Interagency Operations Advisory Group
Optical Link Study Group

Optical Link Study Group
Interim Report

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Executive Summary

In response to the action assigned at 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, command (TTC) would be conducted by a radio frequency (RF) communication system. The motivation for optical space communication systems stems from the expectation that substantially higher data rates (10 times) 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. 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 on a single agency. Special attention was given to studying the effects of potential disruptions of optical communications due to weather (clouds and 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 understanding of this matter is not yet complete, and requires further interaction with the International Civil Aviation Organization (ICAO). The 1550 nm wavelength for uplink is favored due to its higher maximum permitted exposure level to the human eye (eye-safe). The technical means to cope with potential air traffic requirements are available and practiced regularly by laser ranging stations; however, the use of eye-safe wavelengths must be further investigated for regulatory constraints.
2. Optical space communication through the Earth atmosphere is 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 with anti-correlated clouds 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 space-Earth mission scenarios were analyzed for CFLOS and

the results were expressed in a common metric across the scenarios—percent data transmitted (PDT). The analysis indicates ground segment solutions are possible for all scenarios, but require multiple ground stations in view of the spacecraft. Unfortunately, for locations at high latitudes, e.g., Svalbard, the meteorological cloud information was not sufficient to conduct a CFLOS analysis for a LEO scenario with polar stations. 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.

The OLSG addressed the investment cost aspect for the ground terminal solutions by defining realizable optical terminals (e.g., a LEO terminal cost is estimated at 0.8 M€, a Moon/L1/L2 terminal is estimated at 8-9 M€, a deep space [Mars] terminal is estimated at 50 M€). By multiplying by the number of terminals needed to serve a particular mission scenario, a first approximation for the corresponding ground segment cost was made.

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 preliminary assessment using mid-latitude stations shows very high potential for cross support. An assessment using polar stations is recommended to complete the initial analysis. The operational implementation for the overall ground cross-support network is feasible in the near term.
- Moon/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.
- 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. The analysis has demonstrated that a high potential exists for cross support. 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.

The OLSG identified several additional issues that require further analysis. It is proposed to extend the OLSG into a phase 2 in the first and second quarters of 2012 to address the following additional topics and update the final report accordingly:

1. Assess a LEO scenario that includes high latitude stations, based on improved meteorological measurements, e.g., Svalbard, Alaska, Troll, McMurdo
2. Establish contact with the International Civil Aviation Organization (ICAO) with regard to aircraft global laser safety, and continue analysis of eye safety issues.
3. Investigate hosting of optical terminals at existing astronomical observatory sites
4. Investigate re-use of decommissioned optical telescopes as optical terminals at existing astronomical observatory sites
5. Investigate hosting of optical terminals at existing satellite laser ranging sites
6. Investigate re-use of satellite laser ranging terminals at existing laser ranging sites
7. Develop uplink beacon link budget for all scenarios to assess eye safety and backscattering
8. Refine cost estimates for consistency for all scenarios
9. Investigate shared use of optical relay terminals for both inter-satellite GEO-LEO links and GEO-ground feeder links.
10. Investigate how IOAG Service Catalog 1 needs to be amended to include optical communications

Optical space communication would benefit from technical standards that would facilitate cross support between space agencies during routine mission phases for payload data return. However, the OLSG phase 2 effort should be completed first to provide proper guidance for the development of the standards. The following steps are envisioned after conclusion of the OLSG phase 2 study:

1. In-situ meteorological measurements and associated data exchange format
2. Space Earth wavelength, modulation and detection, and pointing, acquisition, and tracking
3. Inter-satellite link wavelength, modulation and detection, and pointing, acquisition, and tracking

4. Investigate existing protocol standards to determine applicability to optical communication

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 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. Furthermore, an optical (uplink) beacon is always assumed as a pointing, acquisition, and tracking (PAT) aid for the onboard optical communication system.

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 Low Earth Orbit (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 to complete the work within the time allotted, only those scenarios with highest potential for cross support were selected for full evaluation. This process resulted in selection of five space-to-Earth scenarios for further analysis: low earth orbit, 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 analysed 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. Link budgets were developed in a standard format, using a prescribed set of candidate ground stations. These links were then analysed 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. A "business case" was also developed for each scenario, addressing potential efficiencies and cost savings that could be achieved through mutual cross support, including evaluation of initial investment and operating cost.

Concluding remarks summarize the business case for all scenarios and provide logical conclusions. Recommendations for future work are also provided to complete the analysis of several issues that are considered essential.

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. In the second class all links are 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. One assumption inherent in this section is that, for the foreseeable future, space missions will have radio frequency (RF) communication systems and the ConOps can include an approach that is a hybrid of optical and RF. In particular, for applications with optical links through the atmosphere, TT&C and critical data functions will most likely be accomplished via the RF links.

2.1.1 Driving Factors in a ConOps

ConOps will 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
- Earth station considerations
    - Geographic locations—with the likelihood of requiring geographically and weather-diverse stations 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 ConOps is that there is a specific amount of data at the source that will be attempted to transfer to the sink in a specific amount of time—not unlike a typical RF scenario. The high-level process assumes a scheduled approach in which the process starts at a specific time, and there is first 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 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 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

Strategies to support high-availability laser communications for future missions from space to Earth are increasingly receiving attention. Such missions will generate an ever increasing amount of data that must be transferred to ground locations on Earth. As an alternative to the current use of radio communications, deep-space to ground optical communications will provide a higher bandwidth to transfer these data with smaller power mass and power consumption subsystems. However, optical communications may be interrupted by cloud cover. Typical clouds have optical fades that far exceed three 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 many 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 cloud-free line of site (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 is the use of "ground station diversity," in which multiple stations have the potential to receive communications when other sites are cloud-covered or unavailable due to geometric visibility limitations. 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." An additional metric for the Percent Data Transferred (PDT) can be computed that determines the amount of mission data transmitted to a ground site based on the network cloud-free availability, data rates/storage, and data volume. The Laser Communications Network Optimization Tool[i] (LNOT) is used to compute the optimal configuration of sites based on a specific scenario (i.e., 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 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. Typical meteorological patterns cause the cloud cover state at stations within a few hundred kilometers to be correlated. Consequently, stations within the network should be placed far enough apart to minimize these correlations, 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 that 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. LNOT performs this analysis on a high-performance computing platform, using a long-duration cloud analysis to mitigate against the inter-annual variations in clouds over the globe.

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 (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]). For 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. The spatial resolution of all existing cloud data is 4 km and is available at temporal resolutions as high as 15 minutes. This allows trade studies using LNOT for different optical communication scenarios such as LEO, Lunar, L1, L2, and Deep Space.

2.2.1.3 Predictive Weather

Depending on the scenario, free space optical communications can take advantage of cloud prediction at each ground site to maintain Cloud Free Line of Sight (CFLOS) and thus maximize availability. This can be accomplished by knowing whether the line of sight to each ground site is cloud free at a certain time, and knowing how many minutes into the future each site is expected to remain cloud free. In a study using the *Lasercom Simulator* it was 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 1 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 for decision making reduced the number of slews by an order of magnitude. In addition, the performance 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.

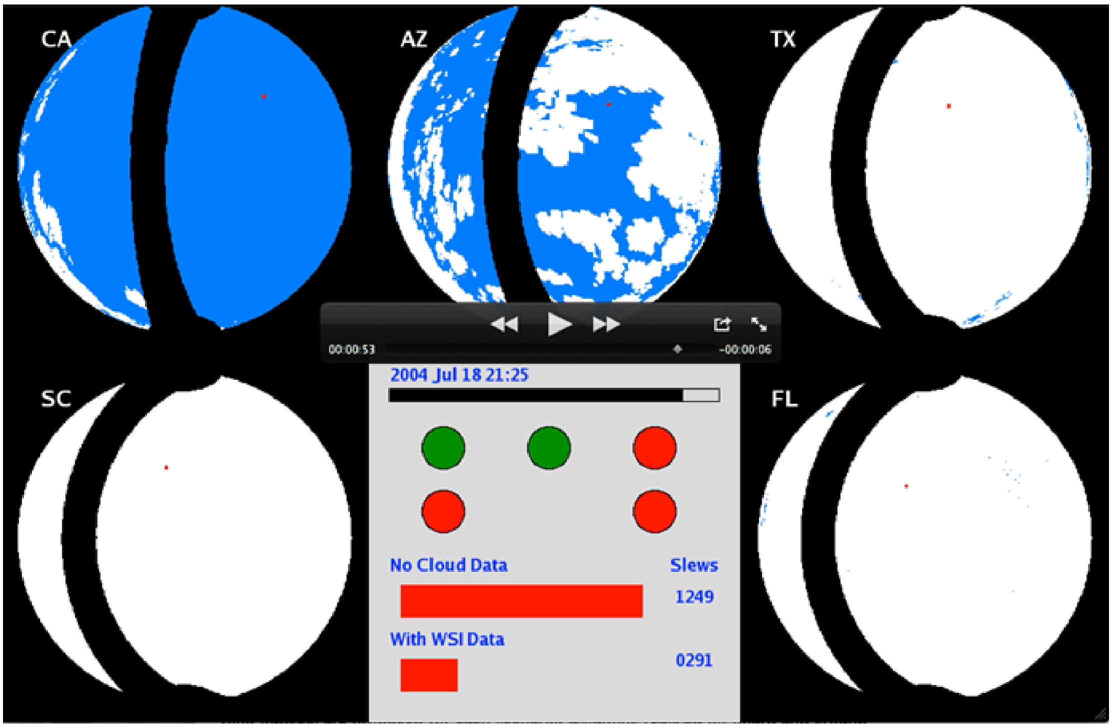


Figure 1: Lasercom Simulator output showing the benefit of local cloud instrumentation on minimizing link handovers.

