Table 21 provides a cost estimation of the optical ground stations for the L1 Scenario.

Table 21: Ground station costs for the L1 Scenario (k€).

L1 Scenario Ground Station Costs in k€	Tenerife	Hartebeest-hoek	Total
Initial Station Investment Costs:			
Terminal (telescope, dome, and electronics)	6,230	6,230	
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	1,560	393	
Wide Area Communication Investment Costs (ground comm)	0	1242	
Weather and Atmospheric monitoring	250	250	
Aviation Safety System	350	350	
Subtotal Initial Station Investment Costs	**8,390**	**8,465**	**16,855**
Recurring Operating Costs:			
Site and Terminal Operating Costs	1,168	1,168	
Communication Operating Costs	390	390	
Subtotal Recurring Operating Costs	**1,558**	**1,558**	**3,116**

3.6.7 Business Case

Analysis of the L1 Scenario indicates that cross support would be beneficial, because of the need to maximize contact time via geographical diversity to maintain continuity of data, and the desire to use meteorologically diverse ground stations.

3.7 Deep Space Scenario

3.7.1 Concept of Operations

3.7.1.1 Basic Concept of Operations

Deep space in this context refers to distances beyond the Sun-Earth L2 point, or approximately 1.5 million kilometers from Earth. These distances are large enough that they are generally measured in Astronomical Units (AU ~150 million kilometers). Destinations in deep space include the solar system's planets and their moons, asteroids, comets, and other such bodies, as well as anything beyond the solar system. Applications of optical communication in deep space are data return from robotic science missions, communication and navigation relays, and human exploration.

Two important characteristics of deep space scenarios are

- Large and varying distances and the resulting long round-trip times
- Varying angles between the Sun and probe as seen from the spacecraft (SPE Angle) and between the Sun and spacecraft as seen from Earth (SEP angle)

The above characteristics are both functions of the celestial dynamics of the destination body relative to Earth. The variation in Mars range over the July 29, 2018 to October 29, 2020 period is 0.39 AU (58.5 million km) to 2.7 AU (405 million km), as shown in Figure 44, with commensurate round trip time delays of 6.5 minutes and 45 minutes. Note that this scenario also implies a point-ahead angle of up to 400 microradians. The SPE angle varies from slightly less than one degree to almost 47 degrees, while the SEP varies from approximately one degree to 177 degrees.

Because of the large distances involved in deep space scenarios (and hence weak signals), photon counting detectors are required on both ends of the link for the most efficient operation.

The example to be used here is that of a Mars orbiter using NASA's Deep space Optical Terminals (DOT)—which consists of a 22-cm diameter, 4-W average output power, optical terminal on the orbiter; and a 12-meter diameter receiving telescope and a 1-m transmit telescope on Earth as described later in this section.

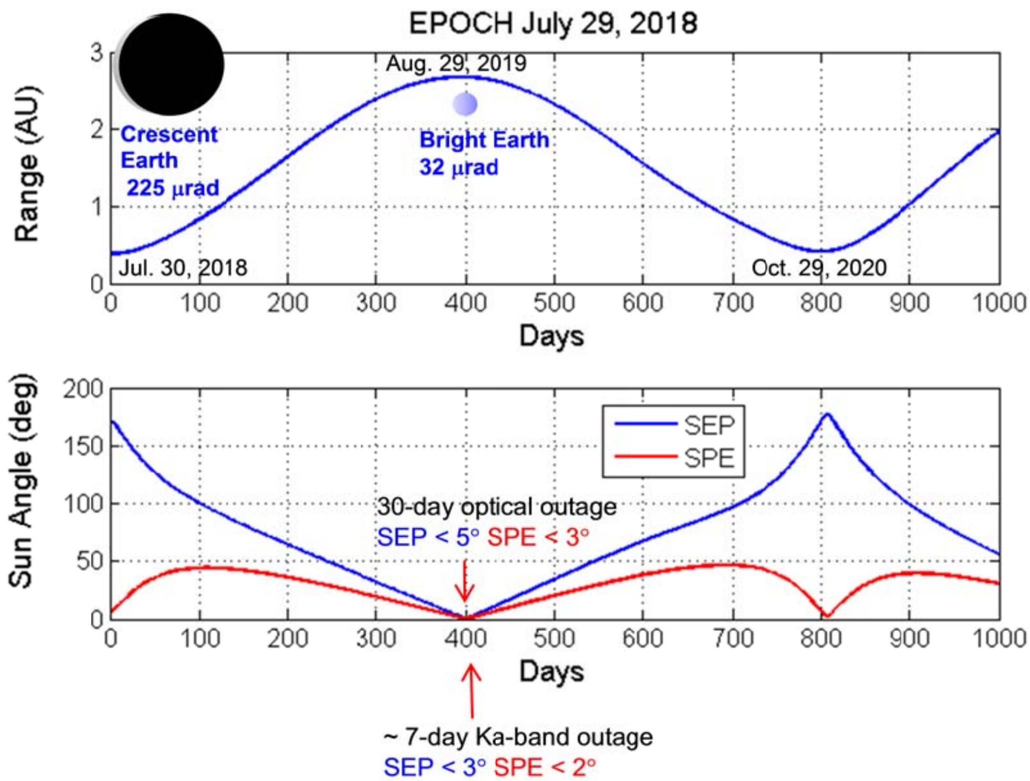


Figure 44: Range and Sun angle variations for Mars.

As previously described, optical communication is used primarily for high-rate data downlinking. At ranges up to about 10 AU (equivalent Saturn distance) there will be an uplink for PAT in the space terminal, with the potential added feature of uplinking data and performing ranging—potentially in conjunction with the downlink—but not spacecraft commanding. Beyond 10 AU, alternative PAT methods not requiring an uplink will need to be developed.

The basic deep space ConOps assumes that the spacecraft has onboard storage for the science and other data to be downlinked to Earth. A primary pass (space-Earth link) has been scheduled ahead of time via an RF link for a specific ground station. Link budgets have been developed to determine the data rate based upon knowledge of the space and ground terminal characteristics and weather/atmospheric conditions assumed for the time of operation. At closest range, the assumption is that the entire data storage is emptied in one pass. As the range increases, and hence the data rate decreases, the data volume will be scaled proportionally. If there is geometric line-of-sight, CFLOS, and the assumptions about the weather and atmosphere are within specification for the entire pass, then the data is downlinked successfully. If not, then some or all of the data must be scheduled for downlinking at another Earth station. It is assumed that there will be enough ground stations so that if geometric and CFLOS conditions are met, the data will be downlinked within the required time, e.g., 24 hours.

3.7.1.2 Scenario ConOps

Under the assumption of sufficient conditions for establishing a link, the ConOps for this scenario is as follows. The ground transmit station blind points to the location of the spacecraft and transmits an uplink beacon. The spacecraft blind points to the location for the ground terminal. The spacecraft may be required to perform a spatial scan to find the uplink, but this action must not consume much of the pass time. Once the spacecraft acquires the uplink, it begins transmitting the downlink, and processing the uplink data and ranging if those functions are included. If the spacecraft detects a loss of uplink, it will attempt to flywheel through this loss for a short time; otherwise, it will initiate reacquisition. On the ground—where much more information is known about the weather and atmospheric conditions—if the signal is lost, the receiver will either wait for signal reacquisition or operations will be terminated.

Since optical links are affected by the amount of atmosphere through which they pass, the elevation angle at the receiving station is an important consideration in the ConOps. For this particular deep space scenario, Figure 45 shows the complementary nature of reception at the Goldstone Deep Space Communications Complex (GDSCC) and an assumed receive station at Alice Springs (AS), Australia over approximately one-half the epoch considered. Note that the second half of the epoch will be approximately the mirror image of Figure 45.

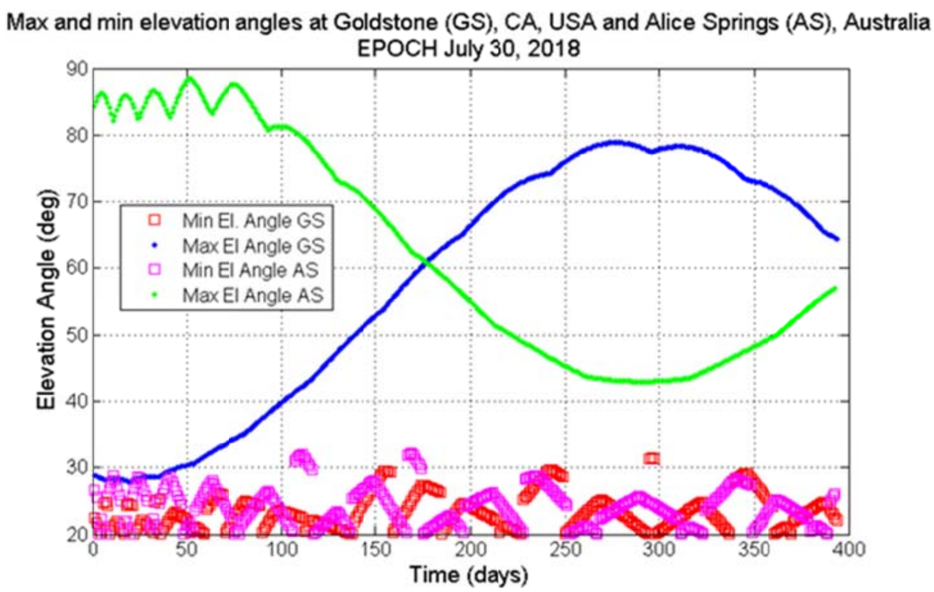


Figure 45: Elevation angles of a Mars-orbiting spacecraft relative to GDSCC and Alice Springs.

Figure 46 also shows the contact times at GDSCC and Alice Springs, strictly based upon geometric line of sight and for elevation angles above 20 degrees—which is always considered the minimum elevation angle for operations.

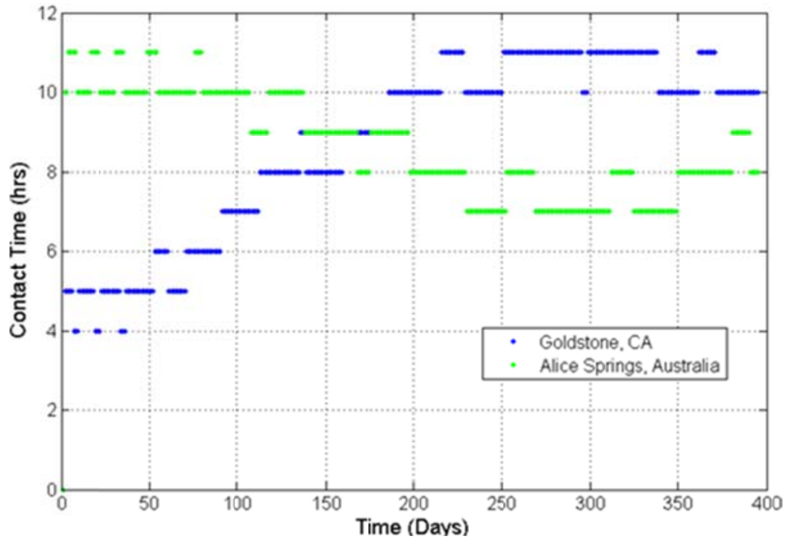


Figure 46: Contact times at GDSCC and Alice Springs.

The importance of a good geographically diverse cross support is shown Figure 47 by the addition of stations in Teide (T), Canary Islands and La Silla (LS), Chile. On July 30, 2018, the maximum elevations at GDSCC and Teide are relatively low (<40 degrees), whereas at Alice Springs and La Silla, the maximum elevations are very high (>80 degrees). On August 30, 2019, none of the elevation angles get above 70 degrees but there is good support from all four stations.

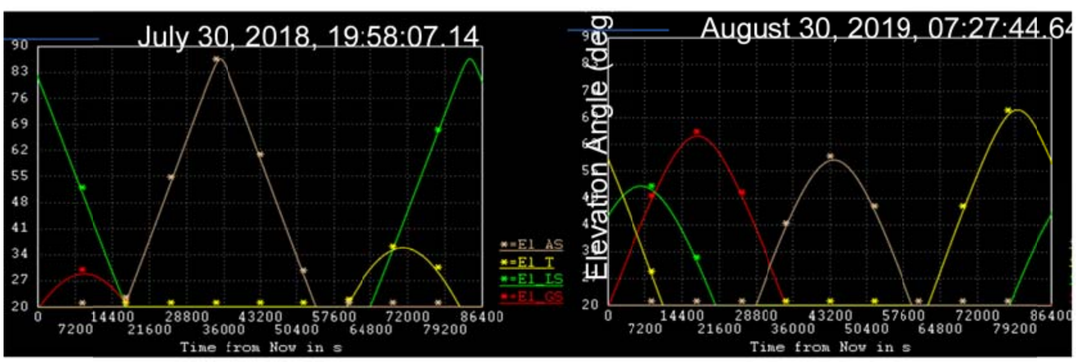


Figure 47: Elevation angles to four potential receive stations.

The link budgets (see Section 3.7.5 below) for the potential implementation (see sections 3.7.2.1 and 3.7.3.1 below) were computed for every view period in the July 2018-October 2020 interval at the GDSCC. Since this is a statistical phenomenon, the 90th percentile and 50th percentiles are shown for optical—assuming perfect CFLOS. Figure 48 shows the data rate versus distance for GDSCC. The performance of NASA's Mars Reconnaissance Orbiter (MRO) Ka-band telecom system with 90% weather and a 34 m receive antenna is also shown for comparison. Considering the data rate and the duration of each pass, the data volume delivered during each pass can also be computed, as shown in Figure 49. If the 66% average CFLOS at GDSCC is taken into account, the integrated data volume returned over the entire period is 2.5×10^5 to 3.3×10^5 Gbits versus 3.8×10^4 Gbits for the MRO Ka-band system. Note that the portion of Figure 49 for which the SEP angle is small is shown in Figure 50. Figure 50 shows the time when the optical communications system is not downlinking because the SEP is less than 5 degrees, while the Ka-band is still downlinking down to an SEP of 1 degree. The data volume difference due to this longer optical communication outage is small, given that it occurs at the farthest range with the lowest data rates. When the results of a CFLOS analysis are considered and multiple receive stations are incorporated, as discussed above, this data return can be increased substantially.

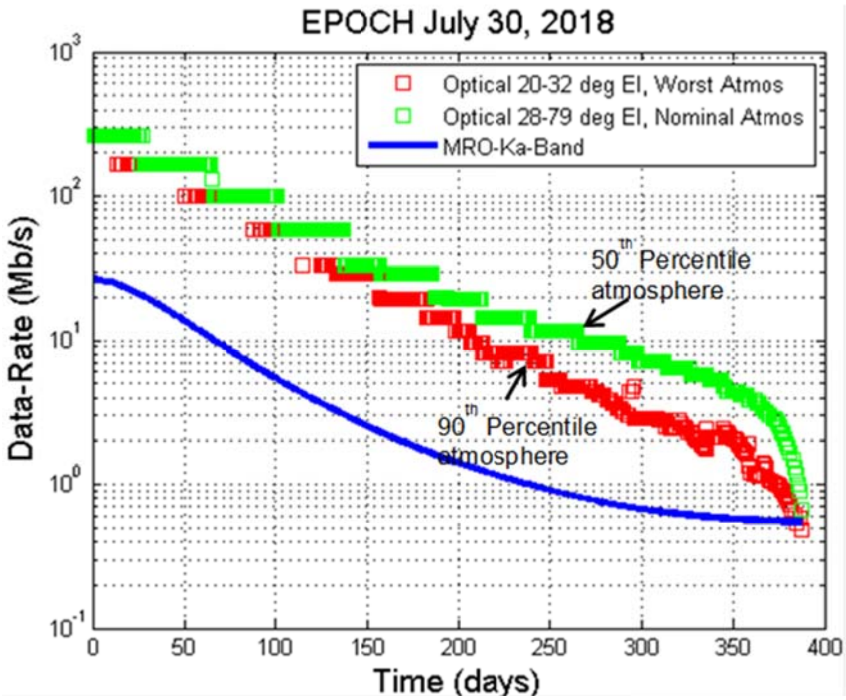


Figure 48: Data rate vs. distance at GDSCC.

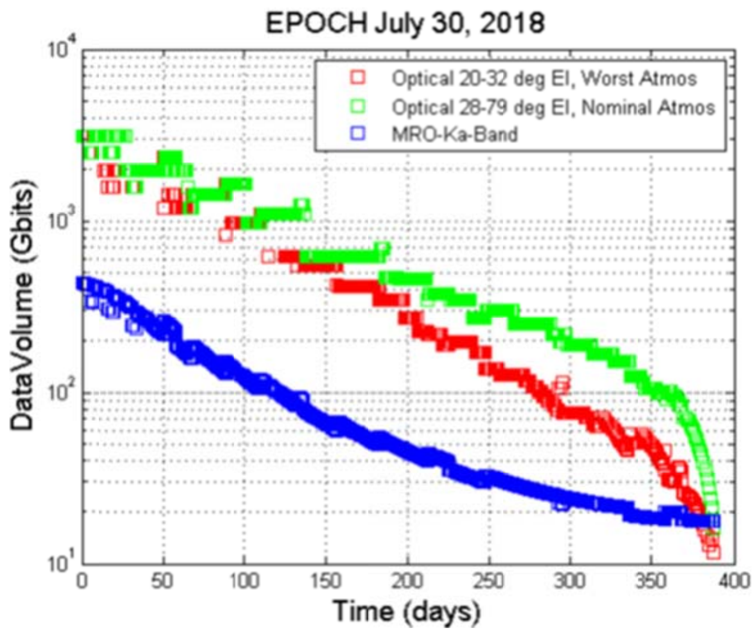


Figure 49: Data volume versus distance for GDSCC.

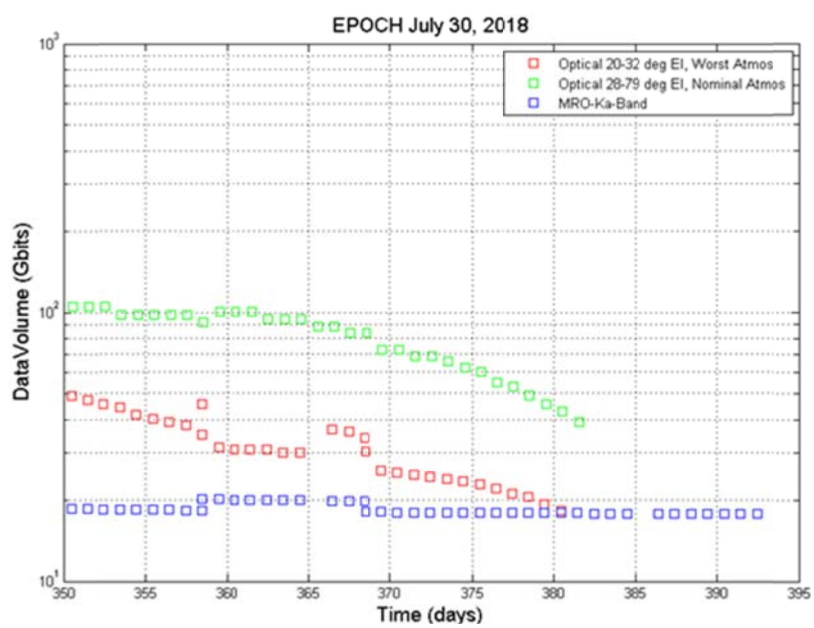


Figure 50: Data volume versus distance for GDSCC detail for low SEP days.

Note that the same analysis was done for Alice Springs, which has a much higher maximum elevation and longer passes at the closest ranges, and there is a dramatic increase in the data volume in early days—see Figure 51 and Figure 52.

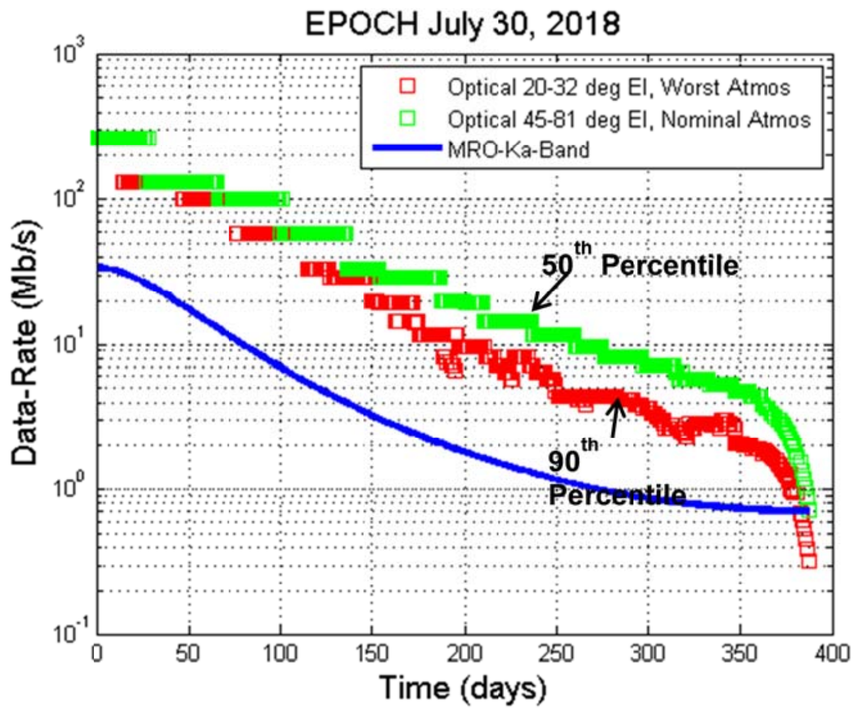


Figure 51: Data rate versus distance for Alice Springs.