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 beamwidths 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, so the sink terminal (e.g., Earth terminal) transmits an uplink signal, and the source terminal must acquire this signal and transmit data "in the blind." Note that signals used for the acquisition process may be different from those used for communication, and potentially an RF link could 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

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 studies in this report, the required uplink communications will be provided by an existing RF link. Therefore, the optical uplink communications scenario is 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. This case is treated in the 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 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 link budget for a lunar mission (Lunar Atmosphere and Dust Environment Explorer, or LADEE) as an example (see Figure 2), the structure and content selected for the link 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
Uncoded Slot Rate	5.0E+09	s^{-1}
Bits Per Word	4.00	
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
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
Required Photons / Pulse	3.74	
Code Rate	0.50	

LINK BUDGET		
Tx Ave Power	**26.99**	**dBm**
Tx Photons / Pulse	6.27E+09	
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
Total Optical Path Loss	**-88.80**	**dB**
Ave Power at Rx Detector	**-61.81**	**dBm**
Photons / Pulse at Rx Detector	**8.26**	
Required Photons / Pulse	3.74	
Link Margin	**3.44**	**dB**

Figure 2: Sample link 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	Significance
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		M-ary PPM order, no deadtime assumed
7	Uncoded Slot Rate	s^{-1}	Resulting PPM slot rate
8	Bits Per Word		Bits transmitted per PPM symbol
9	Tx Aperture Diam	m	Tx telescope aperture diameter D_{TX} [m]

#	Quantity	Unit	Significance
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} 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 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 in an array N_{array}
23	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
24	Code Rate		Non-redundant proportion of the data stream when forward-error-correction is employed
	Link budget		
25	Tx Ave Power	dBm	Tx laser average power $P_{TX\ ave}$ [dBm]
26	Tx Photons / Pulse		Number of photons per laser pulse $N_{TX\ pulse} = E_{pulse}/(hc/\lambda)$

#	Quantity	Unit	Significance
27	Tx Antenna Gain	dBi	Tx telescope gain $G_{TX} = 20\times\log_{10} \pi D_{TX}/\lambda$ [dBi]
28	Tx Transmission Loss	dB	Tx telescope optical transmission losses $L_{TX\ opt}$ [dB] due to internal absorption and scattering
29	Tx Pointing Loss	dB	Tx telescope depointing loss $L_{TX\ pt} = -10\times\log_{10}(2J_1(m_{TX})/m_{TX})^2$ [dB]
30	Isotropic Space Loss	dB	Isotropic free-space path loss over link range $L_{FS\ ISO} = 20\times\log_{10} 4\pi R/\lambda$ [dB]
31	Atmospheric Loss	dB	Atmospheric loss $L_{ATM} = 10\times\log_{10} T_{ATM} + L_{SCINT}$ [dB]
32	Rx Antenna Gain	dBi	Rx telescope gain $G_{RX} = 20\times\log_{10} \pi D_{RX}/\lambda$ [dBi]
33	Array Gain	dB	Array gain $G_{array} = 10\times\log_{10} N_{array}$ [dB]
34	Rx Transmission Loss	dB	Rx telescope optical transmission losses $L_{RX\ opt}$ [dB] due to internal absorption and scattering
35	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)
36	Total Optical Path Loss	dB	Sum of losses and gains in lines 27-35 L_{OPT} [dB]
37	Ave Power at Rx Detector	dBm	Average TX power incident on RX detector $P_{RX\ ave} = P_{TX\ ave} - L_{OPT}$ [dBm]
38	Photons / Pulse at Rx Detector		Photons per pulse incident on RX detector $N_{RX\ pulse} = N_{TX\ pulse}\times 10^{-0.1\times L_{OPT}}$
39	Required Photons / Pulse		Detector sensitivity at the assumed data rate, including quantum efficiency and sky noise background
40	Link Margin	dB	Difference between the detector sensitivity and the actual number of photons

2.3.2 Uplink

An optical communications ground terminal may be required to transmit a powerful laser uplink beacon to assist the space terminal in accurately tracking the position of the ground terminal so that the pointing accuracy necessary to avoid signal fades in the downlink can be achieved.

The uplink power ranges between 500 mW and 5 kW. Lagrange or planetary missions may require even higher beacon powers, though eventually the beacon signal flux incident at the space terminal will succumb to space loss, and will no longer allow a sufficiently high tracking bandwidth. Thus, missions to the outer planets will probably have to rely on a combination of star tracking and observation of the Earth limb to provide a pointing reference, eliminating the ground beacon.

Optical uplinks are potential hazards to people and equipment on ground, in the air and in space. The operation of such high powered laser transmitters are subject to various national legal frameworks.

Classification of laser sources, operation, and hazard mitigation are subject to national regulations (workplace safety) and differ from country to country. Regulations are updated and subject to change over time. The following national and international bodies issue codes and standards that may be found applicable, pending further study:

- USA: ANSI (American National Standards Institute) - e.g., Standards Z136.1-7
- UK: BSI (British Standards Institution)
- Germany: DIN (Deutsches Institut für Normung) – e.g., DIN EN 60825, DIN EN 60825-1…4
- European Community: CEN (European Committee for Standardization) – e.g., EN 207, EN 208, EN 60825
- International Bodies:
    - ISO (International Organization for Standardization)
    - IEC (International Electrotechnical Commission) - e.g., IEC 60825-1 (Safety of Laser Products) and PD IEC TR 60825-14 (User's Guide)

The transmission of lasers through the atmosphere is subject to additional regulation and control. In Europe the approval of Eurocontrol and various national agencies have to be sought (Deutsche Flugsicherung [DFS], etc.).

In the United States, the use of lasers requires coordination with the Federal Aviation Administration (FAA[ii]). Lasers may have to be shuttered periodically to avoid illuminating aircraft. Particular system specifications (e.g., power, operational elevation angles) will dictate how often shuttering is required, and a safety system that includes on-site radar may be required.

Impacts on operations will be dependent on many factors, among them the proximity to air traffic routes (remote sites may have fewer outages), laser power and characteristics (e.g., pulse repetition, beam divergence angle), and the system operations concept. For example, use of NASA facilities in Southern California may be impacted by air traffic coming into/leaving Los Angeles International Airport. All international aviation regulations are coordinated with the International Civil Aviation Organization[iii] (ICAO), including laser transmission through navigable airspace.

In the United States, the Laser Clearinghouse (LCH) may impose outage periods to prevent the illumination of sensitive satellites. This process mandates the laser operator to submit a transmission schedule to the LCH in advance, to which the LCH will respond with a list of prohibited times. [iv, v, vi]

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. A telescope pointing in the direction of the beacon will image it as a line emanating from the ground terminal and extending to the position of the space terminal.

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. 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.

Detailed uplink link budgets for each scenario are not included in this analysis.

2.3.3 Modulation and Detection

An important factor in the system and link design is the choice of modulation and detection. Examples are On-Off Keying (OOK) with noncoherent detection, Serially Concatenated Pulse Position Modulation (SCPPM) with noncoherent photon counting detection, Binary Phase Shift Keying (BPSK) with coherent/homodyne detection and 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 work 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. These 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 3 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 lasercom 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.

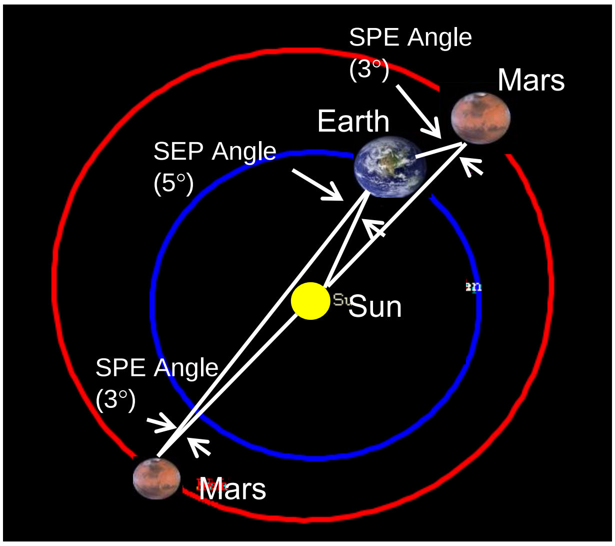


Figure 3: Sun-Earth-Probe and Sun-Probe-Earth Angles

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 2. The objective of ground terminal design will be to minimize the number of outage days. For example, LLCD will operate with an SPE of two degrees.

Table 2: 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

Note that in the scenarios to be examined in Section 3, the analysis is 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 Sun-Probe-Earth 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 4. In both transmit and receive, there may be both a coarse and fine pointing capability.