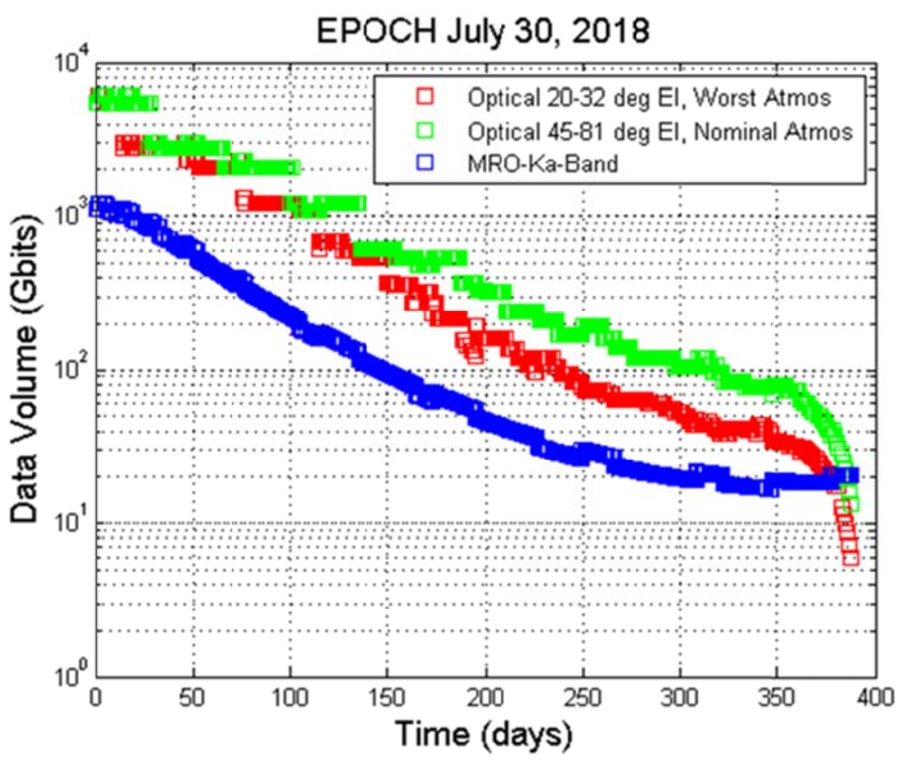


Figure 52: Data volume versus distance for Alice Springs.

Table 22 summarizes the ConOps parameters used for the Deep Space Scenario analysis.

Table 22: Deep Space Scenario Concept of Operations Parameters

Deep Space Scenario			
Onboard Data Collection Rate	**Onboard Storage Capacity**	**Hours of CFLOS Required per Day**	**Data Rate used for Link Budget**
Up to 1.1 Tb/day	1.1 Tb	Varies as a function of distance and data rate	Varies between 0.764 Mbps and 260 Mbps (data rate varies with distance)

3.7.2 Space Terminal

The space terminal must provide the functions described in the deep space ConOps. The optical communication space terminal consists of an optical head, which contains the basic optics and uplink detector—potentially photon counting; a vibration isolation platform to isolate the optical head from the spacecraft or a high performance inertial reference unit; and an electro-optics box that includes lasers, laser amplifiers, encoder and modulator, demodulator and decoder, data formatter, processors, power converters, and spacecraft electrical and thermal interfaces. This hardware implements both uplink and downlink functions.

3.7.2.1 Space Terminal Potential Implementation

The DOT space terminal (see Figure 53) consists of a 22 cm off-axis Gregorian telescope with optics to direct the uplink signal onto the photon counting detector. The uplink signal is then processed in the opto-electronics box for four functions: platform/downlink stabilization; data synchronization, demodulation and decoding and deframing; ranging; and spacecraft interface. The opto-electronics box performs three functions for the downlink: spacecraft interface; downlink signal encoding framing and modulation onto the amplified laser signal; and point-ahead signal for the fast steering mirror in the optical head. For this implementation the downlink signal is a serially-concatenated PPM that uses orders between 16 and 128. The 1550 nm laser amplifier has 4 W average output power. Coarse pointing (~3 mrad) is presumed to be provided by the spacecraft, while precision pointing is provided by the flight terminal. It should be noted that this terminal was specifically designed to require no more mass and power than the MRO Ka-band telecom system. If one allows higher power or a larger mass for the RF system, then the optical power and mass would also increase and, to first order, the data return results above would scale accordingly. It is also assumed that there is 1.1 Tb of data storage onboard—10 times larger than current MRO capability, though this is ultimately a mass-power-cost trade that would be made for any new mission.

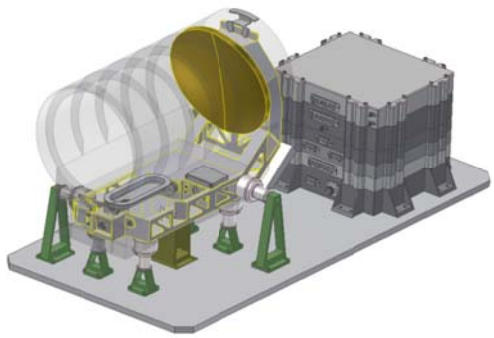


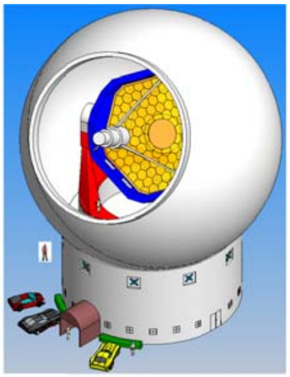
Figure 53: 22 cm DOT Flight Terminal with Vibration Isolation and Opto-Electronics Box.

3.7.3 Ground Terminal

The ground terminal must provide the functions described in the deep space ConOps. The ground terminal performs transmit and receive functions for data and ranging, makes weather and atmospheric measurements, and provides interfaces to a ground communications system (WAN, etc.) and the mission operations function. The transmit and receive functions can be provided by separate stations, though they must be in close proximity and certainly within the downlink beam. In general, the ground terminal must operate during daytime, as well as nighttime, and hence must be able to point close to the Sun. In some cases, it may be possible to use existing large astronomical telescopes for nighttime operations or scenarios not requiring pointing close to the Sun.

3.7.3.1 Ground Terminal Potential Implementation

The DOT ground terminal consists of a 12 m diameter segmented spherical primary mirror receive telescope (see Figure 54) and a 1 m diameter transmit telescope (see Figure 55). The 12 m receive telescope blind points to 50 μrad prior to acquisition and 10 μrad after acquisition, and can operate down to a SEP of 5 degrees. It includes optics to focus the signal on the photon counting detector, and the detected signal is then passed to the demodulator, synchronizer, decoder and data deframing system. The transmit station blind points to 16 μrad (3σ) and operates down to an SEP of 5 degrees. It will generate 2 to 5 kW of multi-beam optical uplink power at 1550 nm and provides data and ranging signals on the uplink. Per the discussion above about comparable spacecraft resources for the flight terminal: a 12 m ground receiver is, to first order, equivalent to a 34 m RF antenna in cost. If one allows larger RF antennas or multiple antennas arrayed for data return comparison, then the optical aperture and the data return results above would also be scaled accordingly.



New 12-m Telescope

Figure 54: 12 m segmented spherical primary receive telescope.

Figure 55: 1 m Transmit Telescope (OCTL).

3.7.4 CFLOS Analysis

LNOT was used to determine the performance of a representative deep space scenario using the specifications described above for the period 2005-2010. This period of time represents approximately three Mars orbits around the Sun. This analysis provides a good representation of the performance that might be expected. The Deep Space Scenario differs from the other scenarios (e.g., L1 and L2) in that the distance of the satellite from Earth varies considerably through time. This factor impacts the data rate, since the data rate is proportional to $1/r^2$, where r indicates the range of the satellite to Earth. As stated in the Basic ConOps section, the Deep Space Scenario is designed such that the entire data storage from a Mars orbiter can be emptied in one pass. Specifically, at its closest range of 0.42 AU, the amount of data collected per day is 1.1 Tb, and the data rate is assumed to be 260 Mb/s. Using these specifications, an entire day's data can be transmitted in 73 minutes, or in just over one hour. As the range increases, and hence the data rate decreases, the daily data volume is scaled proportionately, so that an entire day's data can always be transmitted in 73 minutes, no matter the range. This assumption allows the computation of PDT to be independent of the range of the Mars orbiter.

As in all space-to-ground optical systems, the performance is a function of many factors, and the trade space may be vast. The analysis in this section demonstrates the impacts of the main performance driver—the number of ground stations. Increasing the number of ground stations improves the probability of having a cloud-free site at any given time, while also providing sites around the globe to ensure geometric line-of-sight from at least one site to the satellite at all times. The nine example candidate ground sites for the Deep Space Scenario are displayed on a map in Figure 56. They include four NASA sites (Table Mountain

Facility, Haleakala, Canberra DSN ground station, and Madrid DSN ground station), four ESA sites (the Tenerife OGS, Hartebeesthoek in South Africa, New Norcia in Australia, and a site in Chile), and one JAXA site in Japan. Using the six years of cloud data and the position of the satellite, LNOT dynamically tracks the data collected (in Gb), the data stored onboard the satellite, and the data sent to the ground at hourly resolution. At each hour, LNOT determines whether there is at least a 20° elevation angle to the satellite and whether there is CFLOS from the satellite to any ground station. If there is, data is sent to Earth at the specified data rate, and the onboard data buffer is reduced by the amount of data sent. If no site has CFLOS to the satellite, the amount of data in the buffer is increased. If the buffer is full, the oldest data is purged, and the amount of data lost is recorded. The PDT is computed at the end of the simulation as the amount of data successfully sent to the ground divided by the total amount of data collected by the satellite.

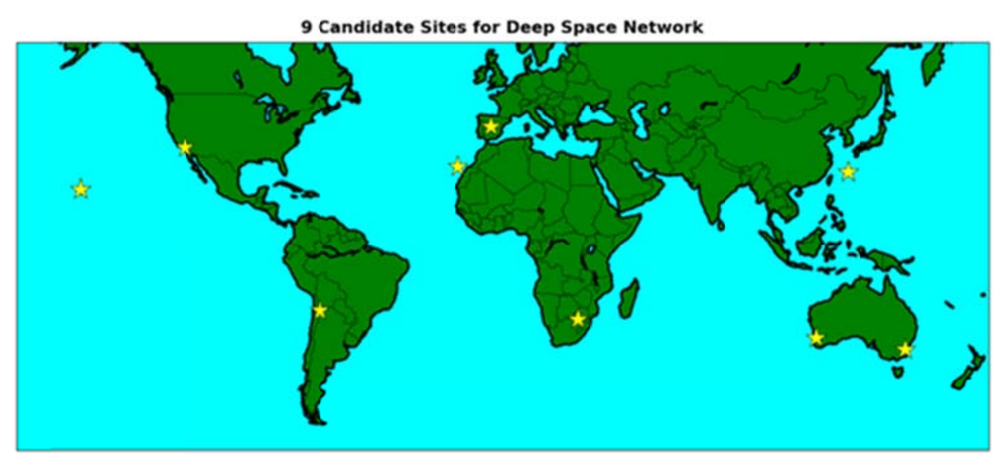


Figure 56: Candidate ground stations used for the Deep Space Scenario.

In this analysis, the PDT is calculated for ground station networks of 1 – 9 sites. Each particular combination of ground stations is chosen to maximize its global coverage (longitudinal diversity). For example, the 3-site network is comprised of Haleakala (156.3 West Longitude), Tenerife OGS (16.5 West), and New Norcia (116.1 East). Figure 57 shows the PDT of each network size. The result accounts for the variable data rate and data volume, since the scenario is defined such that one day's data is sent in one hour (by proportionately scaling both the data rate and data volume with range). For this scenario, a single site (Tenerife) provides a PDT of greater than 90%. This large PDT is possible because it only takes about 1 hour to transmit an entire day's data. Since a single site is visible to Mars for 8-12 hours per day, there is a high likelihood of having at least one hour of CFLOS on 90% of days for a ground station with good cloud-free statistics. When a second site is combined with the first site, such that the two sites provide longitudinal as well as cloud diversity, the PDT is increased to near 99%. Three or more sites produce values of PDT of well above 99%.

By reducing the data volume proportionately with the data rate, the data requirements are easily met with three sites.

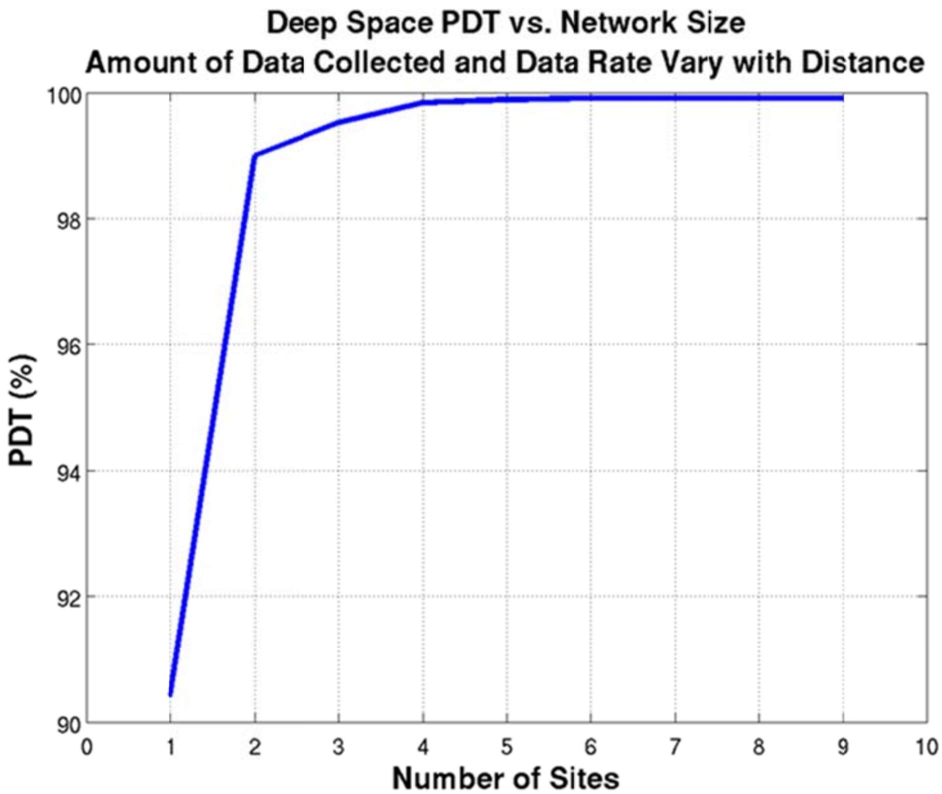


Figure 57: Overall PDT for the Deep Space Scenario for 1-9 site networks of ground stations for six different data rates.

At closest range, the assumption is that the entire data storage is emptied in one pass. As the range increases, and hence the data rate decreases, the data volume will be scaled proportionally. If there is geometric line-of-sight, and CFLOS, and the assumptions about the weather and atmosphere are within specification for the entire pass, then the data is downlinked successfully. If not, then some or all of the data must be scheduled for downlinking at another Earth station. It is assumed that there will be enough ground stations that under geometric and CFLOS conditions, the data will be downlinked within the required time, e.g., 24 hours.

3.7.5 Link Budget

The CFLOS analysis of the previous section indicates geometric and CFLOS conditions. In assessing link quality, the characteristics of the flight and ground systems, as well as atmospheric conditions, must be taken into account.

Moreover, the distance between Earth and Mars varies between roughly 69 million kilometers at opposition and about 400 million kilometers at conjunction. Since Mars is one of the outer planets, it is visible in the night sky when it is at opposition, and during the day when it is at conjunction, as illustrated in Figure 58 below. At opposition Mars is in the night sky and can come as close as 69 million kilometers to the Earth. At conjunction Mars appears in the daytime sky at a maximum distance of 400 million kilometers.

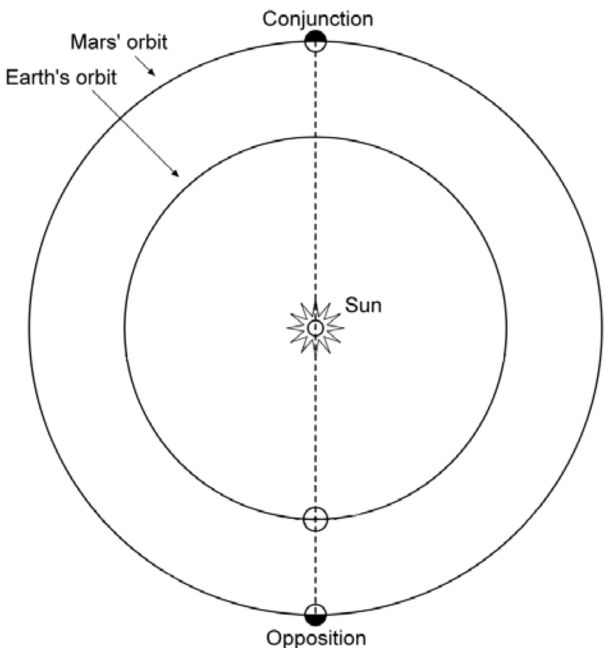


Figure 58: Schematic of the orbits of Earth and Mars.

It is assumed that the same communication terminals will be used during an entire Mars mission, during which typically Mars will pass through conjunction and opposition several times. Since that means that wavelength, bandwidth, and power are fixed, the maximum data rate and order of the PPM modulation will need to be adjusted to close the link at the best possible data rate in all phases of the mission.

3.7.5.1 Downlink Budget

Below are sample link budgets for a near-range (around opposition, see Figure 59) and a far-range (around conjunction, see Figure 60) scenario. At far range, the space loss is more than 15 dB greater than at near range. For this reason, in the far-range link budget calculation a lower data rate is considered with a higher PPM modulation order. In addition, when Mars is near conjunction, the presence of copious amounts of solar stray light in the atmosphere during daytime communication opportunities increases the number of signal photons per pulse required to achieve an adequate signal-to-noise ratio for detection. In the calculation, this effect is not taken into account. However, the far-range budget shows a good margin, which could accommodate a 4.4 dB increase to mitigate this effect.

MARS (NEAR RANGE) DOWNLINK BUDGET

INPUT PARAMETERS

Slant Range	6.88E+07	km
Elevation	30	deg
TRANSMITTER		
Modulation Type	16-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	4.0	W
Tx Data Rate	260.0E+06	Hz
Tx Aperture Diam	0.22	m
Tx Angular Diam	1.85	arcsec
Tx Footprint Diam	6.17E+05	m
Tx Optical Transmission	30.3	%
Tx Depointing	0.10	arcsec
Uncoded Slot Rate	2.1E+09	s^{-1}
Uncoded Bits Per Word	2.00	
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-0.2	dB
RECEIVER		
Rx Aperture Diam	12.00	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	32.4	%
Rx Array Size	1	apertures
Required Photons / Pulse	1.89	
Code Rate	0.50	

LINK BUDGET

Tx Ave Power	**36.02**	**dBm**
Tx Photons / Pulse	2.40E+11	
Tx Antenna Gain	112.98	dBi
Tx Transmission Loss	-5.19	dB
Tx Pointing Loss	-0.05	dB
Isotropic Space Loss	-354.93	dB
Atmospheric Loss	-0.64	dB
Rx Antenna Gain	147.72	dBi
Array Gain	0.00	dB
Rx Transmission Loss	-4.89	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-105.00**	**dB**
Ave Power at Rx Detector	**-68.98**	**dBm**
Photons / Pulse at Rx Detector	**7.59**	
Required Photons / Pulse	1.89	
Link Margin	**6.05**	**dB**

Figure 59: Example downlink budget for a Mars (near-range) Deep Space scenario.

MARS (FAR RANGE) DOWNLINK BUDGET

INPUT PARAMETERS

Slant Range	4.00E+08	km
Elevation	30	deg
TRANSMITTER		
Modulation Type	128-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	4.0	W
Tx Data Rate	10.0E+06	Hz
Tx Aperture Diam	0.22	m
Tx Angular Diam	1.85	arcsec
Tx Footprint Diam	3.59E+06	m
Tx Optical Transmission	30.3	%
Tx Depointing	0.10	arcsec
Uncoded Slot Rate	365.7E+06	s^{-1}
Uncoded Bits Per Word	3.50	
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-0.2	dB
RECEIVER		
Rx Aperture Diam	12.00	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	32.4	%
Rx Array Size	1	apertures
Required Photons / Pulse	1.87	
Code Rate	0.50	

LINK BUDGET

Tx Ave Power	**36.02**	**dBm**
Tx Photons / Pulse	1.09E+13	
Tx Antenna Gain	112.98	dBi
Tx Transmission Loss	-5.19	dB
Tx Pointing Loss	-0.05	dB
Isotropic Space Loss	-370.22	dB
Atmospheric Loss	-0.64	dB
Rx Antenna Gain	147.72	dBi
Array Gain	0.00	dB
Rx Transmission Loss	-4.89	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-120.29**	**dB**
Ave Power at Rx Detector	**-84.27**	**dBm**
Photons / Pulse at Rx Detector	**10.22**	
Required Photons / Pulse	1.87	
Link Margin	**7.38**	**dB**

Figure 60: Example downlink budget for a Mars (far-range) Deep Space scenario.

3.7.5.2 Uplink Budget

Sample uplink beacon budgets for near-range and far-range Mars scenarios are reported in Figure 61 and Figure 62, respectively. The transmitter consists of nine 7 cm apertures, which provide a beam divergence of about 30 µrad (5.82 arcsec). The average power per aperture is 555.6 W, for a total transmitted power of 5 kW. In the calculation, the scintillation loss (or turbulence loss) is computed as Strehl ratio2 and accounts for spread loss and beam wandering, under the assumptions of a seeing of 2 arcsec (Fried parameter r_0 of 5 cm, at zenith, at a wavelength of 500 nm). The considered receiver implements a photon-counter array.

MARS (NEAR RANGE) UPLINK BUDGET

INPUT PARAMETERS		
Slant Range	68.82E+06	km
Elevation	30	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	555.6	W
Tx Array Size	9	apertures
Tx Aperture Diam	0.070	m
Tx Angular Diam	5.82	arcsec
Tx Footprint Diam	1.94E+06	m
Tx Optical Transmission	45.0	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-2.6	dB
RECEIVER		
Rx Aperture Diam	0.22	m
Rx FOV	5.00	arcsec
Rx Depointing	0.10	arcsec
Rx Optical Transmission	30.3	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	4.9E-12	W/m^2

LINK BUDGET		
Tx Ave Power	**57.45**	**dBm**
Tx Antenna Gain	103.04	dBi
Tx Array Gain	9.54	dBi
Tx Transmission Loss	-3.47	dB
Tx Pointing Loss	-0.33	dB
EIRP	**136.23**	**dBW**
Isotropic Space Loss	-354.93	dB
Atmospheric Loss	-3.05	dB
Irradiance at rx aperture	**3.49E-10**	**W/m^2**
Rx Antenna Gain	112.98	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-5.19	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-141.40**	**dB**
Ave Power at Rx Detector	**-83.95**	**dBm**
Req. Irradiance at rx aperture	4.9E-12	W/m^2
Link Margin (Irradiance)	**18.53**	**dB**

Figure 61: Example uplink budget for a Mars (near-range) Deep Space scenario.