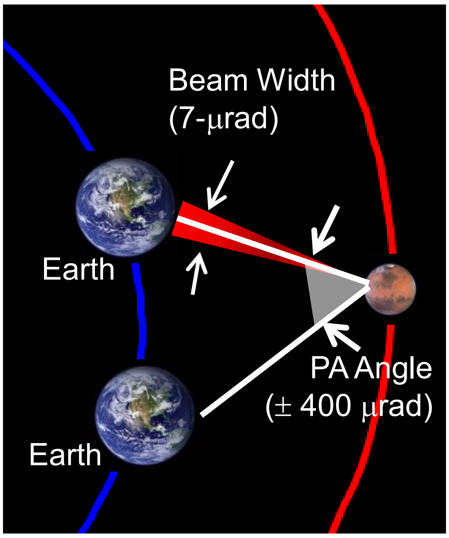


Figure 4: Point Ahead Angle Example

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; 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 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 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 terminal will be presented for each scenario. The basic contributions to the cost estimate are:

- Site preparation
- 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.
- Ground communication
- Weather and atmospheric monitoring

It should be noted that savings can be effected by placing the optical communication station 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.

2.4.3 Space Relay Terminal

In the case of the space-based relay terminal, the same basic functions as the ground terminal above are needed. In addition, there will be a feeder link that gets the data from the relay to ground. This link can be either optical or RF.

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 the RF uplink. There are two paths for getting engineering data (health and status) from the user space terminal—optical or RF.

2.4.5 Laser Safety

The ConOps must also take into account laser safety issues.

Laser uplinks from Earth are usually protected by a multilayer approach.

- Layer 1: onsite occupational health and safety
- Layer 2: coordination with air traffic control authorities, automated airspace monitoring, e.g., by infrared cameras and radars co-aligned with the uplink beam, or eye-safe LIDAR before transmission of high energy beam. May require local observer onsite at ground station.
- Layer 3: coordination with spacecraft operators for illumination avoidance of unmanned and manned spacecraft

For manned missions the safety of astronauts related to optical communication concerns: a) the reception of laser uplinks from Earth, b) the generation of laser downlinks onboard, and c) the generation of laser beam by a third spacecraft, for instance during proximity operation between the manned spacecraft and this third spacecraft.

2.4.6 Weather and Atmospheric Monitoring Equipment

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

- 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 section above. These sensors indicate not only whether there are clouds or no clouds, 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 provide atmospheric loss. At night, a calibrated photometric system that tracks stars of stable emission, e.g., Polaris, can be used.
- Clear Air 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.

2.4.6.1 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 longwave infrared cameras (see Figure 5). Such instrumentation provides 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, imagery from meteorological satellites may be desirable. In any case, more research on operationalizing these instruments should be conducted.

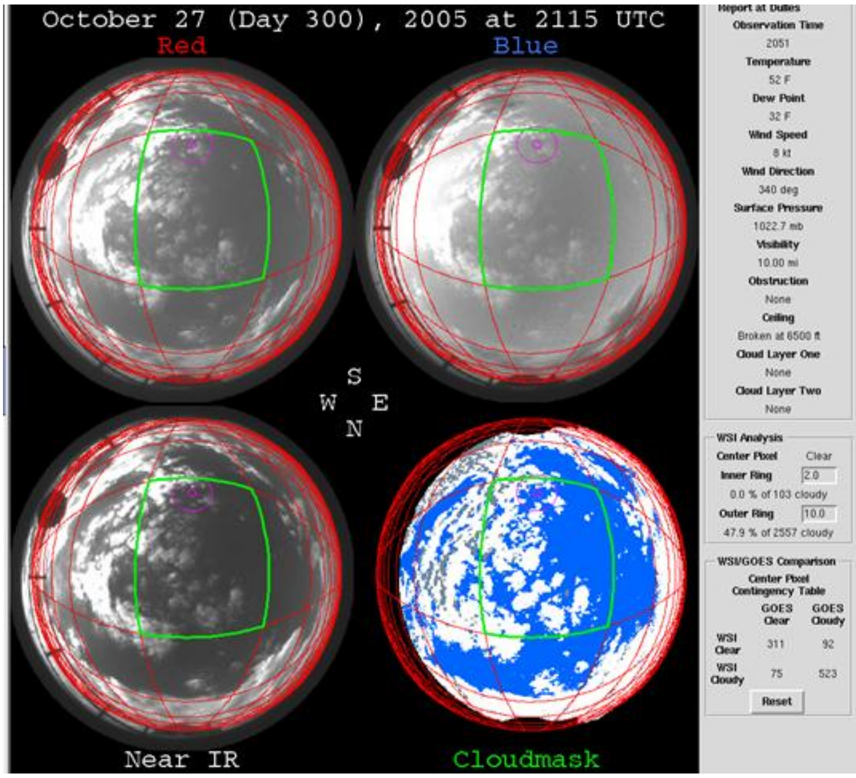


Figure 5: Example of a Whole Sky Imager (WSI) that could be used to support link handover decisions for a free space optical communications network

2.4.6.2 DLR implementation

At DLR-IKN, cloud monitoring is performed with the CloudCam, which uses a camera in the middle infrared (MIR) and a hyperbolic mirror (Figure 6). The CloudCam captures the cloud situation during night and day. The device dimension is 600x600x1300 mm³ (LxWxH).

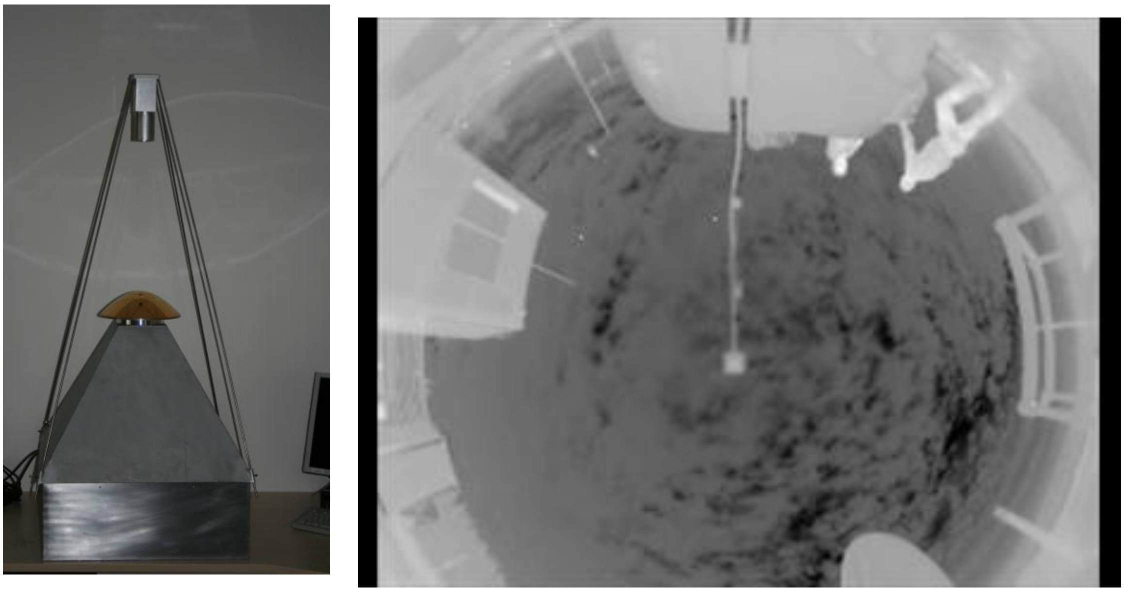


Figure 6: Set up of the CloudCam (left) and example image of cloud situation over the optical ground station Oberpfaffenhofen (right).

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.

2.4.6.3 NASA 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.

2.4.6.3.1 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 (see Figure 7). Data are collected every 15 minutes. Every hour the system transmits the stored data to a geo-satellite. 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.

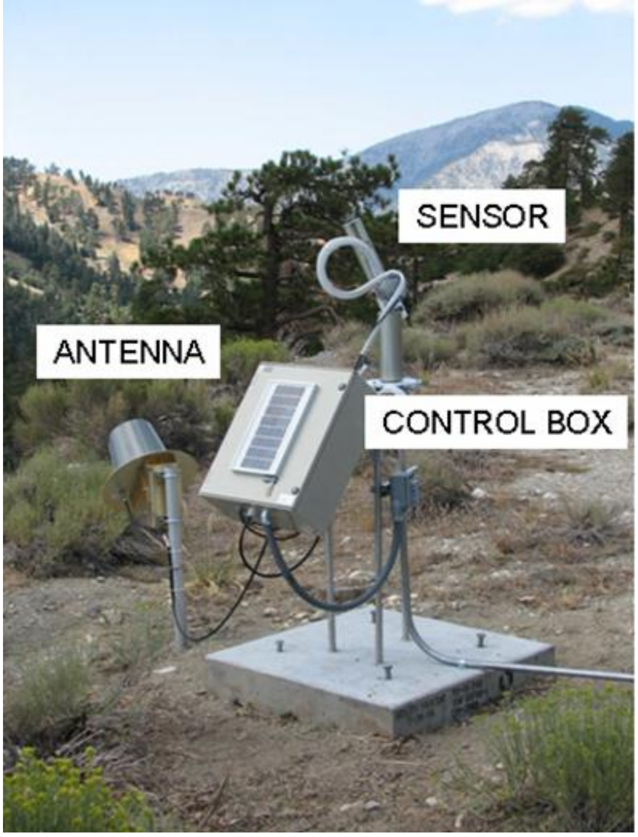


Figure 7: Sun-Photometer at TMF.

- 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 COTS components. The cloud camera is housed in a weatherproof enclosure to guarantee continuous observation of the sky (see Figure 8). The system provides radiometrically calibrated images of the sky with 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.

Figure 8: NASA-JPL cloud camera. The window visible in top of the weatherproof enclosure is made of hard coated germanium.

- Differential Image Motion Monitor (DIMM)--Nighttime turbulence is monitored by a DIMM (see Figure 9). The DIMM consists of a telescope that tracks and images the double images of a star on a 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 and Figure 10).

Figure 9: DIMM for measurements of nighttime turbulence.

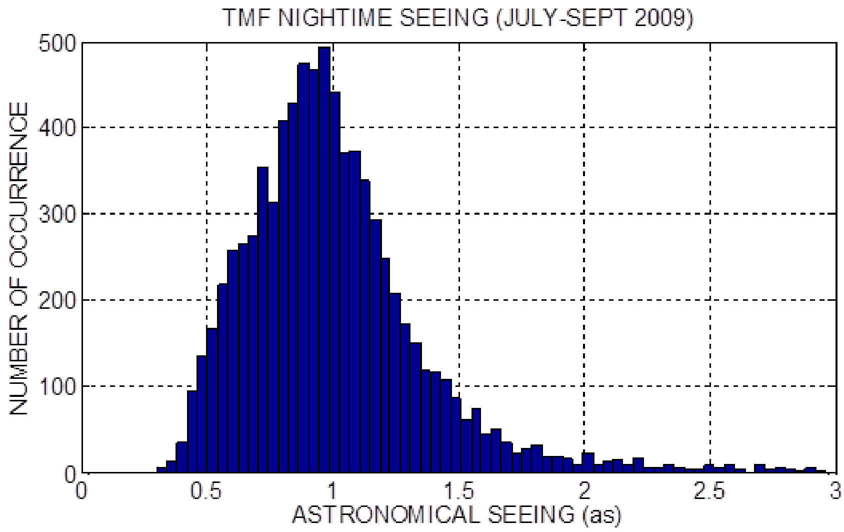


Figure 10: Histogram of astronomical seeing at Table Mountain Facility, CA. The data is from measurements by a DIMM during the period July-Sept, 2009.

- 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.

2.4.6.3.2 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 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—The atmospheric turbulence at the ground layer is measured using a boundary layer scintillometer (BLS). The instrument consists in a LED transmitter and a received 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 11). The periodical minima in Figure 11 correspond to time before sunset and after dawn.

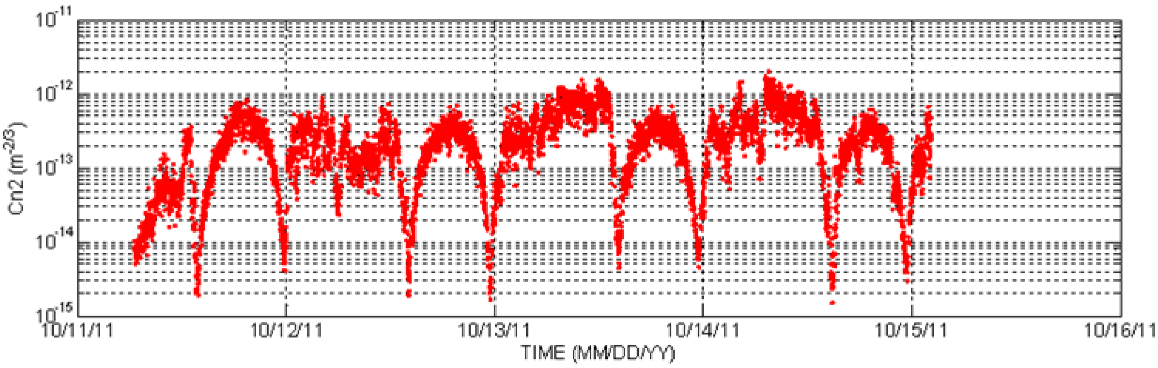


Figure 11: Measurements of the ground layer structure coefficient of the refractive index at Goldstone. (Time is in UTC).

- 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. They follow the structure of a communication system design including a basic concept of operations, a CFLOS analysis and a link budget, followed by a space terminal description and a ground terminal description. These descriptions may include an implementation example, which for the purpose of this document is 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 3 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 3: 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 12 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 5 minutes.

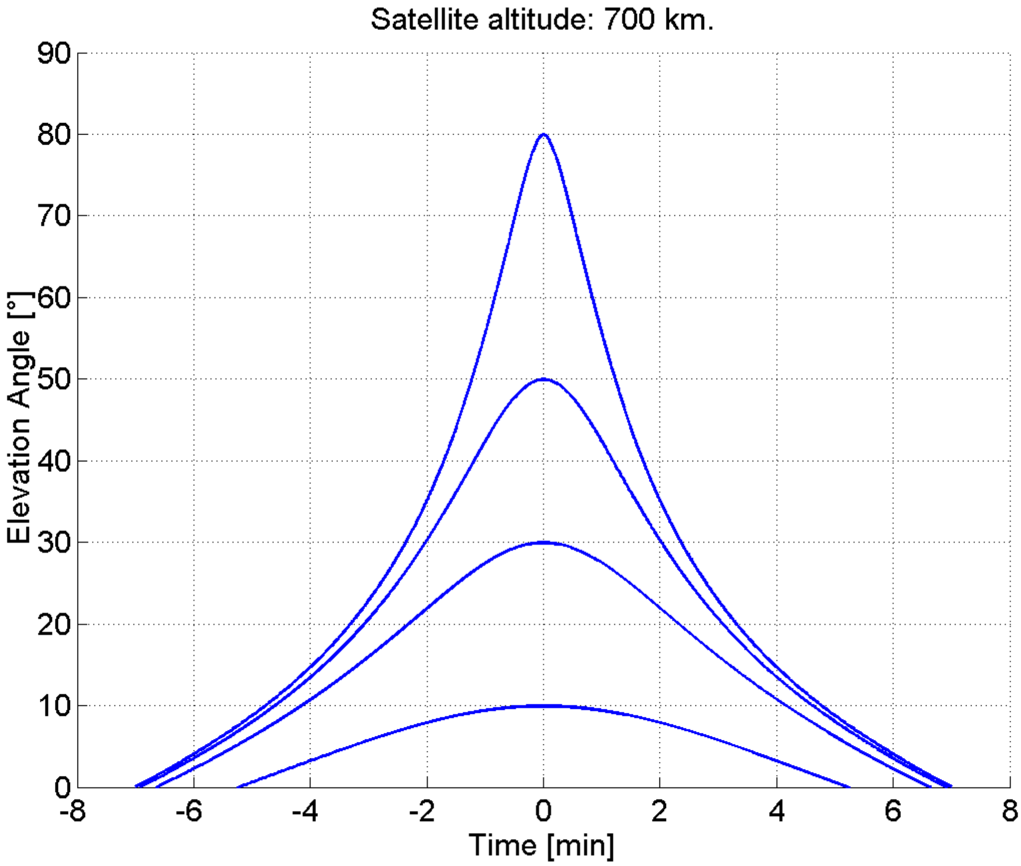


Figure 12: Elevation angle versus time for satellite overflights with various maximum elevations

Figure 13 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.

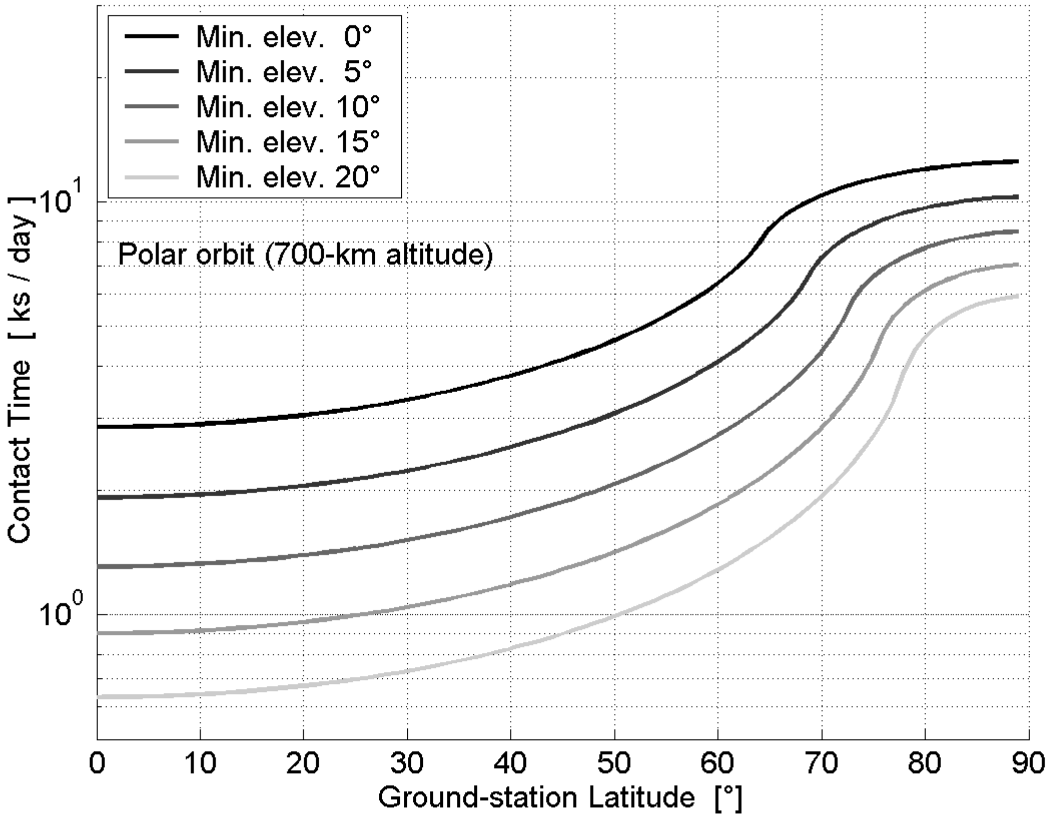


Figure 13: Orbit-limited contact time per day as a function of the ground station latitude for a polar-orbit satellite.