MARS (FAR RANGE) UPLINK BUDGET

INPUT PARAMETERS		
Slant Range	400.0E+06	km
Elevation	30	deg
TRANSMITTER		
Tx Wavelength	1.55	μm
Tx Ave Power	555.6	W
Tx Array Size	9	apertures
Tx Aperture Diam	0.07	m
Tx Angular Diam	5.82	arcsec
Tx Footprint Diam	1.13E+07	m
Tx Optical Transmission	45.0	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.99	
Atm Transmission Along LOS	90.3	%
Scintillation Loss	-2.6	dB
RECEIVER		
Rx Aperture Diam	0.22	m
Rx FOV	5.00	arcsec
Rx Depointing	0.10	arcsec
Rx Optical Transmission	30.3	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	4.9E-12	W/m^2

LINK BUDGET		
Tx Ave Power	**57.45**	**dBm**
Tx Antenna Gain	103.04	dBi
Tx Array Gain	9.54	dBi
Tx Transmission Loss	-3.47	dB
Tx Pointing Loss	-0.33	dB
EIRP	**136.23**	**dBW**
Isotropic Space Loss	-370.22	dB
Atmospheric Loss	-3.05	dB
Irradiance at rx aperture	**1.03E-11**	**W/m^2**
Rx Antenna Gain	112.98	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-5.19	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-156.69**	**dB**
Ave Power at Rx Detector	**-99.24**	**dBm**
Req. Irradiance at rx aperture	4.9E-12	W/m^2
Link Margin	**3.24**	**dB**

Figure 62: Example uplink budget for a Mars (far-range) Deep Space scenario.

3.7.6 Ground Station Cost

Table 23 provides a cost estimation of the optical ground stations for the Deep Space Scenario.

Table 23: Ground station costs for the Deep Space Scenario (k€).

Deep Space Scenario Ground Station Cost in k€	**Haleakala**	**Tenerife**	**Total**
Initial Station Investment Costs:			
Terminal (telescope, dome, and electronics)	51,405	51,405	
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	3,115	3,115	
Wide Area Communication Investment Costs (ground comm)	157	0	
Weather and Atmospheric monitoring	250	250	
Aviation Safety System	350	350	
Subtotal Initial Station Investment Costs	**55,277**	**55,120**	**110,397**
Recurring Operating Costs:			
Site and Terminal Operating Costs	1,560	1,560	
Communication Operating Costs	390	390	
Subtotal Recurring Operating Costs	**1,950**	**1,950**	**3,900**

3.7.7 Business Case

As the CFLOS analysis shows, multiple geographically diverse ground stations are needed to ensure a high probability of downlinking the desired data volume over the life of the mission with reasonable latency (though there are still trades to be explored if large onboard storage and long latencies are allowed). As shown above, the investment for these large optical ground stations is substantial and the ability to share such costs across multiple agencies, (i.e., multiple agencies building and maintain interoperable ground stations) will make it easier to introduce a robust deep space optical communication infrastructure. Involvement of multiple space agencies will also ensure geographic diversity regarding the placement of ground stations.

4 Relay Mission Scenarios

4.1 Earth Relay Scenario

4.1.1 Concept of Operations

4.1.1.1 Basic ConOps

The communications link between spaceborne observatories and Earth has long been a critical mission system driver. Sometimes, information from an Earth observing, scientific or exploration mission must be returned with as low latency as possible. Low latency (high availability) is extremely important for human exploration missions. Earth relay satellites are satellites placed in geostationary orbit (GEO) to relay information to and from non-GEO satellites, aircraft, and Earth stations that otherwise would not be able to communicate at all or would not be able to communicate for long periods of time. A network of Earth relay satellites would increase the amount of time that a spacecraft in Earth orbit, especially in LEO, could be in communications with a Mission Operations Center, and thus would increase the amount of data that could be transferred. Using optical communications in addition to an RF system on an Earth relay satellite would allow

1. A substantial increase in data rate to and from the user spacecraft over an RF-only implementation
2. For the same data rate provided by a comparable RF system, a savings of mass and power on the user spacecraft
3. Some combination of an increased data rate and a savings of mass and power
4. Interference-free operation without the need for coordination and licensing of optical inter-satellite link frequencies

Generally speaking, based on NASA's Tracking and Data Relay Satellite (TDRS) system, each Earth relay satellite can communicate with a LEO user spacecraft for approximately 22 minutes. Longer passes are possible, depending on the actual geometry; in the case of NASA's TDRS system, a TDRS cannot communicate until the user satellite is over the 5 degree elevation point. Thus, a single Earth relay with a single inter-satellite optical communications terminal can support multiple LEO spacecraft, depending on the spacing between them. Of course, if the capability for real-time relaying is required, the relay spacecraft will need another optical communications terminal for optical-to-optical relay, or an RF system for optical-to-RF relay.

4.1.1.2 Scenario ConOps

For the purposes of this report, the OLSG considered two concepts of operations for the Earth Relay Scenario: a concept where the feeder link employs RF and an alternative concept where the feeder link employs optical communications.

The notional Earth relay spacecraft located in GEO will carry two inter-satellite optical communications terminals to support two user spacecraft simultaneously. Each inter-satellite optical communications terminal can support multiple user spacecraft in a round-robin fashion (e.g., time division multiple access). Each inter-satellite optical communications terminal in GEO has line of sight access to a spacecraft in LEO for approximately 22 minutes, with the exact time depending on geometry and the minimum elevation angle. Each optical terminal in the Earth relay is assumed to provide a 1.8 Gb/s inter-satellite optical communications link. The Earth relay will therefore need to support a GEO-to-Earth Feeder Link (or trunk line) of at least 3.6 Gb/s (2 x 1.8 Gb/s); the exact downlink rate required depends on whether the feeder link is an RF link or an optical link and the availability requirement on the relay.

In both the RF feeder link and optical communications feeder link operations concepts, each LEO user spacecraft requires 12 Terabits of information to be transmitted to Earth each day. Each LEO orbit takes about 90 minutes, resulting in 16 passes per day to a single Earth relay. Basically, 750 Gbits/orbit has to be relayed from the user spacecraft. The LEO user spacecraft has enough onboard storage for three orbits of data or approximately 4.5 hours. The LEO spacecraft have the same amount of data volume per day as the LEO spacecraft in the LEO Scenario mentioned earlier, but the instantaneous data rate may be lower because each LEO spacecraft has a longer contact time to transmit its data.

Additional information about the types of links in these operations concepts is contained in the subsections below.

4.1.1.2.1 Earth Relay Inter-Satellite Link (ISL)

The Earth relay Inter-Satellite Link (ISL) is intended for LEO spacecraft communications with a relay satellite and ultimately a mission operations center on Earth via the inter-satellite link and the feeder Link (trunk line) to and from Earth.

Assuming the entire 1.8 Gb/s inter-satellite optical communications link is available for user data (i.e., zero overhead), then a data rate of 750 Gbits/orbit requires 417 seconds (6.95 minutes) of contact time per orbit. Thus, each LEO user spacecraft requires 111.2 minutes of contact time per day to transmit all of the daily information.

This means twelve spacecraft could theoretically be supported by a single Earth relay's inter-satellite optical communications terminal if they were spaced just perfectly. Assuming 80% "contact efficiency" instead of an ideal case, one terminal could support about nine spacecraft. Thus, with two inter-satellite optical communications terminals on an Earth relay, each relay satellite can support approximately 18 user spacecraft.

A second Earth relay satellite would allow more user spacecraft to be supported and/or act as a backup to the first relay satellite.

4.1.1.2.2 Earth Relay RF Feeder Link (in RF Feeder Link Operations Concept only)

The feeder link needs to transmit 3.6 Gb/s to Earth (2 x 1.8 Gb/s) to maximize the usability of the relay. This scenario assumes each 1.8 Gb/s inter-satellite optical communications terminal is always being used.

NASA has examined transmitting this data rate via RF in various studies over the past decade and the technology and spectrum (via Ka-Band or higher) is available. Using RF on the feeder link provides the overall relay with high availability due to RF's ability to penetrate most clouds that would block an optical communications based feeder link. In theory, only one RF ground station would be required to support the Earth relay with very high availability.

That said, an RF-based feeder link can be a limiting factor in the design of an Earth relay if a higher data rate is required (i.e., if the inter-satellite optical communication links are increased or if there are more terminals on the relay) or if the necessary RF spectrum is not available, as access to spectrum in Ku-band and Ka-band is limited.

4.1.1.2.3 Earth Relay Optical Feeder Link (in Optical Feeder Link Operations Concept only)

Instead of relying on an RF feeder link, an optical feeder link could be employed instead. This option is particularly attractive, as the downlink data rate on the feeder link increases. It is easy to envision Earth relays in the not-so-distant future with tens of Gb/s of downlink. However, the availability of a pure optical feeder link could be impacted by clouds. To provide high availability, the Earth relay would have to use a combination of RF and optical communications and onboard storage, or employ a number of optical communication ground terminals to support the feeder link. For example, a future Earth relay could have onboard memory and an RF feeder link at 1 or 2 Gbps, coupled with an optical feeder link at 10 Gbps. Thus, some data could be transmitted to Earth via RF, even if all of the optical ground stations were covered by clouds. The RF feeder link could be eliminated by increasing the amount of onboard storage or the number of available optical ground stations.

A previous DLR study concluded that 11 optical communication ground terminals scattered generally throughout Europe to a GEO satellite would provide 99.67% availability.[3] That same study showed that 10 ground terminals placed only in the south of Europe would provide 99.89% availability. Analysis in that study also showed that 8 carefully placed ground terminals in Europe and Africa would provide 99.971% availability. Likewise, a study by NASA/NGC showed that five ground terminals carefully located over Maui, California, Chile, Israel, and Europe (Uzbekistan) would result in about 91% availability.1 The large number of ground stations quoted above assumes that the relay satellite is simply a traditional real-time high-availability link (bent pipe) like most RF communications satellites in orbit today. In other words, the optical signal arrives at the relay satellite and then has to be transmitted to the ground instantly. That architecture (here called “Case a”) is one of many possible architectures; it is simple and based on RF heritage, but it may not be the ideal architecture for the future. A future architecture (here called “Case b”) could use a data volume transfer optimized link with storage and networking protocols to provide sufficient availability, while reducing the number of required ground stations. This Case b concept will be further explored in this report.

An Earth relay satellite with both an RF feeder link and an optical feeder link could provide high availability. Suppose a downlink data rate of 5 Gb/s was required on the feeder link. The Earth relay could have an RF feeder link with a maximum data rate of 2 Gb/s and an optical feeder link with a maximum data rate of 5 Gb/s. Assuming there is only one ground terminal on Earth to support the optical feeder link, the RF feeder link would be a slow-speed backup when the optical link is not available (due to cloud coverage, for example). Of

[3] Bischl H. et al., *Feasibility Assessment of Optical Technologies & Techniques for Reliable High Capacity Feeder Links (Executive Summary)* (ESA Study Contract Report, 21991/08/NL/US, 2011).

course, there would have to be enough buffer onboard the Earth relay to make this approach work, or the capacity (number of users supported) would have to be limited. If more optical ground terminals were added to support the optical feeder link, the capacity of the overall Earth relay would increase. A systems engineering trade would have to be conducted to determine the optimal solution from both a technical and cost perspective; since technology and its related costs are constantly changing, such a study would have to be performed when a space agency was ready to deploy an operational system.

An optical terminal could be designed to support both the optical feeder link and the optical inter-satellite link to a LEO spacecraft. NASA's Laser Communications Relay Demonstration (LCRD) Project will demonstrate just such a terminal design. NASA's LCRD consists of two optical communications terminals on a GEO satellite, each with a 10 cm optical module. The same 10 cm optical module can be used for both the feeder link and the inter-satellite link on the GEO satellite. In addition, NASA is studying using that same 10 cm optical module on a LEO satellite; however, the output laser power would have to be increased to provide a higher data rate due to the increased distance.

In the optical feeder link concept studied by the OLSG, the Earth Relay will have two optical terminals to support the inter-satellite optical communication links just as in the case of the RF feeder link concept. However, instead of an RF feeder link, the feeder link will be an optical communications link using a third optical terminal on the spacecraft with a downlink of 10 Gbps. The Earth Relay will also have onboard storage of 10 Terabits. At 10 Gbps, and if it was possible to have 100 percent availability to the ground station, all of the information from the 18 LEO spacecraft mentioned earlier could be relayed to the ground in 6 hours. The OLSG decided to assume 10 Gbps for the downlink because such a system could be built with today's technology. In this architecture, the Earth Relay has a high-performance, high-bandwidth optical communications terminal on one relay spacecraft while the 18 LEO spacecraft have lower performing, lower mass and power, terminals.

Table 24 summarizes the ConOps parameters for the Earth Relay optical feeder link operations concept.

Table 24: Earth Relay Scenario Parameters (Optical Feeder Link Concept of Operations)

Earth Relay Scenario			
Onboard Data Collection Rate of Relay Spacecraft	**Onboard Storage Capacity of Relay Spacecraft**	**Hours of CFLOS Required per Day**	**Data Rate used for Link Budget**
216 Tb/day	10 Tb	6	10 Gbps

4.1.1.2.4 Earth Relay Optical Crosslinks

The overall availability of an Earth relay satellite could be increased by interconnecting Earth relay satellites with optical crosslinks. For example, suppose there were three Earth relay satellites in GEO spaced 120 degrees apart. Each Earth relay has its own optical ground terminal to support the feeder link. If there is cloud coverage blocking one of the relays from transmitting information to Earth, then that Earth relay could transmit its data over an optical crosslink to another Earth relay whose optical ground terminal is available. For this arrangement to work, the feeder links would have to support a higher data rate than that required just to support the user spacecraft, enabling the feeder links to downlink data from another Earth relay satellite from time to time.

4.1.2 Space Relay Terminal

4.1.2.1 Potential ISL Implementations

4.1.2.1.1 DLR/Tesat LCT LEO-to-LEO Links (TerraSAR-X, NFIRE) and LEO-to-GEO Links (Sentinel, Alphasat)

The performance of optical wideband communication links has been verified in-orbit by DLR using LCTs developed and manufactured by Tesat. LCTs have been accommodated on TerraSAR-X and NFIRE (Figure 63) to establish optical inter-satellite LEO-to-LEO links, LEO-to-Ground and Ground-to-LEO links at a data rate of 5.625 Gbps.

Figure 63: Tesat laser communication terminals embarked on TerraSAR-X (left) and NFIRE (right).

Tesat LCTs apply homodyne BPSK. The LCTs operate at a wavelength of 1.064µm. Table 25 summarizes the key parameters of the LCTs for LEO-to-LEO inter-satellite links. A unique pointing, acquisition and tracking technique is implemented here, which functions without an additional beacon laser. Both laser communication terminals search and acquire communication mode autonomously. In a master/slave approach acquisition is reached using the communication laser at 1.064µm only, and the counter terminal is then tracked on the communication channel while the terminals exchange bidirectional data. Regarding this unique pointing, acquisition and tracking technique, the LEO-to-LEO link scenario must be considered the worst case condition with respect to all potential applications up to the GEO distance, due to the high angular velocities involved. Since the first verification of such a LEO-to-LEO link between TerraSAR-X and NFIRE in 2008, inter-satellite links have been performed repeatedly and the link operates reliably. The homodyne BPSK technology at 1.064 µm thus exhibits a technology readiness level of nine.

Table 25: Key parameters of the Tesat LCT for LEO-to-LEO communication

Link	LEO-to-LEO duplex communication
Data Rate	5.625 Gbps
Link Distance	1,000 – 5,100 km
Optical Transmit Power	0.7 W
Telescope Diameter	125 mm
Bit Error Rate	10^{-11}
Mass	35 kg
Power Consumption	120 W
Volume	0.5 x 0.5 x 0.6 m^3

Figure 64 shows the location of a typical LEO-to-LEO inter-satellite link. One satellite traveled across the Pacific Ocean (pink trajectory), the other in opposite direction across Central America (blue trajectory). The link is displayed in green. The LCTs track each other across an angle of about 90°.

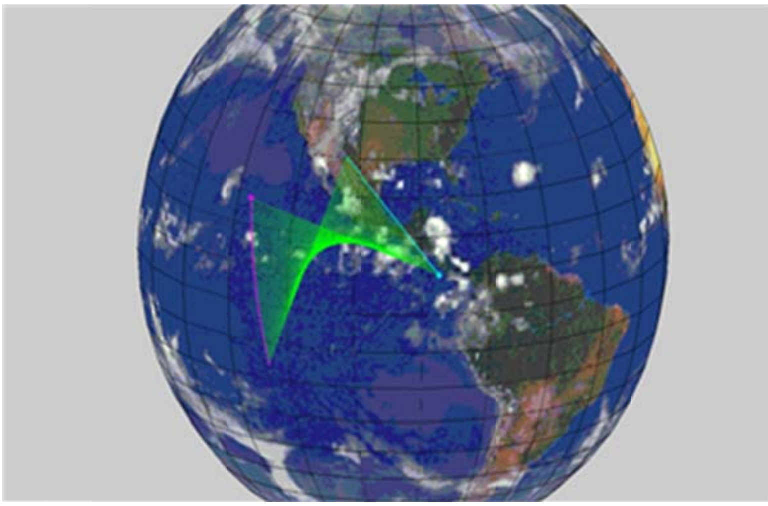


Figure 64: Location of a typical LEO-to-LEO link.

Bit errors are measured in one 225 Mbps data channel (Figure 65) for both directions of communication—from NFIRE to TerraSAR-X and from TerraSAR-X to NFIRE. Communication started at 35 s after establishing the link, and lasted for 350 s, because the optical link is obscured by the satellite structure. Only one faulty bit was detected in the NFIRE-to-TerraSAR-X link, none in the other. On the basis of this and similar results obtained on similar link experiments, the bit error rate of the inter-satellite LEO-to-LEO link is calculated to 10^{-11}.

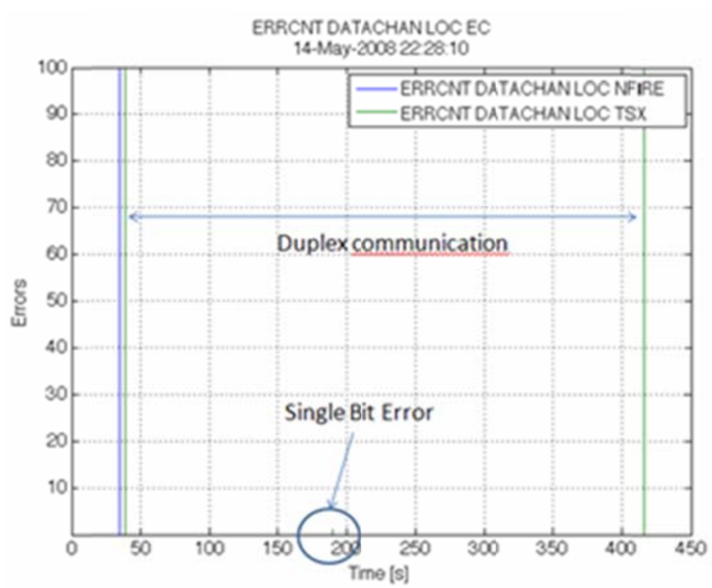


Figure 65: Bit errors measured in a duplex LEO-to-LEO communication link.

As verified, bit error rates for the inter-satellite link are better than 10^{-11} without the use of any code. With pointing accuracies on the order of 100 µrad, acquisition will be closed in seconds to establish the communication link. The LEO-to-LEO inter-satellite link results, together with the tracking results, are the heritage upon which the GEO-relay link budgets are based.

On the DLR roadmap to establish an EDRS the development of laser terminals suited for LEO-to-GEO application was the logic next step. In cooperation with Tesat, DLR space administration initiated the development of a second generation LCT in 2006. The qualification of the LCTs for EDRS will be based on this development. DLR will launch an LCT as a technical demonstrator payload on the geostationary ESA satellite development project Alphasat to serve as the precursor mission for EDRS. The GEO-to-LEO link is planned to be verified between the Alphasat LCT in GEO orbit and LCTs embarked on the Global Monitoring for Environment and Security (GMES) satellites Sentinel 1a and Sentinel 2a in LEO orbit.

Table 26 summarizes the key parameters of the LCT for LEO-to-GEO inter-satellite links. At a data rate of 1.8 Gbps a bit error rate of 10^{-8} is achieved, as is verified by laboratory tests. The LCT to be accommodated on Alphasat is shown in Figure 66. The demonstrator platform on Alphasat (see Figure 67) will, in addition to the verification of the GEO-to-LEO inter-satellite link, serve for investigations of DLR on the GEO-to-Ground link scenario. The launch of Alphasat is scheduled for 2013.

Table 26: Key parameters of the Tesat LCT for LEO-to-GEO communication

Link	LEO-to-GEO duplex communication
Data Rate	1.8 Gbps
Link Distance	> 45,000 km
Optical Transmit Power	2.2 W
Telescope Diameter	135 mm
Bit Error Rate	10^{-8}
Mass	56 kg
Power Consumption Communication end-of-life	160 W
Volume	0.6 x 0.6 x 0.7 m^3

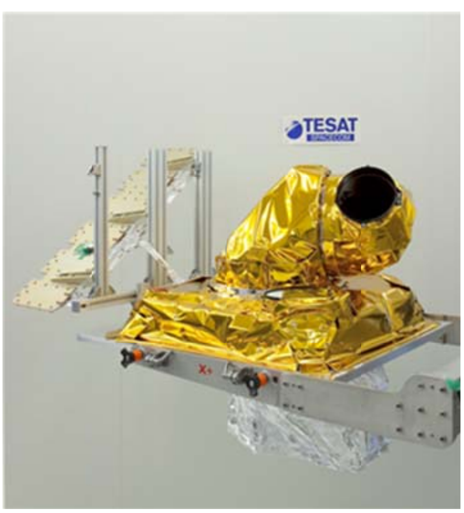


Figure 66: Tesat LCT delivered for Alphasat LEO-to-GEO links.