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 14 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.

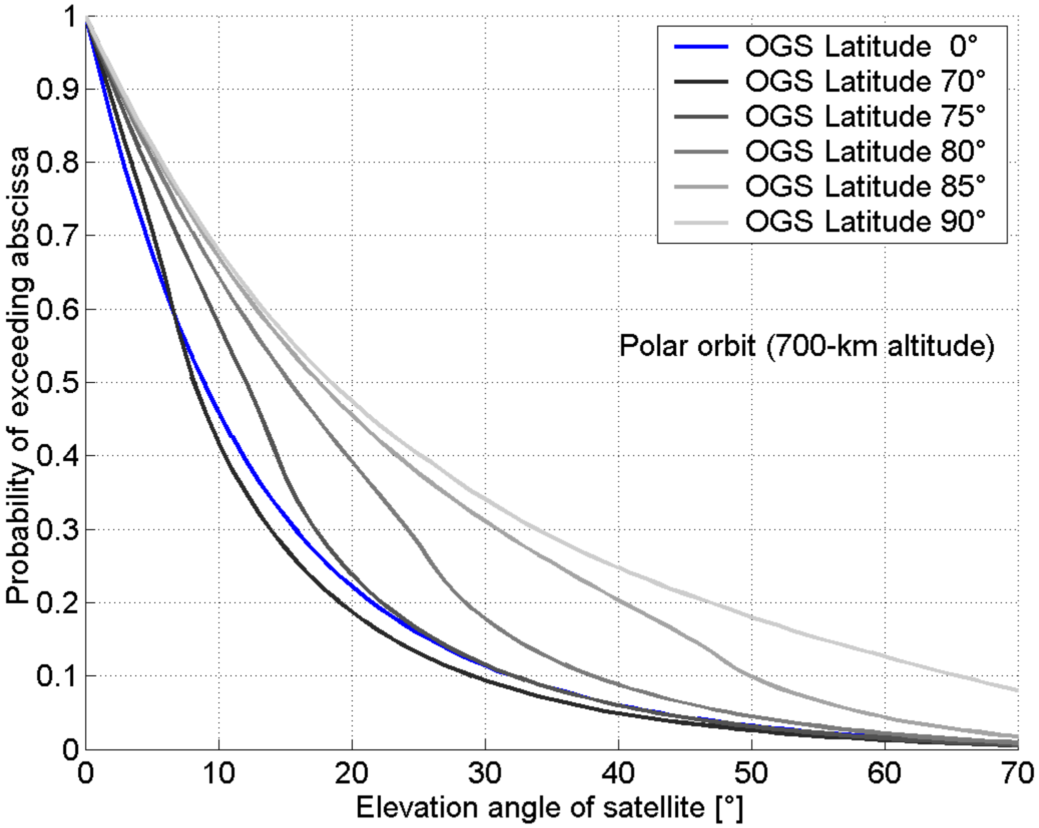


Figure 14: Probability distribution of the satellite elevation (assuming the satellite is above the OGS horizon).

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 15, 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.

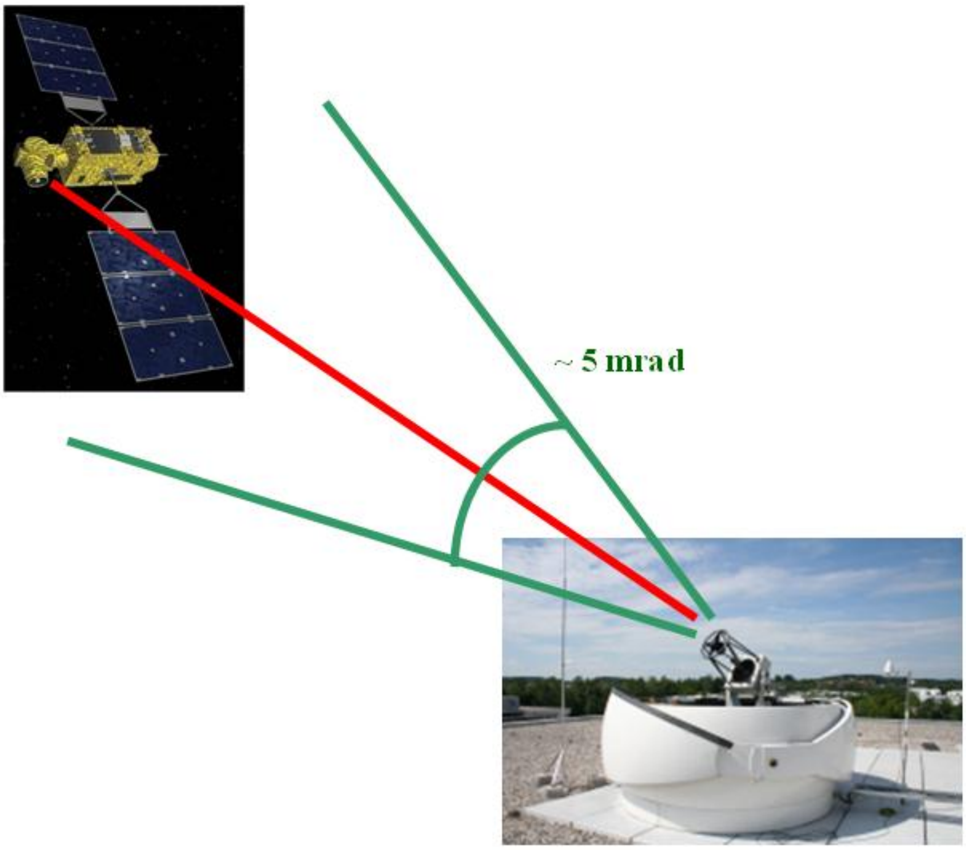


Figure 15: Illustration of a large beacon beam (divergence ~ 5 mrad) emitted by an OGS and a narrow communication beam emitted by the satellite.

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 3).
- 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 3 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.

3.1.2 Space Terminal

In this section, four different concepts of LEO flight terminals are presented: the OSIRIS terminal (Optical Space Infrared Downlink System), the Tesat Spacecom's Laser Communication Terminal (Tesat-LCT), the OPTEL-mu terminal, and JPL's 10-Gb/s terminal.

3.1.2.1 Space Terminal Requirements

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.

3.1.2.2 Space Terminal Potential Implementation

3.1.2.2.1 OSIRIS (from DLR-IKN)

DLR's Institute of Communications and Navigation is developing an experimental laser terminal for compact LEO satellites called OSIRIS. 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.

A laser diode is 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 16.

Figure 16: 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 17.

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.

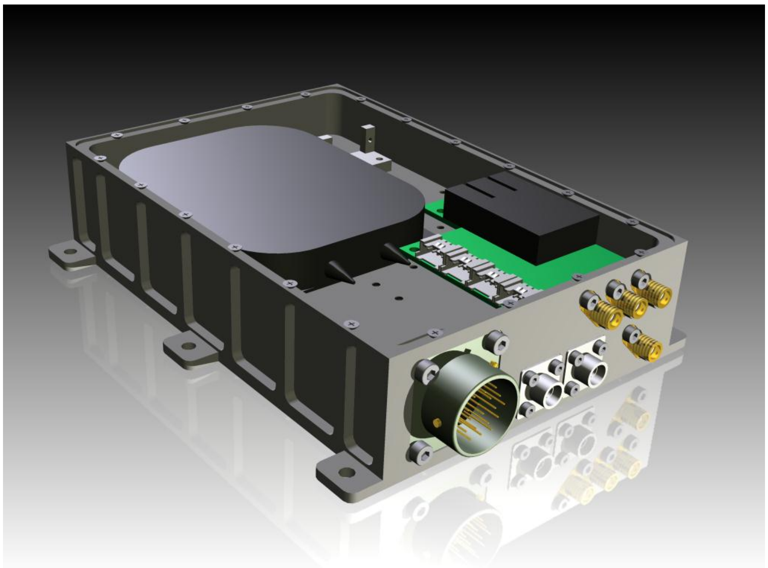


Figure 17: Laser Source using an optical amplifier

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.

3.1.2.2.2 LCT (from Tesat Spacecom)

Tesat Spacecom developed and implemented two identical laser communication terminal (LCT) demonstrations on the TerraSAR-X (Germany) and NFIRE (U.S.) satellites in LEO. While the main purpose was to demonstrate maturity of inter-satellite links, space to ground links (SGL) were investigated, as well. Figure 18 shows the LCTs mounted on the individual spacecraft.

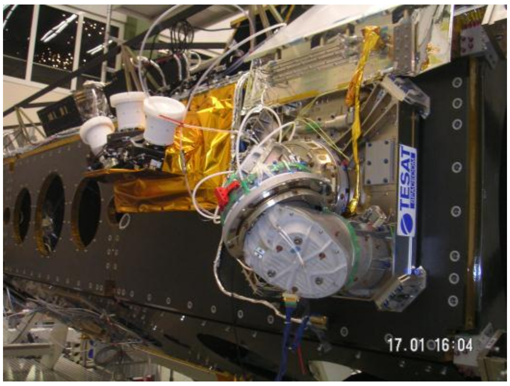


Figure 18: Tesat laser communication terminals embarked on the TerraSAR-X (left) and the NFIRE (right) satellites

Table 4 shows the performance parameters of the two laser communication terminals.