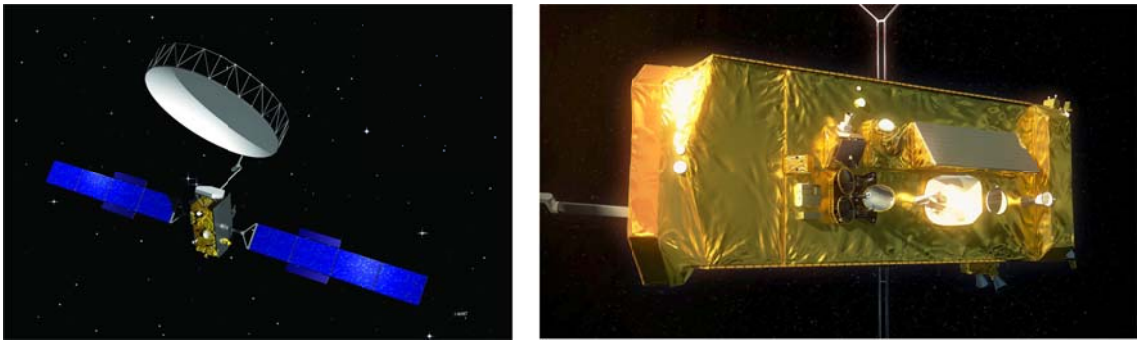


Figure 67: Left: Configuration of the geostationary Alphasat satellite. Right: The LCT is accommodated on the earth deck (at the left hand side of the radiator).

4.1.2.1.2 European Data Relay System (EDRS)

After a successful demonstration of the Semiconductor-laser Inter-satellite Link EXperiment (SILEX) in 2001 between the Artemis GEO satellite and the SPOT-4 LEO satellite, the EDRS will become the first operational European data relay system (see Figure 68).

The EDRS is under implementation within ESA's Advanced Research in Telecommunications Systems Program (ARTES-7). EDRS will provide a wide range of operational data relay services (both optical and Ka-band based).

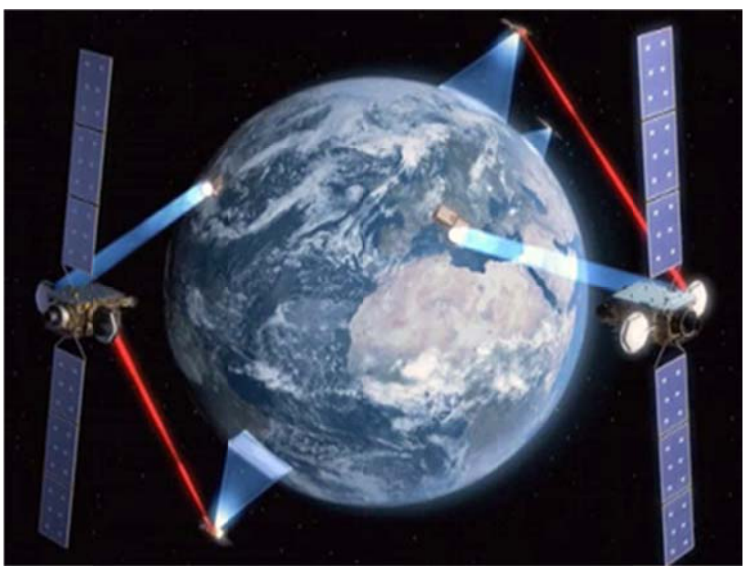


Figure 68: European Data Relay System concept.

With the implementation of the joint European Commission/ESA GMES program, it is estimated that European space telecommunication infrastructure will need to transmit six Terabytes of data every day from space to ground. The joint European Commission/ESA

GMES program will be the first customer of the EDRS service (Sentinel 1A/B and 2A/B LEO satellites).

A major difference between SILEX and EDRS is the selected optical technology and targeted performances of the laser links between the LEO satellite users and the GEO satellite nodes. The EDRS optical inter-satellite links (OISLs) are based on optical LCTs which are developed and qualified by Tesat Spacecom (Germany) under DLR German national funding. These LCTs feature a significantly increased data transmission rate compared to SILEX technology, with reduced mass and size.

The LCTs developed by Tesat Spacecom (Germany) for EDRS can transmit up to 1.8 Gigabits/second over distances in excess of 45,000 km, between GEO EDRS spacecraft and satellites in LEO orbit. The key parameters of the LCTs embarked on the Sentinel S1A / S2A and the EDRS spacecraft are given in Table 25 in subsection 4.1.2.1.1.

The LCT on the EDRS spacecraft will benefit from the space heritage attained in the following in-orbit demonstrations:

- The in-orbit verification of the LEO-LEO optical ISL between TerraSAR-X and NFIRE led by DLR (German Space Agency), which took place in 2008, at a data rate of 5.6 Gigabits/second over link distances of about 5000 km
- The GEO LCT developed by DLR to be embarked on ESA's ALPHASAT satellite, see Figure 66
- The LEO LCTs developed by DLR to be embarked on Sentinel 1A/2A satellites.

EDRS operations will take advantage of the LEO-GEO OISL experiments between the LEO Sentinel 1A/2A satellites and the GEO ALPHASAT satellite. The payload data rate requirement for Sentinel 1A/2A satellites is 600 Mbps, which is well within the capabilities of Tesat's LCTs.

The EDRS will be a constellation of GEO satellites intended to relay data between satellites, as well as unmanned aerial vehicles (UAVs) and ground stations. The EDRS will allow almost full-time communication with satellites in LEO orbit, which often have very reduced visibility from any ground station. The EDRS is envisaged to significantly improve the stringent timeliness requirements of Earth Observation missions (i.e., time-critical services).

The EDRS is being built through a public–private partnership between ESA and Astrium GmbH, BU Services, Germany ("Astrium Services"). Astrium Services has the overall responsibility for designing and developing the complete space and ground infrastructure. Astrium Services will then acquire ownership of EDRS and is committed to its operation for the next 15 years, and to providing services to ESA, starting with the Sentinel 1A and 2A satellites of the GMES program. Sentinel 1A is a synthetic aperture radar satellite and Sentinel 2A is a multi-spectral imager.

The EDRS infrastructure currently under development includes the following space segment items:

- The EDRS-A payload, which contains an LCT and a Ka-band terminal for OISL and Ka-band ISL respectively, will be placed as a piggyback payload on-board Eutelsat's EB9B commercial telecommunication satellite manufactured by

Astrium Satellites (France). The satellite will be launched in late 2014 and will be positioned at 9°E.

- The EDRS-C platform (dedicated spacecraft manufactured by OHB [Germany]) and the EDRS-C payload, also carrying an LCT, will be launched in late 2015.

In addition, EDRS will develop the necessary ground segment infrastructure, consisting of a satellite control center (SCC), a mission operations center (MOC and backup MOC), a feeder link ground station (FLGS and Backup FLGS) and data ground stations (DGS). The primary MOC will be at Astrium's facilities in Ottobrunn, Germany, while the backup MOC will be installed at Redu Space Services in Belgium. User data will be transmitted from LEO user satellites to either of the EDRS payloads and relayed to the FLGS and/or the DGS on the ground, from which it will be made available to the users' sites.

4.1.2.1.3 LCRD

NASA is currently investigating development of a LEO optical terminal that is compatible with the LCRD. The concept is to fly a modified LCRD terminal on the LEO spacecraft. More information on the LCRD is found in Section 4.1.2.2.2.2.

4.1.2.2 Potential Feeder Link Implementations

4.1.2.2.1 RF Feeder Link Implementations

4.1.2.2.1.1 EDRS

EDRS will use an RF feeder link.

4.1.2.2.2 Optical Feeder Link Implementations

4.1.2.2.2.1 Alphasat

The primary objective of the Alphasat mission is the demonstration of the 1.8 Gbps optical LEO-to-GEO link, which will be operationally implemented for EDRS, as described above. However, the second main objective of the Alphasat mission shall be the demonstration of the performance of 1.8 Gbps GEO-to-Ground links at the 1064 nm wavelength. The Alphasat terminal for the GEO-to-ground link and the LEO-GEO link are identical. The description of the Alphasat/EDRS optical terminals can be found in Section 4.1.2.1.1.

4.1.2.2.2.2 NASA Laser Communications Relay Demonstration (LCRD)

NASA's GSFC is currently developing the LCRD as a NASA pathfinder for a future optical communications service provided via an Earth relay satellite, such as the Next Generation TDRS. LCRD consists of two optical terminals flying on a GEO spacecraft, two ground terminals, and a Mission Operations Center. LCRD will be developed to enable:

1. High rate bidirectional communications between Earth and GEO
2. High rate bidirectional communications between LEO and GEO
3. Real-time relay from an optical communications terminal flying on a LEO spacecraft through the GEO spacecraft to one of the LCRD optical communications ground terminals

4. Real-time relay from an optical communications ground terminal through the GEO spacecraft to a second optical communications ground terminal
5. Demonstration of photon counting and pulse position modulation suitable for deep space communications or other power-limited users, such as small near-Earth missions
6. Demonstration of differential phase shift keying modulation suitable for near Earth high data rate optical communications
7. Demonstration of various mission scenarios through spacecraft simulations at one of the LCRD optical communications ground terminals

NASA plans to launch LCRD in December 2016 as a hosted payload on a commercial communications satellite.

4.1.2.2.2.2.1 Flight Payload

The LCRD flight payload will be flown on a GEO spacecraft and consists of:

- Two optical communications modules (heads)
- Two optical module controllers
- Two DPSK modems
- Two PPM modems
- High Speed Electronics to interconnect the two optical modules, perform network and data processing, and to interface to the host spacecraft

An optical communications terminal on LCRD consists of an optical communications module, a DPSK modem, a PPM modem, and an optical module controller.

4.1.2.2.2.2.1.1 Flight Optical Communications Module

Each of the two optical communications terminals to be flown on the GEO spacecraft will transmit and receive optical signals. When transmitting, the primary functions of the GEO optical communications terminal are to efficiently generate optical power that can have data modulated onto it; transmit this optical power through efficient optics; and aim the very narrow beam at the ground station on Earth, despite platform vibrations, motions, and distortions. When receiving, the GEO optical communications terminal must provide a collector large enough to capture adequate power to support the data rate; couple this light onto low noise, efficient detectors, while minimizing the coupled background light; and perform synchronization, demodulation, and decoding of the received waveform.

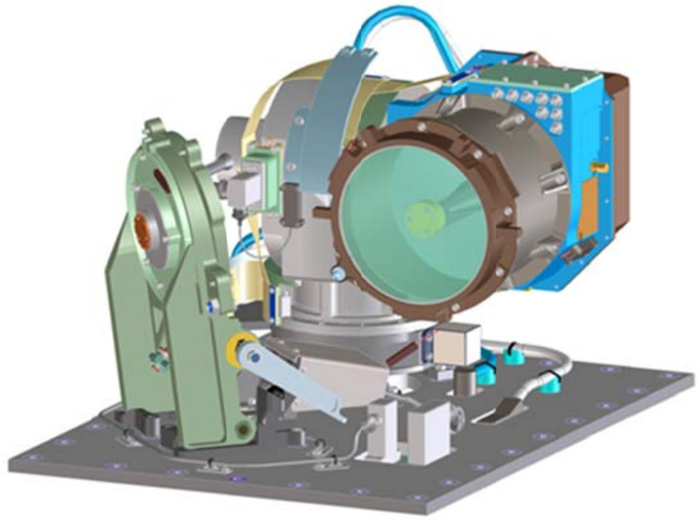


Figure 69: Inertially Stablized Optical Module.

Each optical module, shown in Figure 69, is a 4-inch reflective telescope that produces a ~15-microradian downlink beam. It also houses a spatial acquisition detector, which is a simple quadrant detector with a field of view of approximately two microradians. It is used both for detection of a scanned uplink signal, and as a tracking sensor for initial pull-in of the signal. The telescope is mounted to a two-axis gimbal via a magnetohydrodynamic inertial reference unit (MIRU). Angle-rate sensors in the MIRU detect angular disturbances, which are then rejected using voice-coil actuators for inertial stabilization of the telescope. Optical fibers couple the optical module to the modems where transmitted optical waveforms are processed. Control for each optical module and its corresponding modems is provided by a controller. Each optical module is held and protected during launch with a cover and one-time launch latch.

4.1.2.2.2.2.1.2 Flight Modems

There exist some differences between the technological approaches to optical communications specifically designed for Near-Earth missions versus deep space missions. These differences are mostly due to the vastly differing ranges and data rates for near-Earth versus deep space missions. NASA has been investigating the appropriate modulation, coding, and detection scheme for the two different classes of missions for some time. Photon counting PPM has been identified as the technique of choice for deep space missions, while DPSK is the current preferred choice for Near-Earth missions. LCRD will demonstrate both techniques.

Photon counting PPM is highly photon efficient, although the ultimate data rate is limited due to detector limitations and the requirement for faster electronics. LCRD leverages the PPM modem developed for NASA's LLCD as a cost effective approach to providing a PPM signal. The LLCD modem supports a variable rate downlink from 39 to 622 Mbits/second and variable uplink from 10 to 20 Mbps.

The PPM flight transmitter encodes data with a rate-½ SC-PPM turbo code. The encoded data stream is convolutionally interleaved (to mitigate the effects of atmospheric fading) and modulated with a 16-ary PPM modulation scheme (signal is placed in exactly one of each 16 temporal slots). The maximum data rate is achieved using a 5 GHz slot clock rate; lower data rates are accomplished by combining consecutive slots, effectively lowering the clock rate, with a minimum slot rate of 311 MHz. The optical modulation is accomplished with a MOPA architecture. A continuous wavelength (CW) laser (at ~1550 nm) is modulated with a Mach-Zehnder modulator, and amplified with a two-stage EDFA to a 0.5-W average power level.

The PPM flight receiver is an optically pre-amplified direct detection receiver. After amplification and filtering, the signal is optically split to perform spatial tracking, clock recovery, and communications. The uplink communications signaling is 4-ary PPM, with a simple two comparator demodulator performing binary hard decisions. The received uplink data streams are de-interleaved and decoded (rate-½ SC-PPM coding is applied on the uplink).

LCRD will also support DPSK, which has superior noise tolerance, can be used at extremely high data rates, and supports communications when the Sun is in the field of view. LCRD leverages a previously designed Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL) DPSK modem as a cost effective approach to providing a DPSK signal. It can both transmit and receive data at an (uncoded) rate from 72 Mbps to 2.88 Gbps. In future relay scenarios, it could be replaced by a higher rate DPSK modem that would support data rates beyond 10 Gbps.

The DPSK modem employs identical signaling for both the uplink and downlink directions. The DPSK transmitter generates a sequence of pulses at a 2.88 GHz clock rate. A bit is encoded in the phase difference between consecutive pulses. As demodulation is accomplished with a Mach-Zehnder optical interferometer, the clock rate remains fixed. The DPSK transmitter utilizes a MOPA architecture similar to the PPM transmitter. The EDFA amplifies the optical signal to a 0.5-W average power level. Data rates below the maximum are accomplished via “burst-mode” operation, where the transmitter sends pulses only a fraction of the time, sending no optical power the remainder of the time. Since the EDFA is average power limited, the peak power during the bursts is increased; thus, the rate reduction is accomplished in a power efficient manner.

The DPSK receiver has an optical pre-amplifier stage and an optical filter, at which the light is split between a clock recovery unit and the communications receiver. The receiver uses a delay-line interferometer, followed by balanced photo-detectors, to compare the phases of consecutive pulses, making a hard decision on each channel bit. While coding and interleaving will be applied in the ground terminal to mitigate noise and atmospheric fading, the DPSK flight receiver does not decode nor de-interleave. The modems instead support a relay architecture where uplink and downlink errors are corrected together in a decoder located at the destination ground station.

4.1.2.2.2.2.1.3 High Speed Electronics

To be an optical relay demonstration, LCRD will create a relay connection between two ground stations. A significant objective of LCRD is to demonstrate advanced relay operations on the GEO spacecraft. LCRD will enable a wide variety of relay operations through the high-speed electronics (HSE) that connect the two optical terminals. In addition to real-time relay operations, the electronics will allow scenarios where one link uses DPSK signaling and the other PPM. A known challenge with optical communication through the atmosphere is the susceptibility to cloud cover. The HSE will include a significant amount of data storage to demonstrate store-and-forward relay services for when the uplink is available, but the downlink is unavailable. The HSE will support delay tolerant networking (DTN) protocols. To support DTN over the DPSK optical links, the HSE will implement any required decoding and de-interleaving so the payload can process and route the data (at a rate less than the maximum DPSK throughput). The link operations will be configurable to allow support for a variety of scenarios.

4.1.3 Ground Terminal

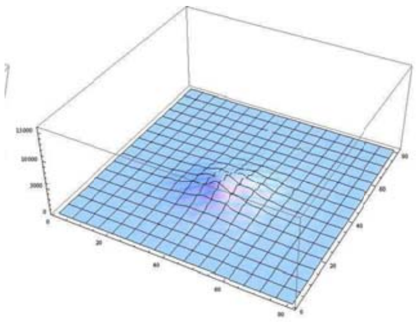
4.1.3.1 Potential Implementations

4.1.3.1.1 DLR/Tesat Ground Terminal Implementation

Ground stations for wide band GEO-to-ground communications are under development. Due to larger space losses, GEO-to-ground links require larger telescope apertures on the ground than is the case for LEO-to-ground links. Depending on the data rate transmitted, typical telescope apertures range from 500 mm up to 1m. The wavefront across an aperture of this size is expected to be distorted, and the distortion needs to be compensated by adaptive optics. To verify optics for wide band optical communication in the Space-to-ground scenario, transportable optical ground stations equipped with adaptive optics are under development by Tesat and funded by DLR (see Figure 70). The transportable adaptive optical ground station will be suited for homodyne BPSK communication at 1.064 µm both with the LEO-to-LEO LCT generation employed on TerraSAR-X and NFIRE and with the second generation GEO-to-LEO LCT developed for Alphasat, the Sentinels and EDRS.

Figure 70: The transportable adaptive optical ground station currently developed by Tesat is fitted into a standardized shipping container.

First tests performed under worst case conditions on the ground demonstrate the feasibility of this approach for 1 m telescopes. The wavefront of a coherent beam propagating horizontally 20 km through the atmosphere and impinging on a 1-m aperture is highly disturbed by the atmosphere, as is shown by the blurred beam profile in the focal plan (Figure 71, upper scheme). Adaptive optics restores the wavefront such that more than 80% of the received photons are coupled into one single spatial mode, as is shown in the lower scheme of Figure 71. This approach results in a detection sensitivity of 80% compared to the undisturbed channel.



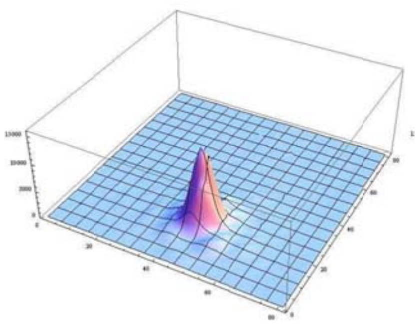


Figure 71: The beam profile of a highly disturbed coherent beam (upper scheme) compensated by adaptive optics (lower scheme).

In the next step adaptive optics shall be used to verify the performance increase for optical 5.625 Gbps LEO-to-ground links. Thereafter, an optical 1.8 Gbps GEO-to-ground link shall be established from Alphasat to Tenerife.

4.1.3.1.2 LCRD Ground Segment

The LCRD Ground Segment is comprised of the LCRD Mission Operations Center (LMOC) and two ground stations. The LMOC will perform all scheduling, command, and control of the LCRD payload and the ground stations.

Each Earth ground station must provide three functions when communicating with one of the two optical communications terminals on the GEO spacecraft: receive the communications signal from the GEO space terminal, transmit a signal to the GEO space terminal, and transmit an uplink beacon beam so that the GEO space terminal points to the correct location on the Earth.

The receiver on Earth must provide a collector large enough to capture adequate power to support the data rate; couple this light onto low noise, efficient detectors while trying to minimize the coupled background light; and perform synchronization, demodulation, and decoding of the received waveform.

The uplink beacon, transmitted from each Earth ground station, must provide a pointing reference to establish the GEO space terminal beam pointing direction. Turbulence effects dominate the laser power required for a ground-based beacon. Turbulence spreads the beam, reducing mean irradiance at the terminal in space, and causes fluctuations in the instantaneous received power.

4.1.3.1.2.1 LCRD Ground Station 1

JPL will enhance its Optical Communications Telescope Laboratory (OCTL) so that it can be used as LCRD Ground Station 1 of the demonstration.

This section describes the major modifications that will be made to the OCTL to support LCRD, including the dome, the adaptive optics optical train, the atmospheric monitoring system the Monitor and Control (M&C) system, and the LCRD User Service Gateway (LUSG). The OCTL is located in the San Gabriel mountains of southern California, and houses a 1-m f#75.8 coudé focus telescope. The large aperture readily supports the high data rate DPSK and PPM downlinks from the LCRD space terminal with adequate link margin. Required to operate 24 hours per day, 7 days per week, in the presence of winds, and as close as a 5-degree solar angle, the OCTL telescope shown in Figure 72 will be enclosed in a temperature-controlled dome with a transparent window to allow laser beam and radar transmission. The Laser Safety System at the OCTL (LASSO) will ensure safe laser beam transmission through navigable air and near-Earth space.

Figure 72: OCTL telescope will be modified with an optical flat to support links in the presence of more windy conditions.

The seven coudé mirrors will be coated with high-reflection low-absorption coatings to reduce the amount of sunlight scattered into the receiver (when it is pointed at the required 5-degree solar angle) and the backscatter from the uplink laser. The estimated reflection loss from all seven mirrors is 0.4 dB.

The integrated optical system (IOS) at the telescope coudé focus is shown in Figure 73. A shutter controlled by a Sun sensor protects the adaptive optics system, should the telescope inadvertently point closer to the Sun than specified. The downlink is collimated by an off-axis parabolic mirror, and is incident on a fast tip/tilt mirror and dichroic beam splitter, before reflecting off a deformable mirror (DM). A fraction of the beam is coupled to the wavefront sensor to measure the aberrations in the downlink beam. A scoring camera monitors the quality of the corrected beam that is focused into a fiber coupled to the DPSK/PPM receiver. A wave plate adjusts the polarization into the fiber to the DPSK Mach-Zehnder interferometer, and a slow tip/tilt mirror ensures maximum signal input to the fiber. In the uplink system the beacon and communications beams are first reflected from a slow tip/tilt mirror to track out satellite motions and then coupled to the telescope through a dichroic mirror.

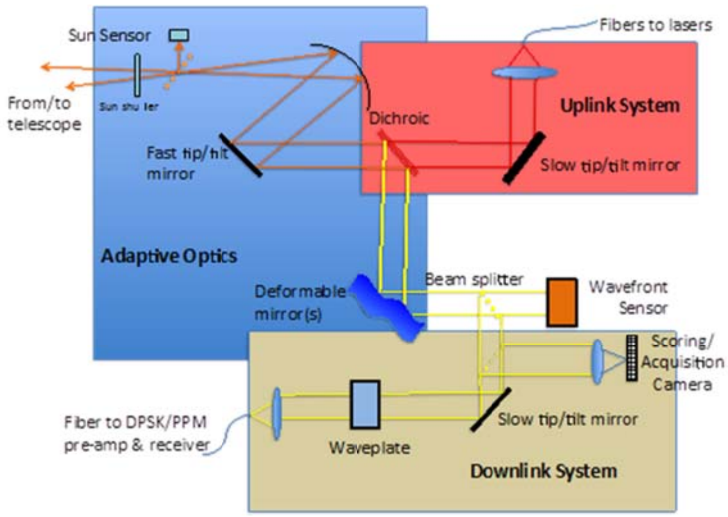


Figure 73: Schematic of the integrated optical system to be located at coudé focus in OCTL.

As a prelude to an operational system, understanding the optical channel and the performance of the link under a variety of atmospheric conditions informs the definition of requirements for future operational ground stations. Figure 74 shows some of the atmospheric monitoring instruments that will be implemented at the OCTL. The Sun photometer measures atmospheric transmission and sky radiance, the ground scintillometer measures the boundary layer turbulence that is the major contributor to the scintillation in the downlink signal, and the cloud imager measures cloud coverage and cloud optical depth. In addition, a differential image motion monitor integrated into the IOS will measure the Fried coherence length r_0 using the downlink signal. The weather station measures wind speed and direction along with relative humidity, and temperature at the OCTL.

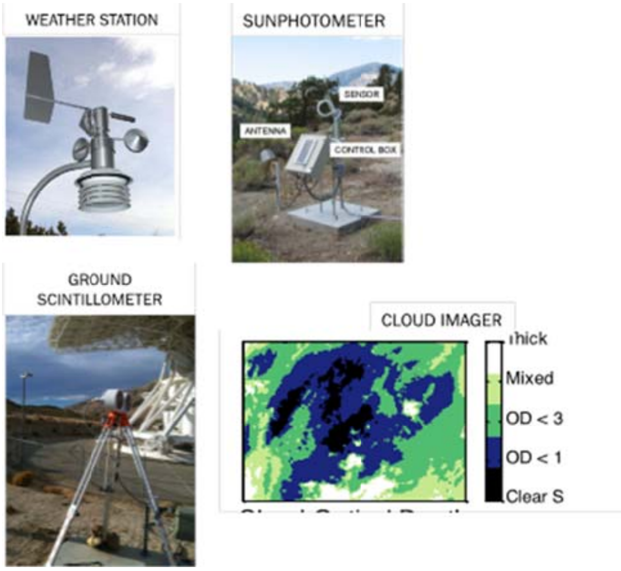


Figure 74: Suite of atmospheric monitoring instruments to characterize the optical channel.

The LCRD PPM modem will support the 16-ary PPM downlink modulation format at data rates of 39, 78, 155 311 and 622 Mb/s, and 4-ary PPM uplink at 10 and 20 Mb/s with rate ½ serially concatenated coding. The modem will support transfer frame formation, convolutional interleaving, and multiplexing. The asymmetry in modulation is characteristic of deep space optical links, where the uplink is a command link and the downlink returns the large volume of science data from the deep space probes.

The PPM modem will support real-time uplink and downlink processing in support of DTN provided by the LUSG. The LUSG will interface simulated (and potentially real) users to the LCRD optical service network, providing real-time bit stream and store-and-forward DTN services. The LUSG provides network data performance measurements, and coordinates with the M&C subsystem.

The M&C subsystem will provide the intelligent control of the LCRD ground terminal. It will implement the software to provide the interface for remote control and status monitor of all of the OCTL subsystems. It will provide a gateway to the LMOC to support remote control, status reporting, and data return. The M&C subsystem will also implement a high-speed data recording system and engineering interface. The data recorder will archive all of the OCTL system data for post-analysis of the system performance. The engineering interface will be a temporary user interface for early evaluation of the integrated OCTL subsystem prior to delivery of the user simulator and LMOC connection.

The DPSK ground modem supports the same signaling structures as the DPSK flight modem, namely phase modulated pulses at a 2.88 GHz slot rate and burst-modes to vary the channel data rate between 72 Mbps and 2.88 Gbps. In addition, the ground modem must implement forward error correction coding—anticipated to be a low density parity check (LDPC) code from the digital video broadcasting second generation (DVB-S2) standard—and interleaving to mitigate atmospheric scintillation.

4.1.3.1.2.2 LCRD Ground Station 2

MIT Lincoln Laboratory designed and is building the LLGT for NASA's LLCD. The LLGT, shown in Figure 75, will be refurbished and enhanced to serve as Ground Station 2 for LCRD. A summary of the LLGT, as designed for LLCD, follows below. The primary enhancements for LCRD will be an adaptive optics system to couple received light into single mode fiber (to support the DPSK receiver), and further development of the single photon detectors (to support the PPM receiver), including the development of more robust and scalable optical packaging, cabling, and readout electronics.

The LLGT is an array of four 40-cm receive reflective telescopes and four 15-cm transmit refractive telescopes. For the uplink, the optical signal (PPM for LLCD, to include DPSK for LCRD) is modulated onto four separate carrier wavelengths, each very slightly detuned. Each modulated signal is amplified to a 10-W average power, and coupled to a transmit aperture via single-mode fiber. For the downlink, the receive apertures couple into few-mode multi-mode fibers connected to an array of superconducting nanowire single photon detectors (SNSPDs). The SNSPDs must be cryogenically cooled to ~3K, and it is impractical to locate them in the focal planes of the receive apertures. The multi-mode fiber was designed to efficiently couple the received light from the aperture to the detector over a distance of 22 meters. By using multi-mode fiber, efficient coupling is achieved without an adaptive optics system.

Figure 75: Lunar Lasercom Ground Terminal will be enhanced with Adaptive Optics and a DPSK Modem.

For LCRD, the DPSK modem requires the received light to be coupled into single-mode fiber. For this reason, at least one of the receive apertures will utilize an adaptive optics system to support the DPSK receiver. The current LLGT design will continue to support the PPM functionality for LCRD.

Due to their high photon efficiency and fast reset times, the SNSPDs are a significant enabler for high-speed laser communications from deep space terminals to Earth terminals. For this reason, the LCRD project will investigate updates to the detector technology, including efforts to make the detectors more robust, more scalable, and require reduced size, weight, and power (SWaP). The main LCRD efforts will be directed towards optical packaging and improved cabling and cryogenic readout circuitry.

4.1.3.1.2.3 Demonstration Operations

Control of all activities during LCRD operations will take place from the LMOC. The LMOC is connected with all other LCRD segments, and communicates with the two ground stations using high capacity connections. Connection to the space segment will be provided either through one of the ground stations, or through a lower capacity connection to the host spacecraft's Mission Operations Center (HMOC) and then to the LCRD flight payload by RF link.

The LMOC will provide services such as:

- Planning and scheduling
- Control
- Status monitoring
- Reporting and accountability

The mission operations for the spacecraft and the optical communications demonstration are intimately intertwined. The unique nature of the LCRD demonstration is that there is a path to and from the spacecraft that is outside the usual RF connection. Commands for the GEO optical communications terminal can be sent via either the optical uplink or via the Host Spacecraft RF uplink. There are two paths for obtaining engineering data (health and status), again via optical or RF. The LMOC coordinates all optical communications activities and provides an interface to the spacecraft operations.

On the telemetry side there are again two data paths, though for somewhat different reasons. Data (user information or engineering telemetry) can be sent to Earth via the GEO optical communications terminal. It is possible that the GEO terminal may add/multiplex additional engineering data into the data stream. The spacecraft monitors terminal parameters like power and includes those in engineering telemetry that is passed over the RF link. In addition to these, there are many 'test points" within the GEO terminal that are sent via RF as part of the engineering telemetry.

Due to the vagaries of weather and atmospheric conditions, LCRD will explore operations strategies for mitigation of these effects. One possibility would be to have multiple terminals within the same beam simultaneously receive the same data to guarantee that data gets through to at least one terminal for a reasonably high percentage of the time. On the other hand, buffering and retransmission strategies can be used to downlink the data to single geographically (and meteorologically) diverse stations in a form of temporal diversity.

The ground stations will have the capability to simulate both user spacecraft and user MOC data systems, allowing the demonstration of high data rate scenarios without the requirement for high data rate connections external to the ground stations. The simulators will also allow multiple user and user-type scenarios. The LCRD payload itself will also include the ability to simulate user spacecraft data and multiple relay user spacecraft data systems.

The system will be continuously operating, as much as possible, over the two year mission. The system will either be configured to be demonstrating or testing a specific Direct-to-Earth (DTE) scenario, relay scenario, or be continually characterizing the optical channel and hardware. The DTE and relay scenarios will emulate different user and relay locations, orbits, and/or trajectories.

4.1.4 CFLOS Analysis

In the Earth Relay Optical Feeder Link Scenario, there will be a single optical terminal in geostationary orbit pointed at Earth. The relay satellite will be located at 60° West Longitude and have visibility to three ground sites. These sites include White Sands, New Mexico; La Silla, Chile; and Tenerife in the Canary Islands. These sites were chosen to explore the potential cross support of an optical downlink system. Figure 76 shows the 20° elevation contour for a satellite and terminal located at 60° West Longitude. As shown in Figure 76, all three sites have an elevation angle greater than 20° to the satellite. The objective of this scenario is to quantify the PDT for a three-site network under the following assumptions. The data volume collected by 18 LEO spacecraft and uplinked to the relay in geostationary orbit will be 216 Tb /day. The optical data rate from the relay spacecraft to the ground will be 10 Gb/s and the satellite will have onboard storage of approximately 10 Tb, which is equivalent to roughly one hour of no CFLOS. Six hours of CFLOS are required per day to downlink this data volume to the ground.

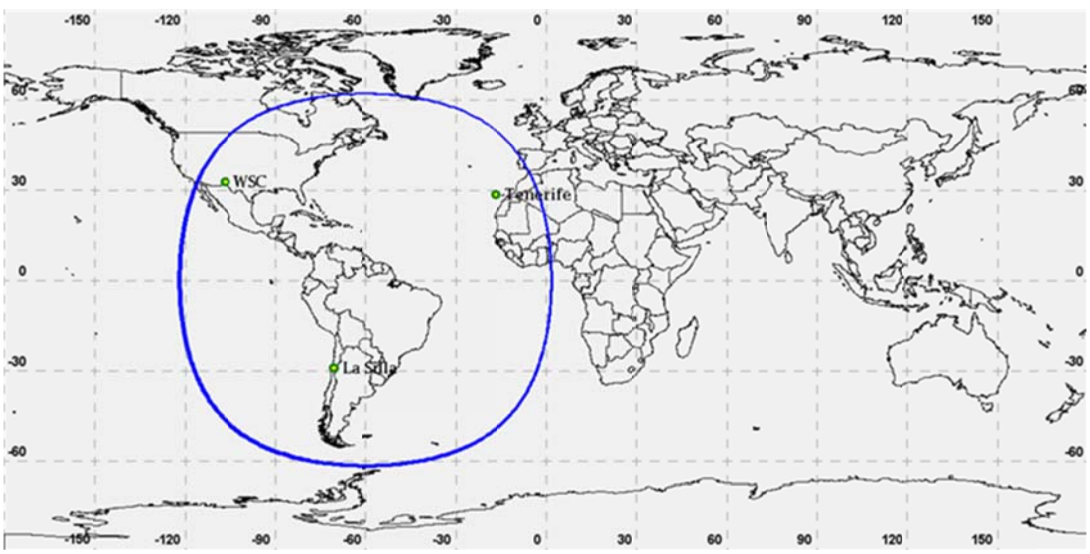


Figure 76: Locations of ground sites for the Earth Relay Optical Feeder Link Scenario with the 20° elevation contour overlaid.

LNOT was used to evaluate the performance (i.e., PDT) of the sites individually, and as a network of two and three sites. Results are based on seven years of CFLOS data from 2005-2011 at one-hourly resolution. The mean overall PDT values for White Sands Complex (WSC), Tenerife and La Silla are approximately 52.8%, 75.7% and 80.3%, respectively. Figure 77 shows the CDF of the monthly PDT for the three single sites used in the study. Although Tenerife and La Silla both have high PDTs, Figure 77 indicates that the probability that any months have a PDT of 100% is nearly zero.

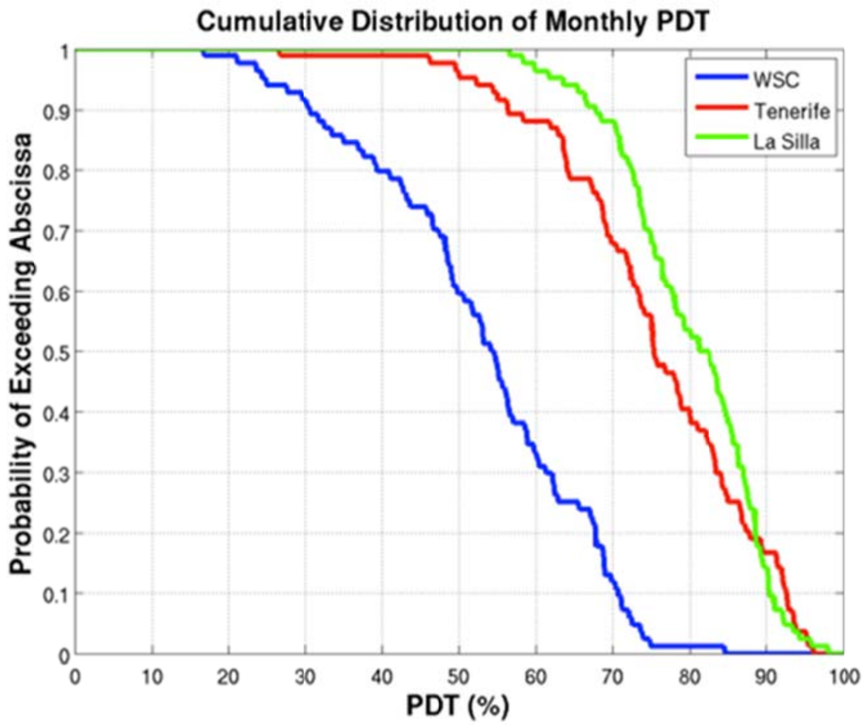
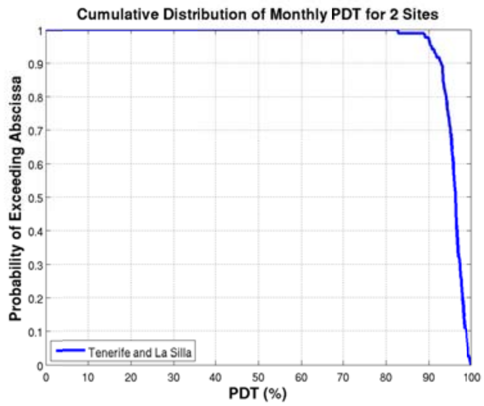


Figure 77: CDF of Monthly PDT for the three single sites used in the Earth Relay Optical Feeder link.

When sites are combined to create multi-site networks, the overall PDT increases dramatically. The geographic diversity of the three sites is on the order of 10,000 km. Therefore, the correlation of clouds between them is nearly independent. This situation results in networks with high PDT, since there is nearly always one sight with both access and CFLOS. The best two-site network, consisting of Tenerife and La Silla, has a PDT of nearly 96% and the three-site network performs at approximately 98%. The distribution of the monthly PDT for the best two- and three-site networks is shown in Figure 78. The probability of achieving 90% PDT each month is about 98% for the two-site network. For the three-site network, all months exceeded 90% PDT, and there is a 90% probability that the monthly PDT will exceed 95%.



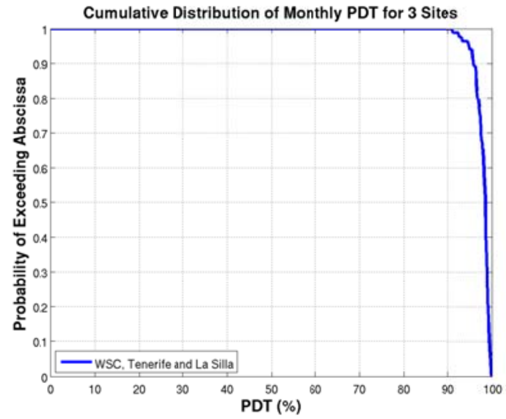


Figure 78: CDF of Monthly PDT for the best two-site network (left) and three-site network (right).

The distribution of data sent to the ground on a daily basis for the three-site network is given in Figure 79. Of the 216 Tb/day that is collected, at least 180 Tb of data are transmitted to the ground on nearly all days, given the storage limit of 10 Tb. At least 216 Tb of data are transmitted to the ground 60% of the time. Moreover, on a few days, the amount of data transferred is slightly greater than 216 Tb, because a small amount of data was carried over in the buffer from the previous day. If the data storage is increased by a factor of ten to 100 Tb, the PDT is 100%, and there are days when as much as 240 Tb are transmitted. Cross support for such a scenario (either 10 Tb or 100 Tb of storage) would be advantageous, as the scenario requires multiple geographically diverse sites of several space agencies.

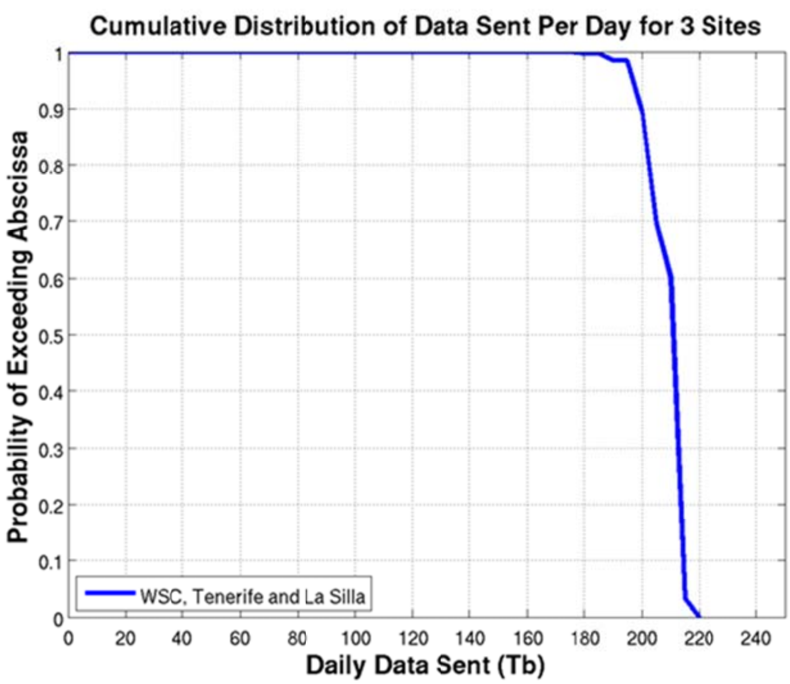


Figure 79: CDF of Daily data sent for the three site network.

4.1.5 Link Budget

4.1.5.1 ISL Link Budget

Given the OLSG's purpose, it is beyond the scope of this report to calculate/verify link budgets of ISL implementations. The capability/data rates of the ISL terminals as presented above are taken as verified reliable values.

4.1.5.2 Feeder Link Link Budget

4.1.5.2.1 RF Feeder Link

A link budget for the RF feeder link is not included in this report, as such link budgets are well understood, and not germane to this OLSG effort.

4.1.5.2.2 Optical Feeder Link

4.1.5.2.2.1 Downlink

Figure 80 shows a sample budget for an optical feeder link. The configuration of the LCRD mission is considered, with Ground Station 2 as a receive terminal. The calculation shows that the high data rate of 10 Gbps, implemented with DPSK modulation, is achievable at the lowest elevation angle in case of a benign atmosphere.

RELAY FEEDER LINK DOWNLINK BUDGET

INPUT PARAMETERS		
Range	39.77E+03	km
Elevation	20	deg
TRANSMITTER		
Modulation Type	DPSK	
Tx Wavelength	1.55	µm
Tx Ave Power	0.5	W
Tx Data Rate	10.0E+09	Hz
Tx Aperture Diam	0.1016	m
Tx Angular Diam	4.01	arcsec
Tx Footprint Diam	7.73E+02	m
Tx Optical Transmission	33.0	%
Tx Depointing	0.50	arcsec
Uncoded Slot Rate	20.0E+09	s^{-1}
Uncoded Bits Per Word	0.50	
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-1.0	dB
RECEIVER		
Rx Aperture Diam	1.00	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	26.3	%
Rx Array Size	1	apertures
Fiber Coupling Loss	-4.00	dB
Required Photons / Pulse	7.00	
Code Rate	0.50	

LINK BUDGET		
Tx Ave Power	**26.99**	**dBm**
Tx Photons / Pulse	3.90E+08	
Tx Antenna Gain	106.27	dBi
Tx Transmission Loss	-4.81	dB
Tx Pointing Loss	-0.27	dB
Isotropic Space Loss	-290.17	dB
Atmospheric Loss	-1.65	dB
Rx Antenna Gain	126.14	dBi
Array Gain	0.00	dB
Rx Transmission Loss	-5.80	dB
Rx Pointing Loss	0.00	dB
Rx Fiber Coupling Loss	-4.00	dB
Total Optical Path Loss	**-74.29**	**dB**
Ave Power at Rx Detector	**-47.31**	**dBm**
Photons / Pulse at Rx Detector	**14.51**	
Required Photons / Pulse	7.00	
Link Margin	**3.17**	**dB**

Figure 80: Example downlink budget for an optical feeder link in an Earth relay scenario

4.1.5.2.2.2 Uplink

A sample uplink beacon budget for the GEO relay scenario is shown in Figure 81. The transmitter, with the configuration of Ground Station 2, consists of four 15 cm apertures. The average power per aperture is 2.5 W, for a total transmitted power of 10 W. The irradiance required at the receiver aperture is based on the acquisition procedure of LLCD. The link closes with a good margin of more than 21 dB; therefore, an average power of about 40 mW per aperture could be sufficient on the ground.