Table 4: Key parameters of the Tesat laser communication terminals used on the TerraSAR-X and NFIRE satellites.

Antenna diameter:	125 mm
Transmit power:	<1000 mW
Data rate:	5.6 Gb/s
Wavelength:	1064 nm
Modulation scheme:	BPSK
Maximum link distance:	<6000 km
Power consumption:	140 W
Mass:	35 kg

3.1.2.2.3 Optel-mu terminal (from RUAG)

Under an ESA contract, RUAG Space Switzerland is developing a terminal for small LEO Earth observation satellites with the properties shown in Table 5:

Table 5: Key parameters of the RUAG Optel-mu terminal

Downlink wavelength	1550 nm
Downlink data rate	2 x 1 Gb/s
Uplink Wavelength:	1.06 µm
Modulation:	OOK/PPM
Mass	4.5 kg
Volume	4 litres
Power consumption:	45 Watts
Satellite class:	>150 kg

RUAG will also build a low cost optical ground station utilizing a 60 cm aperture commercial telescope.

3.1.2.2.4 10-Gb/s LEO terminal (from JPL)

The JPL team has prototyped a 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 ~0.5W 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) telecom grid of EDFA fiber amplifiers. The received uplink beacon wavelength is at 1568 nm
    d. A simple and highly compact, low-jitter 2-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 19, and Figure 20 shows an optical-head prototype. Target mass and power consumption for the flight data transmitter system is less than 10 kg and approximately 60W 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.

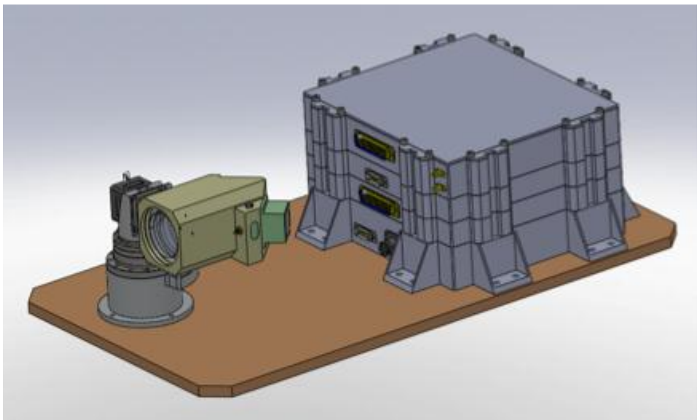


Figure 19: Schematic diagram of the terminal consisting of the optical head on a 2-axis gimbal (left) and an electronics/laser box (right).

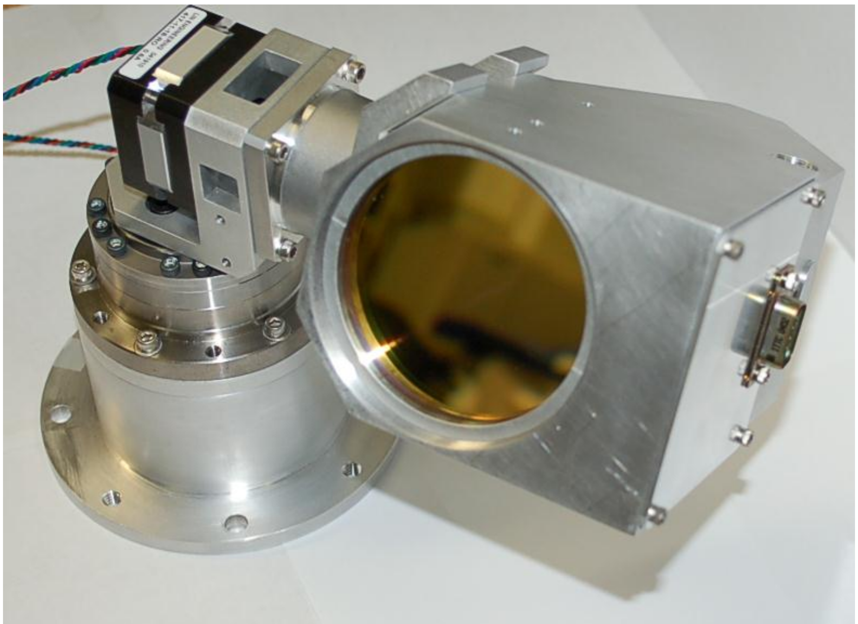


Figure 20: The optical-head prototype for laboratory and in-the-field (communications from an airplane) testing.

3.1.3 Ground Terminal

3.1.3.1 Ground Terminal Requirements

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 made 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.

3.1.3.2 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), National Institute of Information and Communications Technology (NICT)
- OGS-OP (Oberpfaffenhofen), DLR
- Optical Communications. Telescope Laboratory (OCTL) (California), JPL
- Tenerife OGS (Tenerife), ESA

See the annex in section 7 for a description of these ground stations.

As shown in Figure 21, DLR's OGS deployed two beacon beams to be seen by the OICETS satellite.

Figure 21: DLR's OGS at Oberpfaffenhofen during a laser link with the OICETS satellite at nighttime (2009). The two infrared uplink beacons can be seen.

3.1.4 CFLOS Analysis

LNOT was used to determine the performance of a LEO scenario using the specifications described above for 2005-2010. The CFLOS analysis for the LEO scenario is similar to that for the other scenarios. Using the six years of cloud data and the position of the satellite, LNOT dynamically tracks the data collected (in Gb), the data stored on board 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. If a site has CFLOS to the satellite, 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. 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 line-of-sight (LOS) above 20° to a LEO satellite such as Aqua for a few minutes per satellite contact. Taken collectively, the nine example sites shown in Figure 22 below provide an average of about 120 minutes per day of contact above 20° to the LEO satellite. When the effects of clouds are included, this time is reduced at an average of about 60 minutes 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 nine sites in this scenario, the LEO satellite almost always has access above 20° to one or more sites at least once every three orbits. However, sometimes clouds obscure the LOS during the LEO passes, resulting in lost data.

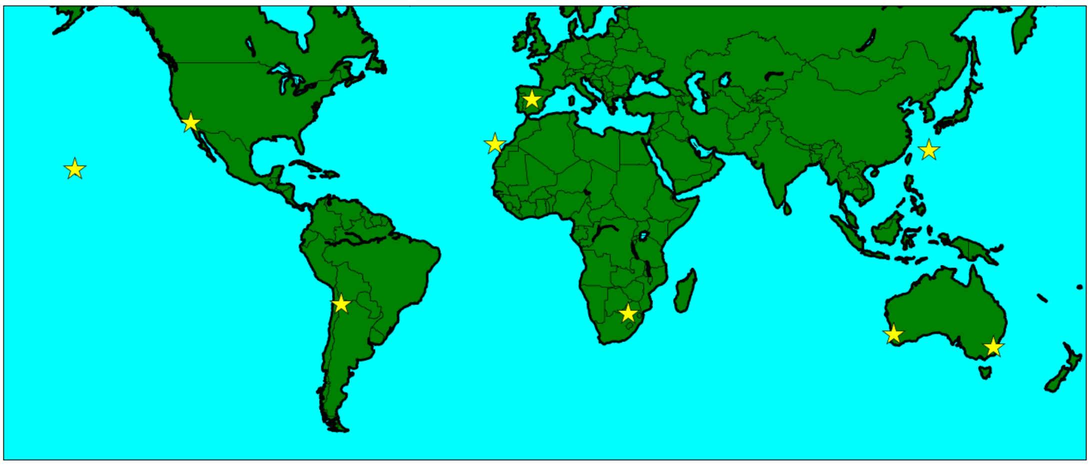


Figure 22: Candidate ground stations used for the LEO scenario.

Figure 23 shows the cumulative distribution of the monthly PDT for the nine-site network of ground stations for this scenario. The PDT is greater than 80% for all months during 2005-2010. The overall PDT for this LEO scenario is 94.1%. Figure 24 shows the cumulative distribution of the amount of data transferred daily from LEO to the nine-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 2005-2010. Note that this performance is achieved without the benefit of polar ground stations. The long-term, high-resolution cloud database available for LNOT analysis does not currently include polar regions. Sites near the poles provide more opportunities per day for LEO downlinks; however, they must have substantial cloud-free time to be used for optical communications. Despite the exclusion of polar sites in this LEO scenario, this analysis indicates that a globally distributed set of mid-latitude ground stations can be used to receive very large amounts of data from a LEO satellite, making cross support very attractive.