RELAY FEEDER LINK UPLINK BUDGET

INPUT PARAMETERS		
Range	39.77E+03	km
Elevation	20	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	2.50	W
Tx Array Size	4	apertures
Tx Aperture Diam	0.15	m
Tx Angular Diam	2.71	arcsec
Tx Footprint Diam	5.23E+02	m
Tx Optical Transmission	46.3	%
Tx Depointing	0.80	arcsec
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	2.90	
Atm Transmission Along LOS	86.2	%
Scintillation Loss	-1.5	dB
RECEIVER		
Rx Aperture Diam	0.10	m
Rx FOV	5.00	arcsec
Rx Depointing	0.00	arcsec
Rx Optical Transmission	33.0	%
Rx Array Size	1	apertures
Req. Irradiance at rx aperture	63.0E-09	W/m^2

LINK BUDGET		
Tx Ave Power	**33.98**	**dBm**
Tx Antenna Gain	109.66	dBi
Tx Array Gain	6.02	dBi
Tx Transmission Loss	-3.34	dB
Tx Pointing Loss	-1.56	dB
EIRP	**114.76**	**dBW**
Isotropic Space Loss	-290.17	dB
Atmospheric Loss	-2.15	dB
Irradiance at rx aperture	**9.18E-06**	**W/m^2**
Rx Antenna Gain	106.27	dBi
Rx Array Gain	-3.01	dB
Rx Transmission Loss	-4.81	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-83.09**	**dB**
Ave Power at Rx Detector	**-49.11**	**dBm**
Req. Irradiance at rx aperture	63.0E-09	W/m^2
Link Margin (Irradiance)	**21.64**	**dB**

Figure 81: Example uplink budget for an optical feeder link in an Earth relay scenario

4.1.6 Ground Station and Relay Constellation Cost

4.1.6.1 Notional Feeder Link Ground Station Cost

Table 27 provides a cost estimation of the three optical ground stations for a single GEO relay, in accordance with Case b, as assumed for the notional optical feeder link consideration, above.

Table 27: Ground station costs for the notional single GEO Relay (Case b) Scenario (k€)

Relay Scenario Ground Station Costs in k€	La Silla	Tenerife	WSC	Total
<u>**Initial Station Investment Costs:**</u>				
Terminal (telescope, dome, and electronics)	6,230	6,230	618*	
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	1,168	1,560	1,560	
Wide Area Communication Investment Costs (ground comm)	1,560	0	0	
Weather and Atmospheric monitoring	250	250	250	
Aviation Safety System	350	350	350	
Subtotal Initial Station Investment Costs	**9,558**	**8,390**	**2,778**	**20,726**
<u>**Recurring Operating Costs:**</u>				
Site and Terminal Operating Costs	780	1,168	1,168	
Communication Operating Costs	390	390	390	
Subtotal Recurring Operating Costs	**1,170**	**1,558**	**1,558**	**4,286**

*assumes reuse of LLCD ground terminal with minor modifications

4.1.6.2 Earth Relay Constellation Cost

The notional optical relay scenario was based on LCRD—a single-satellite relay demonstration, which is not adequate for an operational relay system. The cost estimate for the optical communications relay constellation is for a hypothetical system modeled after the existing NASA TDRS relay constellation. The hypothetical constellation consists of four satellites (three operational and one spare), with six optical terminals on each satellite. Two satellites could be launched on a single launch vehicle. To provide PDT in the 95% range, at least seven ground stations would be required (optimized from the theoretical nine ground stations due to visibility from two relay satellites to the same ground site). The estimated cost of this system would be about 1,652 million Euros as described in Table 28 below. Note that in Table 28, the cost of a single ground station is taken to be the average of the initial ground station investment costs shown in Table 27, above.

Table 28: Optical Communications Relay Constellation Costs (k€)

Optical Communications Relay Constellation Costs in k€		
<u>**Component**</u>	**Amount needed**	**Cost (in k€)**
Satellite	4	194,600 per satellite
Launch Vehicles	2	116,700 per launch vehicle
Optical Terminals	24	70,000 per 6 terminals
Internal Electronics (demod/remod switching)	4	77,780 per satellite
Ground Stations	7	7,000 per ground station
Total Costs		**1,651,920**

The relay constellation cost shown in Table 28 includes the cost of the satellites and their launch into orbit. However, it may be possible to avoid a large portion of that cost in a future system by placing optical communications terminals on commercial communications satellites as hosted payloads. NASA's LCRD project is investigating just such a path by performing the relay demonstration on a commercial satellite.

4.1.7 Business Case

There are two opportunities for interoperability on Earth relay satellites:

1. LEO to GEO inter-satellite links
2. Feeder links

International interoperability is important to be able to transmit all of the information from various user science spacecraft in Earth orbit in a single day. For example, one Earth relay over Europe can only receive and relay a certain amount of data. Addition of a second Earth relay, especially on the other side of the world, allows more data to be transmitted to the ground. Having two Earth relays does not provide 24 hours a day /7 days a week coverage, but it does enable more data to be moved from the user spacecraft to the ground. Also, the second Earth relay can be considered as a backup in case of a catastrophic failure of the first relay.

In the future there will be many user spacecraft with optical communications terminals. Implementation of LEO to GEO inter-satellite links will require multiple relay satellites to be able to relay all of the data, therefore making this scenario a candidate for multiple agencies to share costs.

International interoperability is also important to provide optical communications service 24 hours a day, 7 days a week, which may be important to real-time operations, such as optical communications support to a human-rated vehicle or the International Space Station. At least three Earth relays would be needed in this scenario. For example, JAXA, NASA, and ESA could each fly one relay. Then each space agency only has to fly one Earth relay, as opposed to each space agency flying three satellites; there is also the question of a spare Earth relay.

International interoperability of the LEO-to-GEO inter-satellite links can best be achieved through an international standard covering such things as wavelength, polarization, modulation, coding, framing, etc. However, another way to achieve interoperability without having a standard at the link level is to fly both an ESA and a NASA optical communications terminal on an Earth relay. Interoperability then occurs in the backplane. In other words, the Earth relay can support both a user spacecraft using an ESA-type terminal and a user spacecraft using a NASA-type terminal. The received information can then be transmitted to the ground via the Earth relay's feeder link.

With regards to the Earth relay's feeder link, the CFLOS analysis shows that a strong case exists for cross support if the feeder link is an optical link. A relay satellite with an optical link can provide higher availability by utilizing more ground stations. Since relay satellites might require ground stations with telescopes on the order of 1 m, the cost of the ground station is not negligible. However, in the case of an RF-only feeder link, further study would have to be done to determine if there is a strong case for cross support.

GEO-to-GEO crosslinks are needed only in high availability scenarios and are de-scoped from this document.

4.2 Telecom Mission Optical Feeder Uplink

Telecom mission optical feeder uplinks are not considered in this document, as they are assumed to be in the commercial domain, and thus do not have a need for technical standardization for the purpose of cross support between space agencies. There could of course be a need for technical standardization to allow multi-sourcing of equipment for commercial telecom satellites.

Telecom mission optical feeder uplinks are driven by very high availability requirements, e.g., 99.9%.

The feasibility of optical feeder links will be investigated by ESA in a study that will start in 2012. Utilizing the Artemis satellite in geostationary Earth orbit and the Tenerife OGS, various transmit beam scenarios will be tested to find out how the scintillation effect on the uplink (the feeder link) can be reduced. Scintillations, or intensity fluctuations at the GEO spacecraft, are introduced by atmospheric turbulence close to the transmitting aperture. This so-called “shower curtain effect” renders uplink scintillations much stronger than downlink scintillations, and requires an extremely high dynamic range of the spacecraft-based receiver. Aperture averaging, such as on the downlink, is not possible.

Multiple, mutually incoherent transmit beams will be tested to reduce scintillations on the uplink.

4.3 Moon Relay Scenario

Not considered.

4.4 Mars Relay Scenario

Not considered.

5 Business Case Recommendation

This business case recommendation for optical space communication assumes that cross support will be needed for **routine** spacecraft operations, and that an RF-based communication system exists for TTC of the spacecraft (i.e., the optical communication system is considered an additional system with a dedicated space terminal and associated ground terminals).

Table 29 summarizes the notional technical designs and resulting PDT for the space-Earth scenarios. The single GEO optical Feeder Link (FL) relay (Case b) is included here, as it can be related to any spacecraft in GEO that employs optical communication to the ground for transfer of large volumes of data.

Table 29: Summary of space-Earth scenario analyses

Scenarios	Unit	LEO	Lunar	L2	L1	Deep Space (Mars)	Single Relay Optical FL (Case b)
Scenario ConOps							
Data Volume per day	Tb/d	12	5.72	7.5	7.5	1.1	216
Onboard Storage	Tb	2.3	7.4	22.5	22.5	1.1	10
Data Rate per second	Mb/s	10,000	622	700	700	0.7-260	10,000
CFLOS required per day	h/d	0.33	2.55	3	3	1.2	6
Onboard Terminal							
Aperture	cm	8	10	13.5	13.5	22	13.5
Tx Power	W	0.5	0.5	5	5	4	2.2
Mass	kg	35	30	50	50	< MRO Ka	50
Power Consumption	W	120	140	160	160	< MRO Ka	160
Ground Stations							
Rx Terminal Size diameter	m	0.4	1	1	1	12	1
Tx Apertures and Size		4x 5cm	4x 15cm	8x 15cm	8x 15cm	9x 7cm	4x 15cm
Tx NOHD ICAO (1550nm)	m	451	12,111	27,080	32,042	42,125	6,055
Tx NOHD Near Field (1550nm)	m	0	4,094	24,574	29,957	42,068	0
Number of Terminals		7	2	2	2	2	3
PDT resulting	%	94.8	97.4	99.9	98.5	99.0	98.0

There are two key factors that must be considered for the business case: 1) site diversity for weather mitigation, and 2) cost related to the size of the ground terminal serving a particular scenario. Therefore, an initial agreement on optical space communication cross-support solutions is necessary to distribute the global capabilities and cost among multiple space agencies.

5.1 Space-Earth Scenario Ground Costs

Conceptually, the ground station cost is split into non-recurring investment costs and recurring operating costs. The ground station investment cost is composed of the terminal, aviation safety system, weather and atmospheric monitoring system, site facilities, and wide area communication investment costs. The recurring operating cost is composed of the site and terminal operating running cost and the wide area communication investment cost.

The terminal, site facilities, and wide area communication investment costs are highly location-dependent, and costs were estimated based on stations that together produced 95% PDT based on the CFLOS analysis, as described in Section 2.2.1.2. Note that costs were calculated independently for each site for each scenario; therefore, if a site were to be used as a terminal location for more than one scenario, certain costs (such as wide area communication investment costs) would not be incurred for each additional scenario.

Table 30 summarizes the costs of the ground station infrastructure for the space-Earth scenarios. Cost estimates for the scenarios considered provide the PDT levels indicated; even higher PDT levels can be achieved at additional cost.

In summary, the scenario cost analysis demands standardized technical solutions to allow interoperability, and thereby economical investments and operations.

Table 30: Scenario ground costs

	LEO	Lunar	L2	L1	Deep Space	Single Relay Optical FL (Case b)
Percent data transmitted (PDT)	94.8%	97.4%	99.9%	98.5%	98.0%	99.0%
Number of stations required to achieve PDT:	7	2	2	2	2	3
Initial Scenario Ground Investment Costs (k€):						
Terminal (telescope, dome, and electronics)	3,367	15,264	10,904	12,460	102,810	13,078
Aviation Safety System	2,450	700	700	700	700	1,050
Weather and Atmospheric monitoring	1,750	500	500	500	500	750
Site Facilities Investment Costs (Buildings, Power, energy, etc.)	4,650	3,120	1,953	1,953	6,230	4,288
Wide Area Communication Investment Costs (ground communication)	2,188	157	1,242	1,242	157	1,560
Subtotal Initial Scenario Ground Investment Costs (k€)	***14,405***	***19,741***	***15,299***	***16,855***	***110,397***	***20,726***
Recurring Scenario Ground Operating Costs (k€):						
Site and Terminal Operating Costs	3,120	2,336	2,336	2,336	3,120	3,116
Communication Operating Costs	2,730	780	780	780	780	1,170
Subtotal Recurring Scenario Ground Operating Costs (k€)	***5,850***	***3,116***	***3,116***	***3,116***	***3,900***	***4,286***

5.1.1 Aspects of Site Selection

Because availability of site facilities and wide area telecommunication infrastructure are highly dependent on the chosen location, some aspects of site selection are elaborated further in this section of the report. Prospective sites for future ground stations should be evaluated to determine if they can provide support to multiple missions or scenarios to minimize the number of global sites that must be maintained. Such sites may host more than one type of terminal to achieve this capability, or host single terminals conforming to a common standard that are able to communicate with more than one mission or scenario type.

Site selection depends upon two primary factors:

- Weather—cloud free line of sight statistics, atmospheric conditions, wind, dust, etc.
- Infrastructure—readily available and usable land, electrical power, roads, telecommunications, etc. Note that the telecommunication requirement will ultimately be driven by the mission data rate and the allowable latency in data delivery. For example, a station supporting a downlink from a GEO relay at 10 Gb/s will likely need at least a 10 Gb/s communication link to the user,

while a station supporting one 10 Gb/s LEO pass per day may be able to buffer the data and send it out over a slower link.

The selection of a site will likely require a balance between these two factors to ensure reasonable cost.

5.1.1.1 Initial Set of Sites

Since some space agencies have experimental optical space communication facilities, it is probable that initial technology demonstrations and the first operational ground terminals will evolve out of these pre-existing sites. Additional sites would then be added as needed for particular missions. In general, these pre-existing sites were selected for their good weather and have existing infrastructure.

5.1.1.2 Other Existing Sites

When selecting additional sites to augment the initial set of sites, there is a potential for cost sharing of support facilities at existing RF tracking stations, astronomical observatories, or laser ranging sites. These sites would operate under the assumption that the optical communication terminal operations (particularly the uplink) do not disturb the sites' nominal observations.

5.1.1.2.1 RF Tracking Stations

The locations of the current RF tracking stations of the member space agencies could be considered, since there is existing infrastructure, e.g., roads, power, and telecommunications. These sites were originally selected for good weather relative to their planned operations in the RF spectrum, but may not be ideal from an optical communication perspective. Each location should be evaluated and when locations for new RF stations are being considered, the possibility of co-locating an optical communication terminal should also be considered. Note that if a station is good for optical communications, it will be excellent for Ka-band communications.

5.1.1.2.2 Astronomical Observatory Sites

Existing astronomical observatory sites could be ideal places to locate optical communication terminals (see the annex in Section 7.2 for a list of example sites). These locations were picked precisely because of their good weather and atmospheric conditions. They already have some infrastructure to support the current operations.

Special consideration will have to be given to coordinating operations between the astronomical observations and optical communications operations. The OLSG has developed a survey to assess the suitability of astronomical observatory locations for potential optical communications (see the annex in Section 7.3).

Initial interactions with astronomers at three locations (Mauna Kea, La Silla and USNO) indicate that co-location of optical communication terminals at astronomical sites is possible, but will require coordination. Some astronomical observations occur at or near the wavelengths used for optical communication and would require that the optical communication uplink lasers not affect these observations. The survey in Section 7.3 discusses the possible interference scenarios. With the advent of adaptive optics, the astronomers also use uplink lasers of their own. At sites where these guide stars are employed, there are well-established processes for coordinating laser transmissions to avoid interference. The optical communications transmissions would become a part of this coordination process. The downlinks from the spacecraft will also have to be considered since a "bright" downlink aimed at an astronomical site that is also observing at the same wavelength could disrupt the astronomical observations. For downlinks from LEO satellites, this disruption—if it occurred—would be very brief. For downlinks from the Moon or beyond, the disruptions could be over a longer period of time, but only if the spacecraft was within the beam of the astronomical telescope—which is very narrow. Again, careful coordination would be required.

Some observatory locations have decommissioned telescopes of various sizes that could be considered for use as optical communication terminals. In most cases, these telescopes range from less than 1 m up to 5 m in diameter and were designed for observing celestial bodies, so their domes and mounts would be appropriate for communication with satellites in GEO or at the Moon and beyond. Not having to build a new telescope could save money, but the trade will be that the telescopes may be in need of repair and may not be designed to operate during daytime, particularly at small Sun-Earth-Probe angles. Upgrading these existing telescopes to support LEO satellites would likely require modification to the domes and mounts. Instead of reusing complete existing telescope installations, it might also be possible to reuse only the platforms or domes, which would then be equipped with new telescopes.

5.1.1.2.3 International Space Laser Ranging (ISLR) Sites

Sites that are part of the International Space Laser Ranging (ISLR) network could provide excellent locations for optical communication ground terminals (see Section 7.4 for a list of sample sites). First, these sites were selected for good propagation characteristics and have some infrastructure. Second, since the ISLR stations both transmit and receive, the ability to transmit is a given, though coordination with existing site operations will be required. These sites would be good for hosting optical communications facilities, and in some cases the existing laser ranging telescopes could be modified with appropriate transmitters and receivers for optical communications.

5.1.1.3 Future Collaborative Sites

It is possible that existing sites will not provide the geographic diversity needed to optimize data return relative to the CFLOS statistics. The establishment of new sites capable of providing cross support at favorable locations with existing infrastructure is also a likely approach, as the ground station network is expanded. Several terminals might be sited at any one location to enable support for more than one mission or scenario, and provide infrastructure cost savings. Sharing of sites by multiple agencies (co-location of terminals) can provide global coverage if required. Even if agreement cannot be reached on interoperable standards, a minimum level of collaboration can be achieved through co-location of optical terminals at favorable locations.

5.2 Earth Relay Constellation Cost

The cost estimate for a complete optical Earth Relay Constellation modeled after the NASA TRDS system leads to a cost of 1,651,920 k€ (refer to Section 4.1.6.2 for details)

5.3 Standardization Considerations

Table 31 represents a set of parameters that need to be defined to ensure compatibility in a cross-support scenario using optical space communication. The parameters are split into two categories:

- Cross-support interface parameters describing characteristics that must be mutually communicated and agreed upon in order to ensure compatibility for cross support (i.e., the “What”).
- Implementation parameters describing station-internal engineering characteristics of the ground station’s technical implementation in order to satisfy/meet the interface parameters (i.e., the “How”). Conversely, an existing station’s design/implementation will determine the level of compatibility with a given interface requirement.

Note that the Beacon, Transmit and Receive Telescope and Laser implementation parameters are listed separately, following their logical functions. The actual implementation could well combine some or all of the functions in a single device—or keep them as separate installations.

Table 31: Parameters to be defined to ensure compatibility in an optical cross-support scenario.

Functional breakdown	Cross support interface parameters[4]	Implementation parameters
Acquisition Tracking	1. Re-/ Acquisition sequence a. Handshake / Initiation b. Protocol / Control 2. Uplink Beacon, if needed. If yes, then: a. Wavelength + linewidth b. Polarization + purity c. RSSI[5] range + stability d. Modulation 3. Receive Signal (S/C "beacon"): a. Wavelength + linewidth b. Polarization + purity c. Radiant Intensity[6] range + stability d. Modulation (direct / coherent…) 4. Tracking Method a. conical scan, if needed	A. Beacon Aperture B. Beacon Laser i. Technology ii. Power iii. Spectral & spatial beam characteristics iv. Modulation & control C. Beacon Pointing i. Control (-loop, if needed)/Nutator, if needed ii. Accuracy iii. Stability D. Telescope (Receiver) i. Aperture ii. PSF + FOV iii. Pointing stability E. Optical Bench i. Beam corrector ii. Polarization package, if needed iii. Coherent detection (interferometer, if needed) F. Detector / Focal Plane i. Technology ii. Sensitivity iii. Noise performance iv. Response time G. Receiver Back-end i. Demodulator
Data downlink	5. Downlink beam: a. Wavelength + linewidth b. Polarization + purity c. Radiant Intensity range + stability d. Modulation (OOK, BPSK, PPM, …) & characteristics (frame & slot widths, dead time,..) 6. Data coding a. SCCC, LDPC, Turbo, b. Error correction c. …possibly more…	H. Receive Telescope i. Aperture & (spectral-) throughput ii. PSF & FOV iii. Pointing control, accuracy & stability I. Optical Bench i. Beam corrector ii. Polarization package, if needed iii. Coherent detection (interferometer, if needed)

[4] It is expected that the nominal value, range and variation / stability would be specified for each parameter
[5] Received Signal Strength Intensity [nW/m^{-2}] at satellite
[6] Intensity irradiated from S/C into solid angle in the direction of Ground Station [W/sr]

Functional breakdown	Cross support interface parameters[4]	Implementation parameters
	7. Link protocol + control a. Sync pattern b. Data (frame) structure (CCSDS packet TM, etc.) c. DTN d. …possibly more…	J. Detector / Focal Plane i. Technology ii. Sensitivity iii. Noise performance iv. Response time K. Receiver Back-end i. Decoder ii. De-interleaver iii. …possibly more…
Data uplink	8. Uplink beam: a. Wavelength + linewidth b. Polarization + purity c. RSSI range + stability d. Modulation (OOK, BPSK, PPM, …) & characteristics (frame & slot widths, dead time,..) 9. Data coding a. SCCC, LDPC, Turbo, b. Error correction c. …possibly more… 10. Link protocol + control a. Sync pattern b. Data (frame) structure (CCSDS packet TM, etc.) c. DTN d. …possibly more…	L. Transmit Telescope i. Aperture & (spectral-) throughput ii. Angular beam width iii. Pointing control, accuracy & stability M. Uplink Laser i. Technology ii. Power iii. Spectral & spatial beam characteristics iv. Modulation & control N. Optical Bench i. Polarization control, if needed ii. Beam corrector, if needed O. Transmitter Back-end i. Encoder ii. Interleaver iii. Randomizer iv. …possibly more…

For completeness, Table 32 lists additional parameters, which while not part of the space link, itself, nevertheless are important to determine cross-support compatibility and also relate to station design.

Table 32: Additional parameters (not related to the space link) to be defined.

Scenario-Related Parameters		
	Cross-support related	***Ground station related***
Operational Scenario	11. Site geographic location 12. Orbit ephemeris a. Satellite visibility 13. Daily availability 14. Communication / mission model 15. Station Hand-over	P. Telescope mount i. Elevation, azimuth limits ii. Slew rate Q. Local horizon R. Local (& seasonal) weather[7] i. Weather station ii. Prediction capability S. Scheduling / Handover infrastructure (via control center, if needed)
Data interface on ground	16. SLE 17. File-based distribution 18. Latency requirement 19. …likely more…	20. Ground communications infrastructure 21. Data storage capacity 22. …likely more…

5.3.1 Issues of Interoperability

5.3.1.1 Wavelength

Two wavelengths are considered for optical communications today—1064 nm and 1550 nm. Eye safety considerations for uplinks from the ground favor 1550 nm; however, depending on the required uplink power and number of apertures, neither 1550 nm nor 1064 will be eye safe at the exit of the aperture, and thus will require additional safety measures. For manned spaceflight, additional eye safety factors need to be considered. For downlinks, the OLSG has identified the following options:

- Standardize a single wavelength for all scenarios
- Standardize a single wavelength for each scenario
- Standardize both wavelengths and encourage implementation of both at ground stations

The OLSG recognizes that the existence of national industrial bases for flight terminals may necessitate the adoption of a multiple wavelength strategies at the ground stations. The 1550 nm technology may be advantageous because of its synergy with terrestrial fiber-optic components, however the performance of both the 1064 nm and 1550 nm wavelengths should be considered. The availability of space-qualified or qualifiable parts should also be considered.

[7] Weather includes all relevant effects: clouds, absorption, seeing, winds (requiring dome closure), etc. While clearly NOT an *implementation* parameter, nevertheless *knowledge* and *predictability* of weather determine a station's suitability for a given scenario.

5.3.1.2 Dual Wavelength Telescopes

If agreement cannot be reached on a single wavelength, there is still the potential for cooperation using dual wavelength telescopes. Future telescopes should not preclude the use of both wavelength bands (1064 nm and 1550 nm). Cooperation will happen by deploying mission-specific back end equipment.

5.3.1.3 Detection Schemes

Fundamentally, there are two detection schemes—coherent detection and direct detection. Current consensus for the deep space (photon starved channel) scenario is PPM with a single photon counting detector. For all other scenarios, a conclusion cannot be drawn at this time. The OLSG recommends that only one modulation and detection scheme per scenario be defined wherever possible.

5.3.2 IOAG Services and Optical Links

This section investigates the impact of an optical-space-link standardization on the IOAG Service Catalogue #1. The IOAG Service Catalogue #1 describes the cross-support services that will be provided by the ground tracking assets (services for in-space relay and network scenarios are to be described in a distinct catalogue).

5.3.2.1 Layer Architecture and Consultative Committee for Space Data Systems (CCSDS) Interfaces

For IOAG Service Catalog #1, the currently most relevant Return Services (downlink services) are defined at frame level. Frames are defined in the Data link protocol sublayer (see Figure 82). So, for these relevant services, the interface between a ground station and a control center can be used immediately "as is." The frame structure to follow is defined either in CCSDS 132.0-B TM Space Data Link Protocol (Blue Book) or in CCSDS 732.0-B AOS Space Data Link Protocol (Blue Book). Independently, the "Synchronization and channel coding" sublayer and the physical layer can be modified for the implementation of optical links. These modifications would be associated with the production of new interface standards handling optical parameters instead of traditional ones.

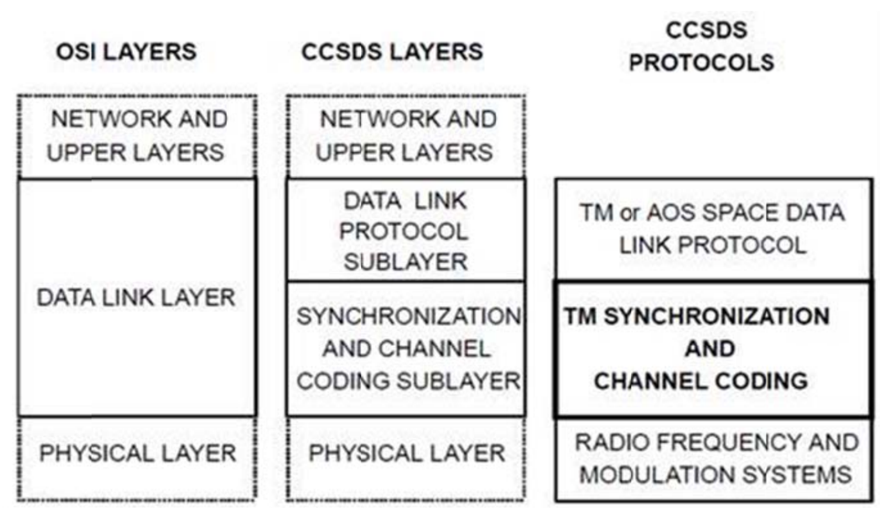


Figure 82: CCSDS Layers and Protocols.

For example, the “Return All Frames” and the “Return Channel Frames” services shown in Table 33 can be used for optical links, but new interface standards will have to be added in the second column. Figure 83 shows how optical standards could fit next to current CCSDS protocols.

Table 33: Description of the Return All Frames Service (copied from the IOAG Service Catalogue #1).

IOAG Service Types	Space Link Interface Standards	Ground Link Interface Standards
Return All Frames Service	1 Radio Frequency and Modulation [RFM] 2 TM Synchronization and Channel Coding [TM-S&C]	1 SLE Return All Frames [RAF]
Return Channel Frames Service	Those for “Return All Frames Service” plus: TM Space Data Link Protocol [TM-DLP] AOS Space Data Link Protocol [AOS]	SLE Return Channel Frames [RCF]

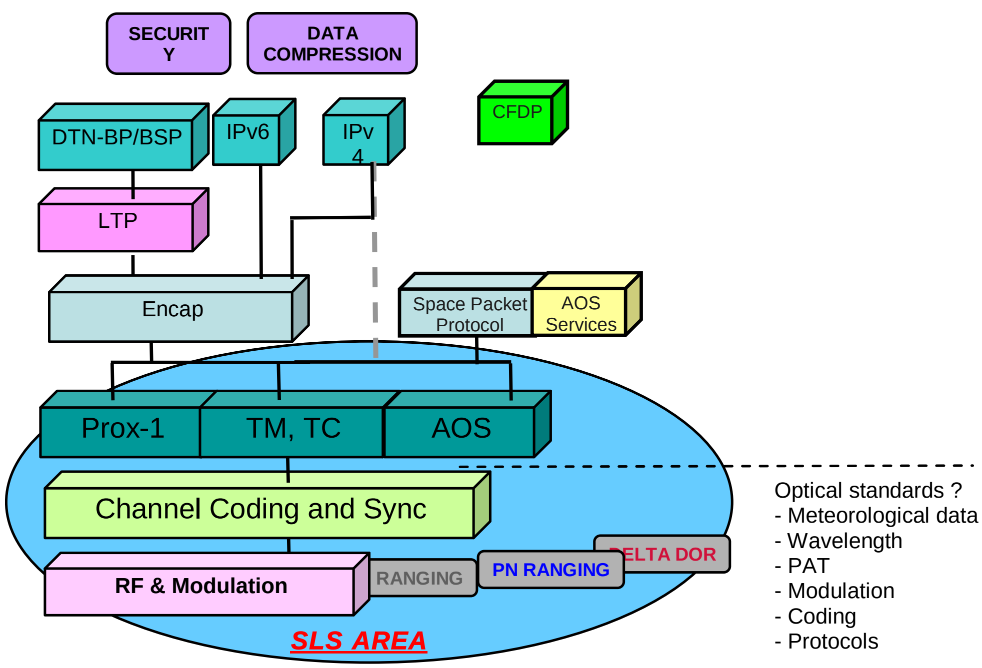


Figure 83: Current protocols of the Space Link Service area. Possible future optical standards would fit in the lowest two layers.

For the sake of simplicity and effort reduction, one may consider, as a first step, optical space link standards that

1. affect only the "Synchronization and channel coding" sublayer and the physical layer,
2. provide an interface to IOAG return services defined on the frame level (data link protocol sublayer and above), and
3. do not impact the ground link standards (which are associated with the Space Link Extension services).

5.3.2.2 Impact of High Data Rates

A large increase of the data rate with respect to current links can imply the need for new protocol standards.

5.3.2.2.1 Space Link

An optical space link can easily support 10 Gb/s. To avoid new standards or services for data rates that are too high, two solutions related to data processing can be considered:

- Increase of the frame coding/decoding speed
- Offline decoding processing (i.e. store and retrieve later "slowly")

The frame format defined by both CCSDS 132.0 and 732.0 is limited to about 16 kbits. Increasing the frame size (to keep the frame rate constant) would require new standards for the data link protocol sublayer, and thus new cross-support services.

5.3.2.2.2 Ground Link

When the space link has repeated periods of unavailability and the ground terminal can store the data, the ground link (from ground terminal to operation center) does not have to support data rates as high as those of the space link. However, it should be guaranteed that the long-term capacity of the ground link is higher than that of the space link. As a guideline, one can consider the Space Link Extension-Application Programming Interface (SLE-API) software which currently shows a performance limit of 700 Mbps excluding frame encoding overhead but including SLE protocol overhead etc. (i.e. a real limit around 90-95% of this figure).

5.3.3 Diversity of Technical Solutions

At this time there are numerous technical solutions being investigated by member agencies. No one solution can be identified for standardization at this time. As an example of this diversity, Table 34 describes the wavelengths and acquisition and modulation techniques planned for demonstration over the next few years, and depicts the level of diversity in the technical solutions.

Table 34: Characteristics of Upcoming Optical Communication Demonstrations

System	Scenario	Wavelength Downlink [nm]	Wavelength Uplink [nm]	Acquisition technique	Detection, Modulation, Coding Downlink	Detection, Modulation, Coding Uplink
Space-Earth						
LCT-125 (DLR TerraSar-X 2009)	LEO-GND	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
Optel-µ (ESA RUAG Space 2017)	LEO-GND	1545, 1565	1064	Beacon	Direct detection, OOK	PPM uplink
OSIRIS (DLR-IKN)	LEO-GND	1545	1560	Beacon – open loop	OOK downlink	N/A
LEOLINK (NASA-JPL)	LEO-GND	1550 C-band CWDM	1568	Beacon – closed loop	OOK downlink	N/A
SOTA (NICT)	LEO-GND	1550 and 975	1064	Beacon	Direct detection	OOK
LCT-135 (ESA Alphasat 2013)	GEO-GND (Earth relay Feeder Link)	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
LCRD (NASA 2017)	GEO-GND (Earth relay Feeder Link)	1550	1558	Beacon	a) Direct detection PPM b) Direct detection DPSK	a) Direct detection PPM, b) Direct detection DPSK
LLCD (NASA 2013)	Moon-GND	1550	1558	Beacon	Direct detection photon counting PPM	Direct detection PPM
DOT (NASA-JPL 2018)	Mars-GND	1550	1030	Beacon	Direct detection, photon counting PPM	Direct detection, photon counting PPM
Earth Relay Inter-Satellite Link (ISL)						
LCT-125 (DLR TerraSar-X <-> NFIRE 2008)	ISL LEO-LEO	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
LCT-135 (ESA Alphasat 2013)	ISL LEO-GEO	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
LCT-135 (ESA EDRS, Sentinel 2014)	ISL LEO-GEO operational	1064	1064	Comm beam uplink	Coherent Detection, Homodyne BPSK	Coherent Detection, Homodyne BPSK
LCRD (NASA 2017)	ISL LEO-GEO	1550	1558	Beacon	a) Direct detection PPM b) Direct detection DPSK	a) Direct detection PPM, b) Direct detection DPSK

6 Recommendations and Conclusions

Having established the benefits of cross support, the OLSG recommends:

1. IOP-3 should consider the question of optical link interoperability in addition to RF interoperability, due to the unique challenges related to weather outages/interference. Optical link interoperability will result in even more benefit to space agencies than interoperability for RF communications, as it will boost scientific data return.
2. Encouragement of early demonstrations of cross-support scenarios that will demonstrate the value of cross support in the optical communication domain and confirm the findings of the OLSG.
3. As the ICAO eye-safety calculation assumes a far-field approximation, and does not consider an extended source for the uplink beacons, the OLSG seeks a dialog with ICAO to develop a more refined calculation method for the near field, which will be more appropriate for the scenarios analyzed by the OLSG in this report.
4. Due to the diversity of technical solutions being implemented by the agencies for operational use (EDRS), and numerous technology preparations and demonstrations, the following strategy is proposed (see Figure 84):
    a. That the OLSG continues its work by producing a "Standardization Guidance Addendum" to this report by November 2012, with the aim to define guidance for the standardization process.
    b. That technical assessments of realized optical communication solutions are shared between the agencies, using the CCSDS Optical Communication Special Interest Group (SIG) as a forum for exchange.
    c. That the CCSDS Optical Communication SIG prepares a concept paper and charter for standardization, taking into account recommendations from the Interagency Operations Panel (IOP-3), leading to the formation of a CCSDS Optical Communication Working Group by Spring 2014.
    d. That the CCSDS Optical Communication Working Group shall within 3-4 years produce agreed standards based on continued technical assessment for implementation in cross supportable missions in the early 2020s.

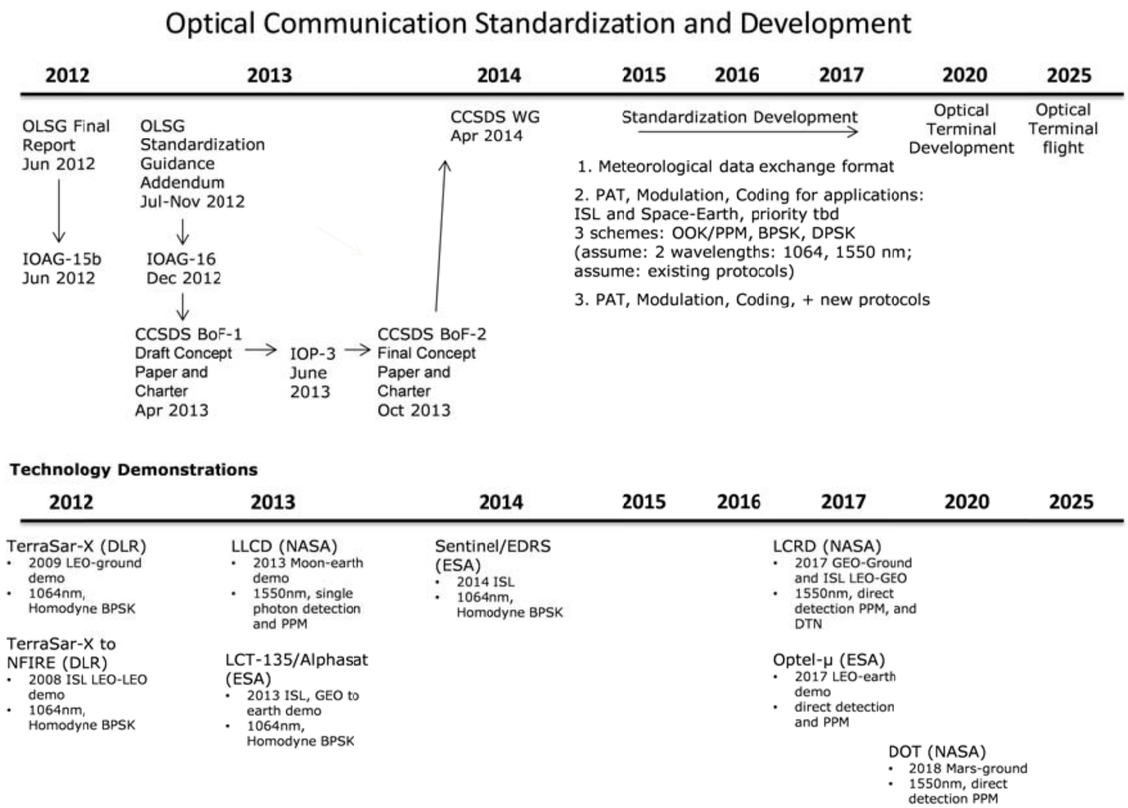


Figure 84: Proposed schedule of optical communication standardization and development.

7 Annex

7.1 Existing and Prospective Optical Assets and Sites

These sites include existing and prospective optical assets in:

- Oberpfaffenhofen, Germany (DLR)
- Tenerife, Spain (ESA)
- Table Mountain, California (NASA)
- Tokyo, Japan (NICT)

CNES has no OGS for the moment, but is preparing to procure its first transportable OGS by the end of 2014. This OGS will be installed in CNES Toulouse initially.

7.1.1 DLR's OGS (Oberpfaffenhofen)

Figure 85 shows DLR's OGS. Short contact durations and atmospheric perturbations require a fast and robust link acquisition procedure. A powerful uplink beacon can be made divergent enough to cover the uncertainty cone of the satellite position. Multiple spatially displaced beacon transmitters can mitigate turbulence-induced fades.

The ground terminal shall perform a fine optical tracking so that the Rx-beam can precisely reach the communication detector.

Geographical location	48.082° N, 11.276° E
Height above sea level	645m
Height above ground	11m
Dome	4m clamshell
Telescope type	40cm Cassegrain

Figure 85: Optical ground station at DLR Oberpfaffenhofen.

7.1.2 ESA's OGS (Tenerife)

ESA's optical ground station (Tenerife OGS) is shown in Figure 86. It is located at the Observatorio del Teide (OT) on a mountain range called Izana in Tenerife, Spain. The Tenerife OGS was initially built to test and commission the laser communication terminal onboard the ARTEMIS satellite. The Tenerife OGS is located at an altitude of 2393 meters, well above the first inversion layer where clouds are formed.

Figure 86: Izana, Tenerife, shown in aerial photograph (left) with Mount Teide in the background and ESA's optical ground station (Tenerife OGS) building (right).

The Tenerife OGS uses a 1-meter Zeiss telescope (see Figure 87) with English equatorial mount. Tracking of LEO satellites has been successfully implemented, although pointing towards northern directions is difficult because of the hour axis singularity.

Geographical location	28.082° N, 16.276° W
Height above sea level	2393m
Height above ground	12m
Dome	12.5m diameter
Telescope type	100cm Richey-Chretien / Coude

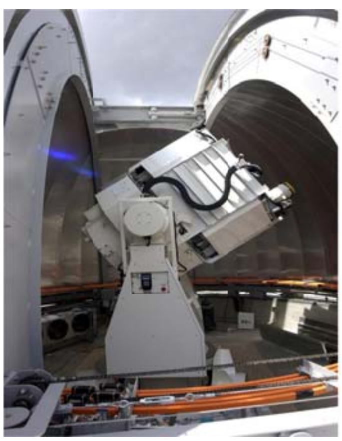
Figure 87: 1-meter Zeiss telescope and English mount of the ESA Tenerife OGS.

7.1.3 NASA's OGS (Table Mountain)

The NASA/JPL OCTL is a research and development facility that could be used operationally for supplying beacon and data to spacecraft. OCTL was developed to investigate and address issues that affect ground-to-space optical communications to NASA's near-Earth and deep space probes. Located at 340 22.9' North Latitude, 1170 40.9' West Longitude and 2.2 km altitude in the San Gabriel mountain range of Southern California, the OCTL facility lies above the densest part of the atmosphere, where atmospheric seeing typically ranges from 0.5 to 2 arc-second at night and 2 to 5 arc-second during the day. The OCTL building is located at 2440-m elevation in JPL's Table Mountain Facility. OCTL's telescope is a 1-m, f175.8 coude focus instrument that can be rapidly accessed from any one of four ports to support high power laser beam propagation and reception (see Figure 88).

Figure 88: NASA's OCTL building and telescope.

A 20-cm acquisition telescope bore sighted to the main telescope allows bi-static operation with transmission and reception from either or both telescope apertures. In addition, this smaller telescope is used as the receiver for line-of-sight cloud detection. Designed to support satellite tracking from low-Earth orbit to deep space, the telescope slews at speeds up to 10°/s in elevation and 20°/s in azimuth. Built to support both daytime and nighttime operation the primary mirror is enclosed in louvered baffles to allow pointing as close as 10° of the Sun.



Geographical location	34° 22.9' N latitude, 117° 40.9' W longitude
Height above sea level	2.2 km
Height above ground	5 m
Dome	6m Sliding Partition Roof
Telescope type	1.0 m Coude

Figure 89: The OCTL telescope and parameters.

For laser propagation out of the facility, OCTL is equipped with a three-tier safety system (see Figure 90).

- Tier 1 - Two wide field-of-view long wavelength infrared cameras for ranges up to ~5 km
- Tier 2 - A radar for ranges up to 42 km
- Tier 3 - Coordination with the Laser Clearinghouse (LCH) for possibility of spacecraft in the beam path

In addition, spotters are used with binoculars to provide an additional safety measure. JPL is in the process of coordinating with the Federal Aviation Administration (FAA) to automate this process based on sensors and data from the LCH and the FAA.

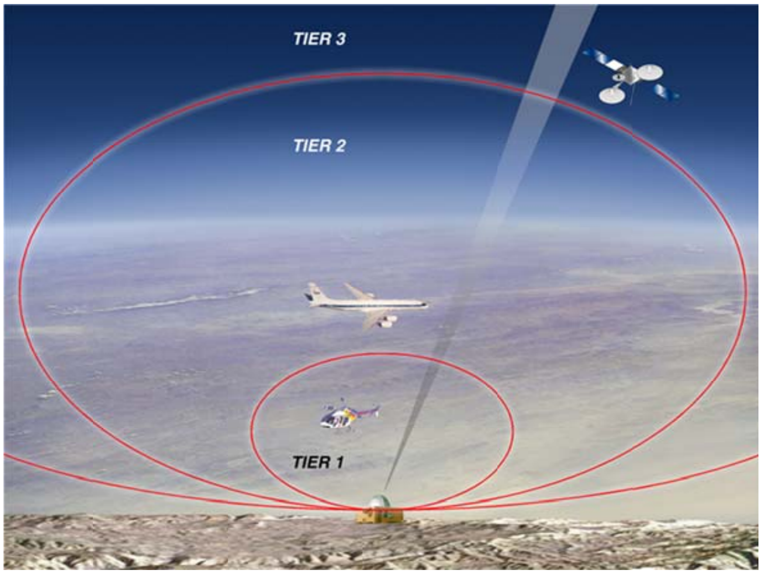


Figure 90: OCTL's Three-tiered safety system.