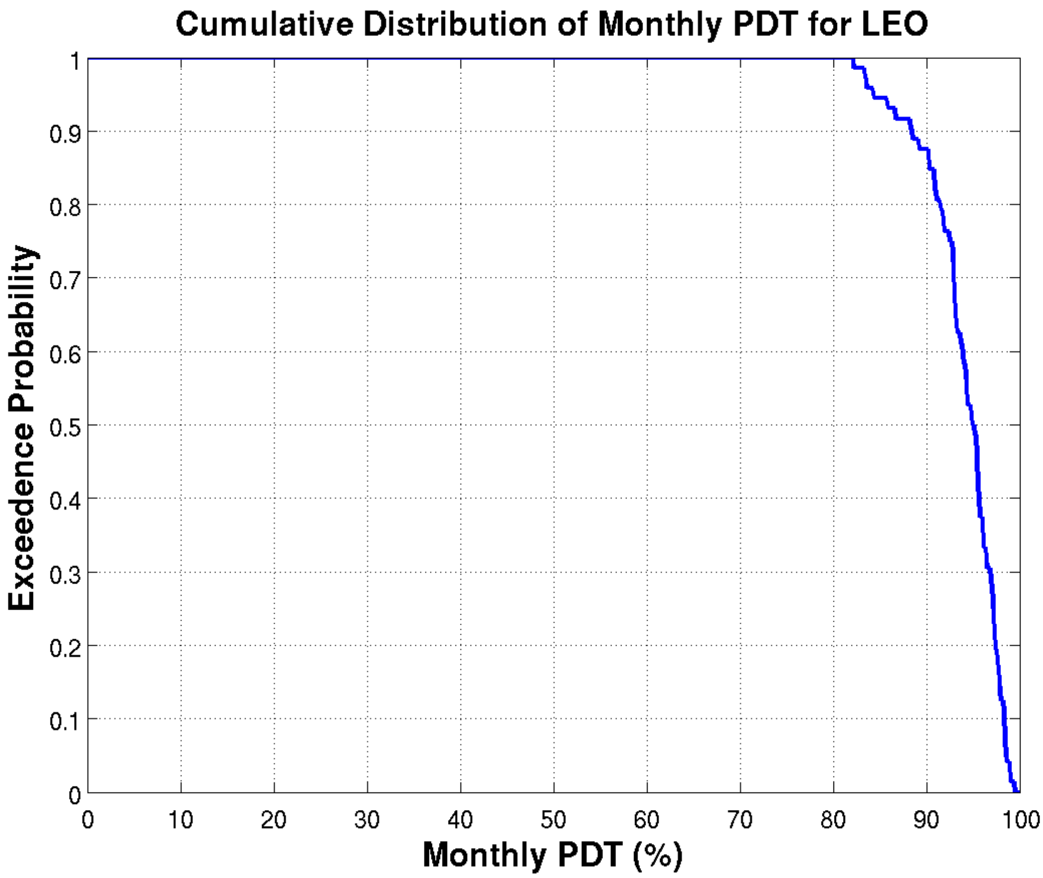


Figure 23: The cumulative distribution of the monthly PDT for the period 2005-2010 for the LEO Scenario.

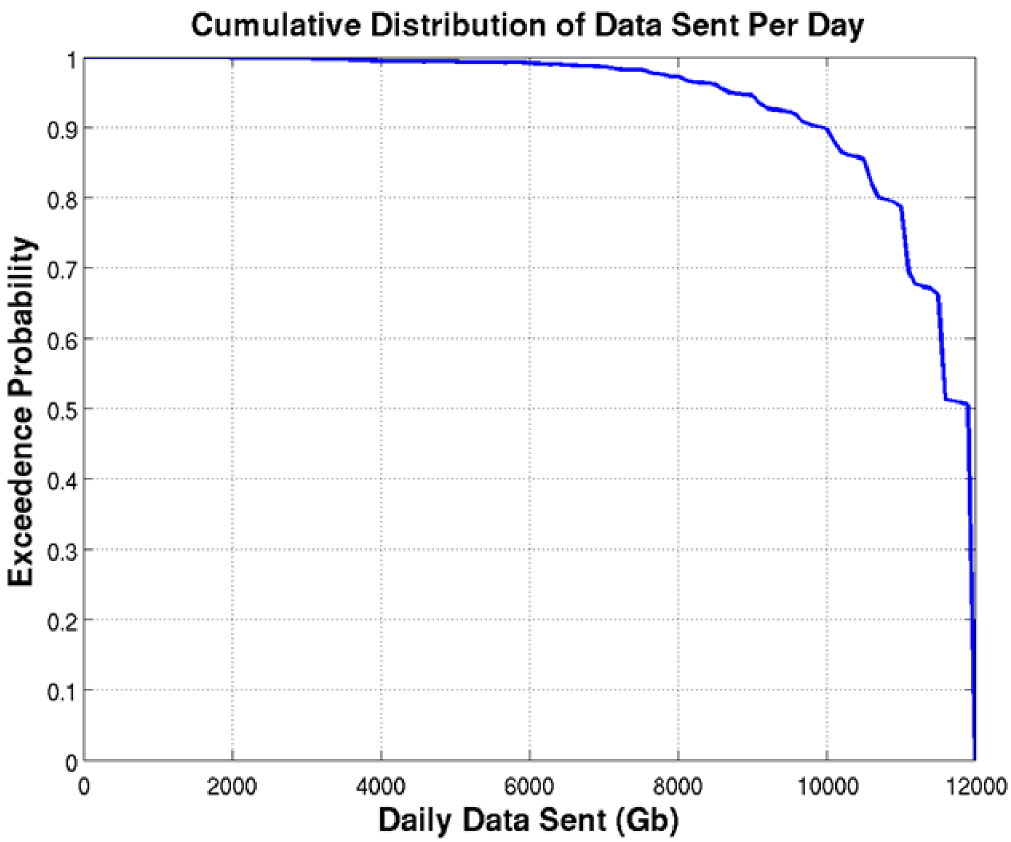


Figure 24: The cumulative distribution of the amount of data successfully sent to the ground by the LEO satellite for the nine-site network of ground stations.

3.1.5 Link Budget

An example link budget for an elevation of 20° is shown in Figure 25. With reasonable Tx- and Rx-aperture diameters (8 and 40 cm respectively), the calculated link margin is 6 dB. The scintillation loss (estimated to -2 dB) can be mitigated by channel coding.

LEO DOWNLINK BUDGET

INPUT PARAMETERS		
Range	1.3E+03	km
Elevation	20	deg
TRANSMITTER		
Tx Wavelength	1.55	µm
Tx Ave Power	0.5	W
Tx Word Rate	10.0E+09	Hz
Tx Aperture Diam	0.08	m
Tx Angular Diam	5.09	arcsec
Tx Footprint Diam	3.21E+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	0.40	m
Rx FOV	5.00	arcsec
Rx Depointing	1.00	arcsec
Rx Optical Transmission	50.0	%
Rx Array Size	1	aperture
Receiver Sensitivity	-26.00	dBm

LINK BUDGET	
Tx Ave Power	**26.99 dBm**
Tx Photons / Pulse	3.90E+08
Tx Antenna Gain	104.20 dBi
Tx Transmission Loss	-3.01 dB
Tx Pointing Loss	-0.11 dB
Isotropic Space Loss	-260.46 dB
Atmospheric Loss	-2.65 dB
Rx Antenna Gain	118.18 dBi
Rx Transmission Loss	-3.01 dB
Rx Pointing Loss	0.00 dB
Total Optical Path Loss	**-46.85 dB**
Ave Power at Rx Detector	**-19.87 dBm**
Photons / Pulse at Rx Detector	8.05E+03
Required Power	-26.00 dBm
Link Margin	**6.13 dB**

Figure 25: Example LEO Downlink Budget

3.1.6 Ground Terminal Cost

Table 6 gives a price estimation of an optical ground terminal for LEO links. Non-recurring engineering costs and operating costs (e.g., repairs) are not taken into account. Estimations do not apply to a 1-m telescope (which would be significantly more expensive). Costs of the Dome, Telescope, Mount, and Cloud monitoring system are estimated from DLR's OGS (Ø = 0.4 m). The cost of the ground terminal is 800 k€.

Costs to connect the ground station to the terrestrial communication network will also be part of the investment costs. Such costs are not mentioned here because they may vary greatly depending on the location of the ground station.

Table 6: Investment costs of a ground terminal for LEO downlink.

	Cost estimation (in k€)
Communication System	
Telescope (Ø = 0.5 m)	60
Mount	60
Tx comm. system (10 Gb/s)	150
Rx comm. system (10 Gb/s)	150
PAT system	50
Total	**470**
Additional Terminal Costs	
Dome	70
Cloud monitoring system	20
Aircraft monitoring system	20
Remote-operation system	200
Total	**310**
Total investment cost	**780**

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. Detailed cloud analyses are required for both high and mid latitude areas based on polar and geostationary orbiting meteorological satellites. Such data are currently not available.

3.2 Highly Elliptical Earth Orbit (HEO) Scenario

The Highly Elliptic Earth Orbit (HEO) scenario is not elaborated as it is considered similar to the Moon scenario with shorter distances.

3.3 Geostationary Earth Orbit (GEO) Scenario

This scenario is discussed in section 4.1.4 Earth Relay Optical Feeder Link and section 4.2 Telecom Mission Optical Feeder Uplink.

3.4 Moon Scenario

The moon scenario refers to an optical communications system from a lunar orbiting satellite to ground station on the Earth's surface. This scenario is of particular interest since the NASA Lunar Laser Communications Demonstration (LLCD) is currently in preparation for a 2013 launch. Much of the 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 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 the Lunar Atmospheric and Dust Environment Evaluator (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 the ground site perspective) 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, Hawai'i. The second ground site is the OCTL, located on Table Mountain, California.

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 Hawai'i are not at the same longitude, the fact that they are in the same hemisphere means that the moon is visible simultaneously much of the time. Consider Figure 26, 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. One can see, however, that the Haleakala site 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.