7.1.4 NICT's OGS (Tokyo)

NICT's optical ground station (shown in Figure 91) is located at Koganei, west of Tokyo in Japan. This ground station is an experimental station for research on optical communications and satellite laser ranging.

Figure 91: Koganei, Tokyo, 1.5m telescope (left) and OGS (right).

This OGS has been used for the feeder link test of Engineering Test Satellite VI (ETS-VI) and for the LEO direct link test of OICETS (in cooperation with JAXA [National Space Development Agency of Japan] and NICT [Communication Research Laboratory]).

As shown in Figure 92, the site is located at an altitude of 121.8 m, and uses a 1.5m telescope from Contraves (Currently Brasher LP). The system has performed all optical communications tests successfully.

The telescope has been operated locally and independently without any communication line interface with the Tsukuba Space Center of JAXA located at Tsukuba city, Ibaraki Prefecture, Japan.

Geographical Location	35.7102° N 139.4879° E
Height above sea level	121.8 m
Height above ground	7 m
Dome	11 m sliding roof
Telescope type	1.5 m Nasmyth/Bent Cassegrain/Cude

Figure 92: 1.5 meter Contraves (Currently Brasher LP).

7.2 *List of Astronomical Observatory Sites*

Table 35 lists some astronomical observatory sites that may be of interest for use as optical communication terminal locations.

Table 35: List of Astronomical Observatory Sites

Designator (a.k.a.)	Location	Dia. (m)
OCTL	Table Mtn, CA	1.00
Oschin	Mt. Palomar, CA	1.20
Swiss 1.2-metre Leonhard Euler Telescope (ESO)	La Silla, Chile	1.20
Danish 1.54-metre Telescope (ESO)	La Silla, Chile	1.50
Palomar 60"	Mt. Palomar, CA	1.50
Kitt Peak 2.1m	Kitt Peak, AZ	2.10
Struve	McDonald Obs., TX	2.10
UH88	Mauna Kea, HI	2.20
Max Planck Gesellschaft/ESO 2.2m	La Silla, Chile	2.20
Bok	Kitt Peak, AZ	2.30
WIRO	Jelm Mt, WY	2.30
SINGLE	Magdalena Ridge, NM	2.40
Hiltner	Kitt Peak, AZ	2.40

Designator (a.k.a.)	Location	Dia. (m)
Hooker	Mt. Wilson, CA	2.50
Smith	McDonald Obs., TX	2.70
IRTF	Mauna Kea, HI	3.00
Shane	Mt. Hamilton, CA	3.00
WIYN	Kitt Peak, AZ	3.50
Starfire 3.5	SOR, NM	3.50
Apache Point 3.5	Sunspot, NM	3.50
Telescopio Nazionale Galileo (TNG)	Canary Islands, Spain	3.58
New Technology Telescope (ESO)	La Silla, Chile	3.58
3.6 m Telescope (ESO)	La Silla, Chile	3.60
AEOST	Haleakala, HI	3.70
UKIRT	Mauna Kea, HI	3.80
Anglo-Australian Telescope (AAT)	Siding Spring Observatory, Australia	3.90
Mayall	Kitt Peak, AZ	4.00
Air Force Academy	Colo. Springs, CO	4.00
Very Large Telescope Array (ESO)	Paranal, Chile	4x8.2 + 4x1.8
Visible and Infrared Survey Telescope for Astronomy (ESO)	Paranal, Chile	4.10
Discovery Channel	Happy Jack, AZ	4.25
Hale	Mt. Palomar, CA	5.00
MMT	Mt. Hopkins, AZ	6.50
Suburu Telescsope (National Observatory of Japan)	Mauna Kea, HI	8.20
Hobby-Eberly	Mt Fowlkes, TX	9.20
Southern African Large Telescope (SALT)	Karoo, South Africa	9.20
Keck 1	Mauna Kea, HI	10.00
Keck 2	Mauna Kea, HI	10.00
Gran Telescopio Canarias (GTC)	Canary Islands, Spain	10.40
LBT	Mt Graham, AZ	11.89

Notes:

- This is not an exhaustive list and does not include the many decommissioned telescopes around the world.
- Most astronomical telescopes are for night use only and may need significant modification for day use.
- The 1.0-2.0 m class telescopes shown are just examples, since there are many in this class.
- The telescopes above 5 m are in heavy use by astronomers.

7.3 *Astronomical Site Survey*

The OLSG has developed the survey below to assess the suitability of astronomical observatory locations for potential optical communications. The survey consists of a brief explanation of the OLSG effort, a series of questions to determine if the site is a good candidate for optical communications operations, followed by background information (including uplink and downlink flux tables and explanatory diagrams) to assist site personnel in answering the questions.

OLSG ASTRONOMICAL SITE SURVEY

The Interagency Operations Advisory Group (IOAG) is a forum for identifying common needs across multiple international agencies for coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications. Member agencies include ASI, CNES, DLR, ESA, JAXA, KARI, and NASA. The IOAG's Optical Link Study Group (OLSG) is investigating the value/feasibility of implementing Earth/satellite communications via optical (laser) links. The OLSG is studying a scenario where optical ground terminals would be placed at various global sites to communicate with spacecraft.

The OLSG is studying sample representative locations for these terminals on Earth. To minimize costs, the OLSG is investigating the co-location of optical terminals at sites that already have infrastructure in place (Internet connections, power, etc.) and are fairly free of clouds, which interfere at this wavelength. Astronomical observatories may be potential candidate terminal sites, if terminal and observatory operations can operate without negative impact to each other.

Could you please assist the OLSG with this feasibility study by answering the following questions?

1. Are you willing to host an optical communications terminal at your site?

2. We are considering uplink transmissions at 1550±20 nm, 1030 nm, and/or 1064 nm (please see Table 1). Do you conduct observations that would be affected by uplinks at these wavelengths? If so, how often?

3. We are considering downlink transmissions at 1550±20 nm and/or 1064 nm (please see Table 2). Do you conduct observations that would be affected by downlinks at these wavelengths? If so, how often?

4. Which wavelengths do you transmit from your site? How often?

5. What is your process for coordinating and controlling laser transmissions to and from the site? How far in advance is the operations schedule distributed?

6. What sort of telecommunications infrastructure do you have at your site? Is high-speed (100 Mb/s or greater) access available onsite and to external locations?

7. Are there any decommissioned telescopes at your site that could be used for optical communications? What types and diameters? Who owns each? When was each last used and what is its mechanical and optical state?

8. Are there requirements for EMI shielding of ground equipment at the site?

9. Do you gather any statistics about clouds, seeing, etc., for your site? Do you monitor any statistics on a real-time basis?

10. Are there any other factors we need to consider? (e.g., Are there any foreseen difficulties regarding the addition of a structure at your site due to local laws/regulations? Are there additional organizations with facilities/telescopes at the site with whom we need to coordinate?)

11. What “rent” would we be charged if we located our transmitter and receiver on the site (could be either one or two structures)? What does the rent cover?

Below is some information that you may find useful in answering these questions:

Each optical communications ground terminal would consist of two telescopes (which could potentially be combined into one): an uplink transmitter and a downlink data receiver. The two telescopes would not necessarily have to be on the same structure and the allowable distance between the two structures would depend on the type of mission supported. We are considering uplink transmission (ground to space) at 1550±20 nm, 1030 nm, and/or 1064 nm and downlink transmissions (space to ground) at 1550±20 nm and/or 1064 nm. The OLSG is considering optical communications support for several types of space missions, including spacecraft in Low Earth Orbit (LEO), in Geostationary Earth Orbit (GEO), in Lunar orbit, at the Sun-Earth L1 and L2 points, and in deep space (e.g., in Mars orbit). For the purposes of this questionnaire, optical ground terminal parameters can be categorized as follows:

- **To support LEO spacecraft:** The receiver (downlink) telescope would be ~ 50 cm and the transmit (uplink) telescope aperture would be ~ 40 cm. The spacecraft transit over the site would be on the order of minutes. The elevation and azimuth tracks could vary widely depending upon the orbit of the spacecraft.
- **To support GEO spacecraft:** The receiver telescope would have a diameter up to 1 m and the transmit telescope would be ~ 40 cm in diameter. Tracking would be limited to basically transmitting and receiving continuously at a fixed point in the sky above Earth’s equator, with the azimuth and elevation dependent upon the orbital slot of the spacecraft.
- **To support spacecraft beyond the geostationary orbit, e.g., Lunar, Sun-Earth L1 and L2, Mars, etc.:** The receiver telescope aperture would be ~ 1 -12 m, and the transmit telescope aperture would be ~ 1 m. The tracking rate would be equivalent to the rotation rate of the Earth and the elevation and azimuth of the track would depend upon the location of the spacecraft in the Solar System. Depending upon the orbital location of the target spacecraft, optical communications would occur in daytime only (for L1 missions), nighttime only (for L2 missions), or during the day and night (for Lunar, Mars, and other deep space missions).

The tables below provide expected parameters for uplink (Table 1) and downlink (Table 2) at 1550 nm for a single spacecraft pass for each mission type. Transmissions at 1030 nm or 1064 nm will yield similar parameters. Note that a ground terminal may support multiple passes per day of different types of spacecraft.

Table 1: Estimated Uplink Laser Scattered Flux from Uplink Beacon (Rayleigh scattering calculated at 1550 nm)

Mission Type	Average Uplink Power (W)	Mean Irradiance (W/m^2) at telescope due to scattered uplink laser. Engagement zone is 1 km away	Mean Irradiance (W/m^2) at telescope due to scattered uplink laser. Engagement zone is 3-km away
LEO	0.5	1 E-14	2.5 E-15
GEO	10	0.2 E-12	0.45 E-13
Lunar	40	0.8 E-12	1.8 E-12
L1	560	1.1 E-11	0.9 E-13
L2	400	8 E-12	0.9 E-13
Mars	5000	0.8 E-10	2 E-11

NOTES:

- Aerosol scattering can vary by a decade or (up or down) depending on the site and time of day or time of year
- See Figures 1 and 2 below for configuration assumed in calculating mean irradiance.

ASSUMPTIONS:

- Worst case analysis
- Ground astronomical telescope with field-of-view of 1 milliradian
- 1550 nm uplink laser
- Uplink beam divergence was ignored
- Station at 1.5 km above sea level
- Assumed no atmosphere loss (appropriate for good sites)
- The zenith angle is 45 degrees

Table 2: Downlink Signal Flux at the Ground Telescope from Deep-space and Near-Earth Spacecraft (assumed 1550nm wavelength) – worst case (upper limit values)

Mission Type	Range	Mean Irradiance Above Atmosphere @ 1550 nm	Peak Irradiance @ 1550 nm	Beam Full Width at Half Maximum (FWHM) Footprint at Ground (m)	Beam 1/e^2 Footprint on Ground (m)	Typical Contact Duration
LEO	800 km	160 µW/m^2	320 µW/m^2	30	50	< 15 minutes
	2,000 km	30 µW/m^2	60 µW/m^2	72	123	<15 minutes
GEO	40,000 km	250 nW/m^2	4 µW/m^2	600	980	continuou s
Lunar	400,000 km	3.6 nW/m^2	57.6 nW/m^2	5760	9603	0.25 to 2 hours
L1	1.83E6 km	5.6 nW/m^2	112 nW/m^2	14800	25084	8-12 hours
L2	1.65E6 km	5 nW/m^2	100nW/m^2	13600	23050	8-12 hours
Mars	0.42 AU	4 pW/m^2	80 pW/m^2	4.4 E+05	7.4 E+05	6 to 11 hours

NOTE: Interference will be an issue only if there is a major overlap of the fields of regard.

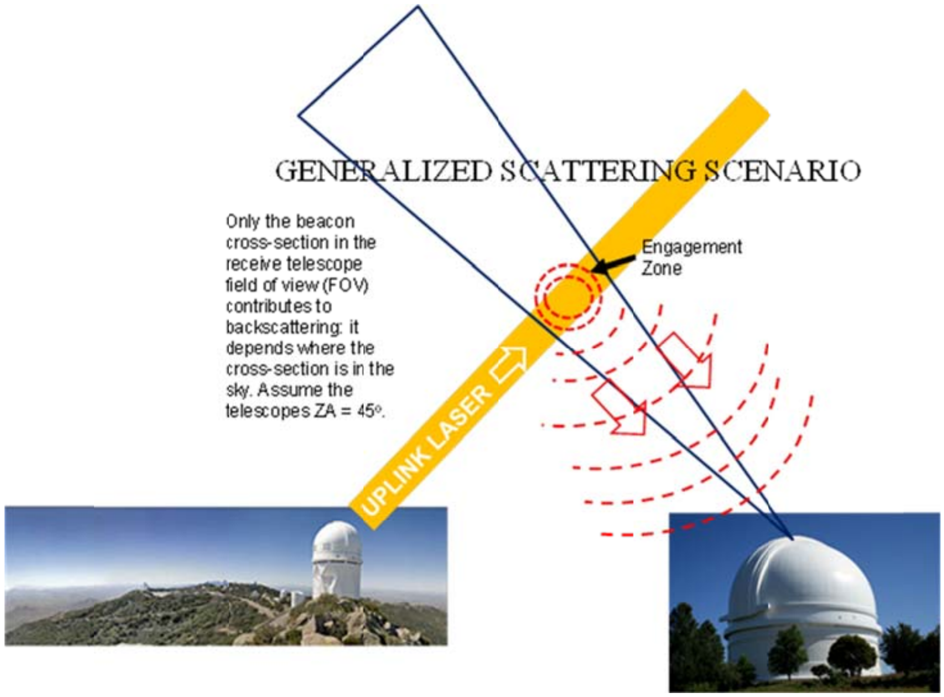


Figure 1: Scattering Scenario

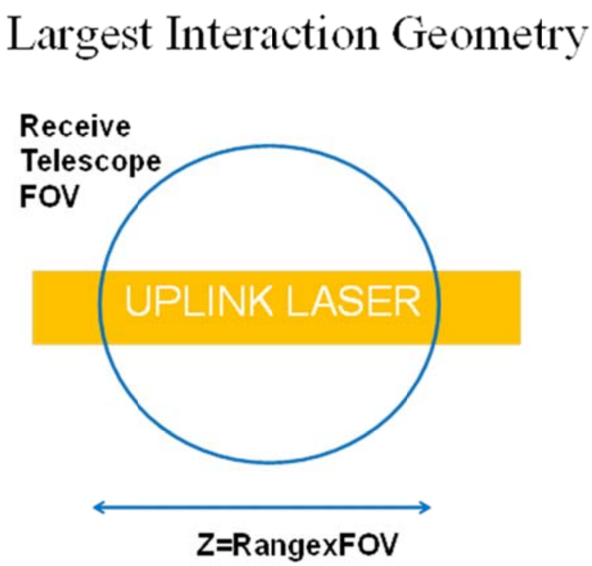


Figure 2: Interaction Geometry

7.4 Laser Ranging Sites

These are some International Satellite Laser Ranging Network sites that might be of interest for optical communication.

- Monument Peak, California, (USA)
- Greenbelt, Maryland (USA)
- Fort David, Texas (USA)
- Mt. Haleakala, Maui (Hawaii, USA)
- Arequipa, Peru
- Hartebeesthoek, South Africa
- Yarragadee, Australia
- Tahiti, French Polynesia
- Metsahovi, Finland
- Zimmerwald, Switzerland
- San Fernando, Spain
- Grasse, France
- Potsdam, Germany
- Herstmonceux, Great Britain
- Matera, Italy
- Wettzell, Germany

Appendix A. List of Acronyms

2-PSK	2-Phase Shift Keying
ACS	Attitude Control Systems
APD	Avalanche photodiode or avalanche photo-detector
API	Application Programming Interface
ARCSEC	Arcsecond or second of arc, a unit of angular measurement equal to 1/3,600 of one degree. In geometry, the full circle is divided into 360 angular degrees (°), each degree into 60 minutes of arc (arcmin or ‘), each minute of arc in turn into 60 seconds of arc (arcsec or ‘’). The full circle corresponds to 1,296,000 arcsec. Alternately, an angle is expressed in units of radians (rad), equal to the ratio between the length of an arc and its radius. The full circle corresponds to an angle of 2π rad. The following table shows the conversions between common angular units and some typical angular pointing requirements expressed in them.

	deg	arcsec	mdeg	rad	µrad
Full circle	360	1,296,000	360,000	2π	6,283,185
One degree	**1**	3,600	1,000	0.01745	17,453
One second of arc	0.00028	**1**	0.27778	0.0000048	4.8481
One millidegree	0.001	3.6	**1**	0.0000175	17.453
One radian	57.296	0.01592	57,295.8	**1**	1,000,000
One micro-radian	0.0000573	0.20626	0.05730	0.000001	**1**
35 m antenna pointing accuracy	0.006	21.6	**6**	0.00010	104.72
Typical DSOT pointing requ.	0.0000556	**0.2**	0.05556	0.000001	0.96963

ARTES-7	Advanced Research in Telecommunications Systems Program
AS	Alice Springs
ASI	Agenzia Spaziale Italiane
BKG	Bundesamt fuer Kartographie und Geodaesie
BLS	Boundary layer scintillometer
BPSK	Binary phase shift keying
C&DH	Command and data handling
CCD	Charge-coupled device
CCSDS	Consultative Committee for Space Data Systems
CDF	Cumulative Distribution Function
CFLOS	Cloud-free line of sight
CNES	Centre National d'Études Spatiales
ConOps	Concept of Operations
COTS	Commercial off the shelf
CPA	Coarse pointing assembly
CW	Continuous wavelength
CWDM	Coarse wavelength division multiplexed
dB	decibel
DGS	Data Ground Stations
DIMM	Differential Image Motion Monitor
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DM	deformable mirror
DOT	Deep Space Optical Terminal
DPSK	Differential phase shift keying
DSN	Deep Space Network
DTE	Direct-to-Earth
DTN	Delay tolerant networking

EDFA	Erbium-doped fiber amplifier
EDRS	European Data Relay System
EMI	Electromagnetic interference
EO	Earth-observation
ESA	European Space Agency
ESO	European Southern Observatory
ETS	Engineering Test Site
EU	Electronics Unit
FAA	Federal Aviation Administration
FL	Feeder link
FLGS	Feeder Link Ground Station
FPA	Fine pointing assembly
FPGA	Field-programmable gate array
Gb	Gigabit
Gb/s	Gigabit per second
GDSCC	Goldstone Deep Space Communications Complex
GEO	Geostationary Earth Orbit
GMES	Global Monitoring for Environment and Security
GOES	Geostationary Operations Environment Satellites
GSFC	Goddard Space Flight Center
HEO	Highly Elliptical Earth Orbit
HMOC	Host Mission Operation Center
HQ	Headquarters
HSE	High-speed electronics
ICAO	International Civil Aviation Organization
IKN	Institut für Kommunikation und Navigation
IOAG	Interagency Operations Advisory Group
IOP	Interagency Operations Panel
IOS	Integrated Optical System
ISL	Inter-satellite link
ISLR	International Space Laser Ranging
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KARI	Korea Aerospace Research Institute
LADEE	Lunar Atmosphere and Dust Environment Explorer
LASSO	Laser Safety System at the OCTL
LCH	Laser Clearinghouse
LCRD	Laser Communications Relay Demonstration
LCT	Laser communication terminal
LDCP	Low density parity check
LED	Light-Emitting Diode
LEO	Low Earth Orbit
LL	Lincoln Laboratory
LLCD	Lunar Laser Communication Demonstration
LLGT	Lunar Lasercomm Ground Terminal
LLOT	Lunar Lasercomm OCTL Terminal
LLST	Lunar Lasercomm Space Terminal
LMOC	LCRD Mission Operations Center
LNOT	Laser Communications Network Optimization Tool
LOS	Line of sight

LRO	Lunar Reconnaissance Orbiter
LS	La Silla
LU	Laser Unit
LUSG	LCRD User Service Gateway
M&C	Monitor and control
M-ary PPM	M-ary Pulse Position Modulation, where M is the number of possible symbols
Mb/s	Megabits per second
MetOP	Meteorological Operational Satellite
MIR	Middle infrared
MIRU	Magnetohydrodynamic Inertial Reference Unit
MIT	Massachusetts Institute of Technology
MOC	Mission Operations Center
MODIS	Moderate Resolution Imaging Spectroradiometer European
MOPA	Master-oscillator power amplifier
MPE	Maximum permissible exposure
MRO	Mars Reconnaissance Orbiter
MSG	Meteosat Second Generation
MTSAT	Multi-functional Transport Satellite
NASA	National Aeronautics and Space Administration
NICT	National Institute of Information and Communications Technology (Japan)
NOHD	Nominal Ocular Hazard Distance
OCTL	Optical Communications. Telescope Laboratory
OGS	Optical Ground Station
OHU	Optical Head Unit
OICETS	Optical Inter-Orbit Communications Engineering Test Satellite
OISL	Optical Inter-satellite Links
OLSG	Optical Link Study Group
OOK	On-Off Keying
OSIRIS	Optical Space Infrared Downlink System
PA	Point ahead
PAA	point-ahead angle
PAT	Pointing, acquisition, and tracking
PDT	Percent data transferred
PPM	Pulse position modulation
RF	Radio Frequency
SCC	Satellite Control Center
SCPPM	Serially Concatenated Pulse Position Modulation
SEP	Sun-Earth-Probe angle
SIG	Special Interest Group
SILEX	Semiconductor-laser Inter-satellite Link EXperiment
SLE	Space Link Extension
SLE-API	Space Link Extension-Application Programming Interface
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal-to-noise ratio
SNSPD	Superconducting nano-wire single photon detectors
SOHO	Solar and Heliospheric Observatory
SOTA	Small Optical Transponder
SPE	Sun-Probe-Earth angle
SWAP	Size, Weight and Power
SWIR	Short-wave infrared

T	Teide
TDRS	Tracking and Data Relay Satellite
TMF	Table Mountain Facility
TTC	Telemetry, tracking, and command
UAV	Unmanned Aerial Vehicle
WAN	Wide Area Network
WSC	White Sands Complex
WSI	Whole sky imager
μRAD	Micro-radian or 1/1,000,000 of one radian, s. “ARCSEC”