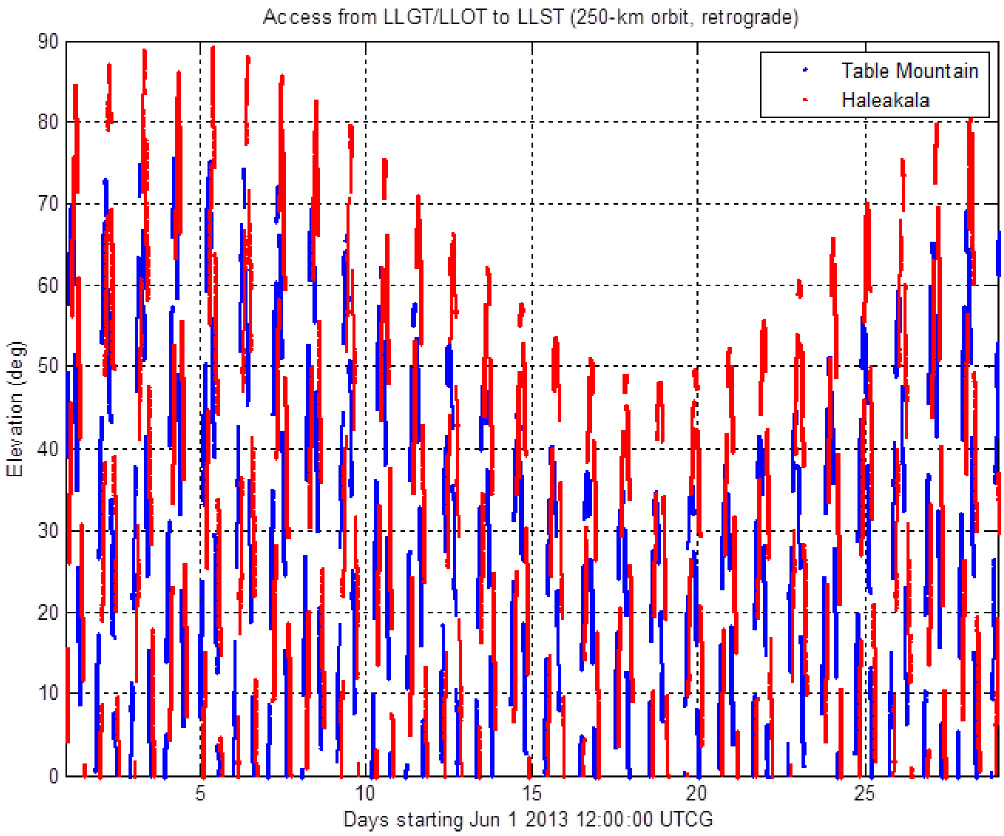


Figure 26: Access from LLGT/LLOT to LLST.

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 easier to see in Figure 27, 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. One notes, however, that though the Haleakala site has the largest maximum elevation angle, it does not always have the higher elevation angle for each pass.

Figure 28 summarizes the overlap of access from the two sites. One can see 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. One can note, however, that during days 6 and 7, 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 28 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.

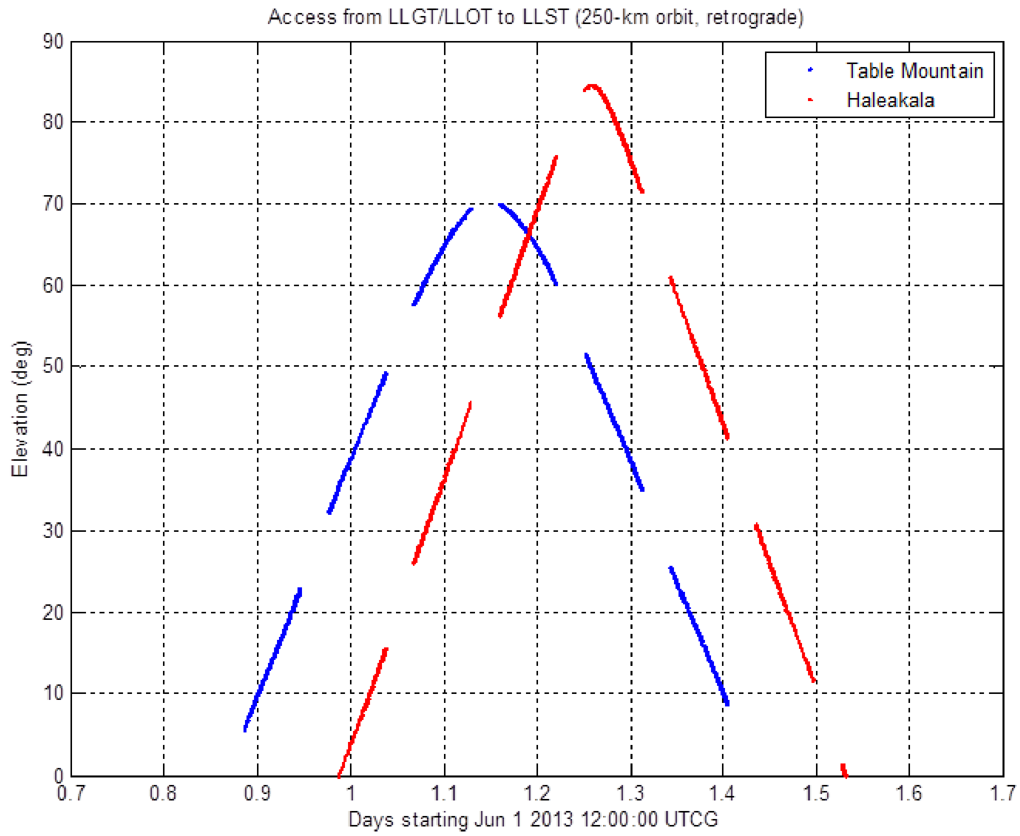


Figure 27: LLGT/LLOT access to LLST June 1-2, 2013.

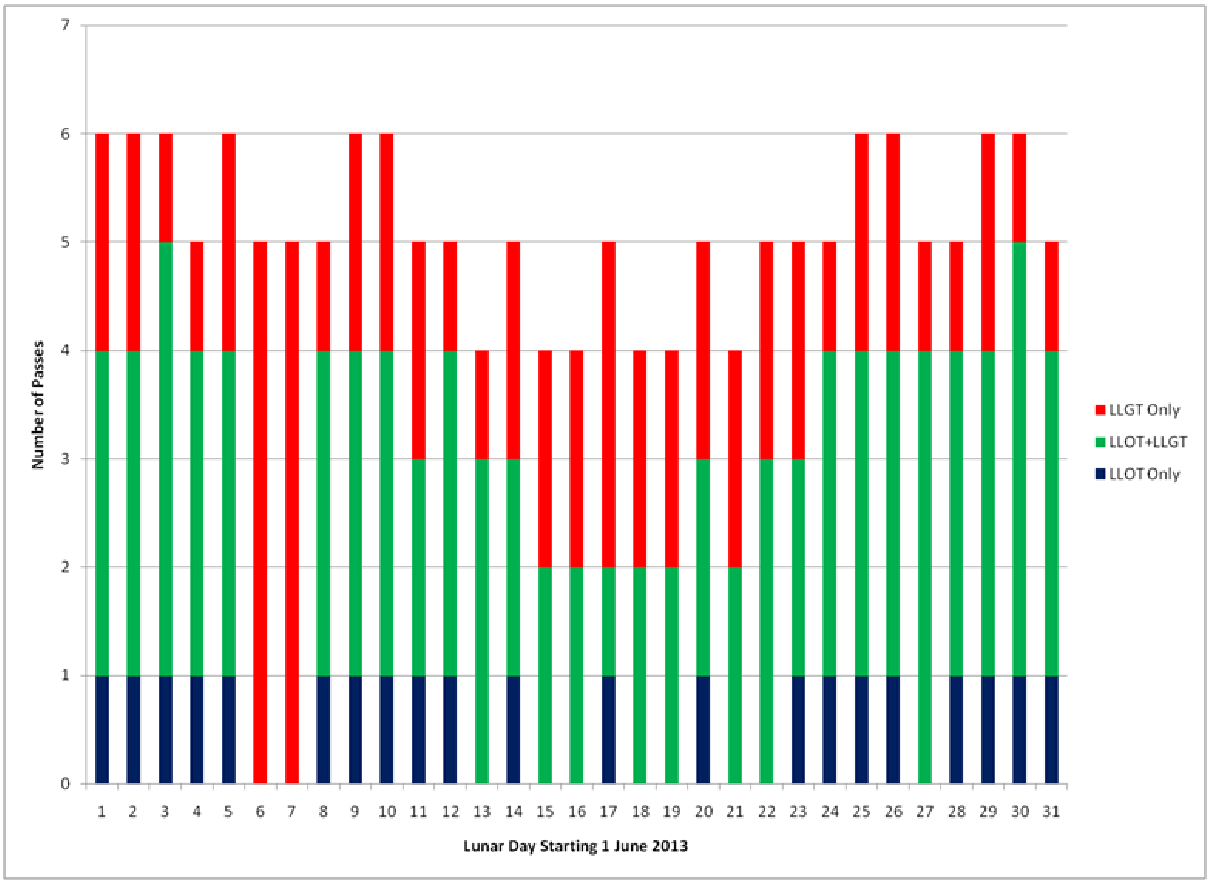


Figure 28: Number of passes with access from LLGT and/or LLOT to LLST.

While the California and Hawai'i 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). From Figure 29, one can see first 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 30). 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.

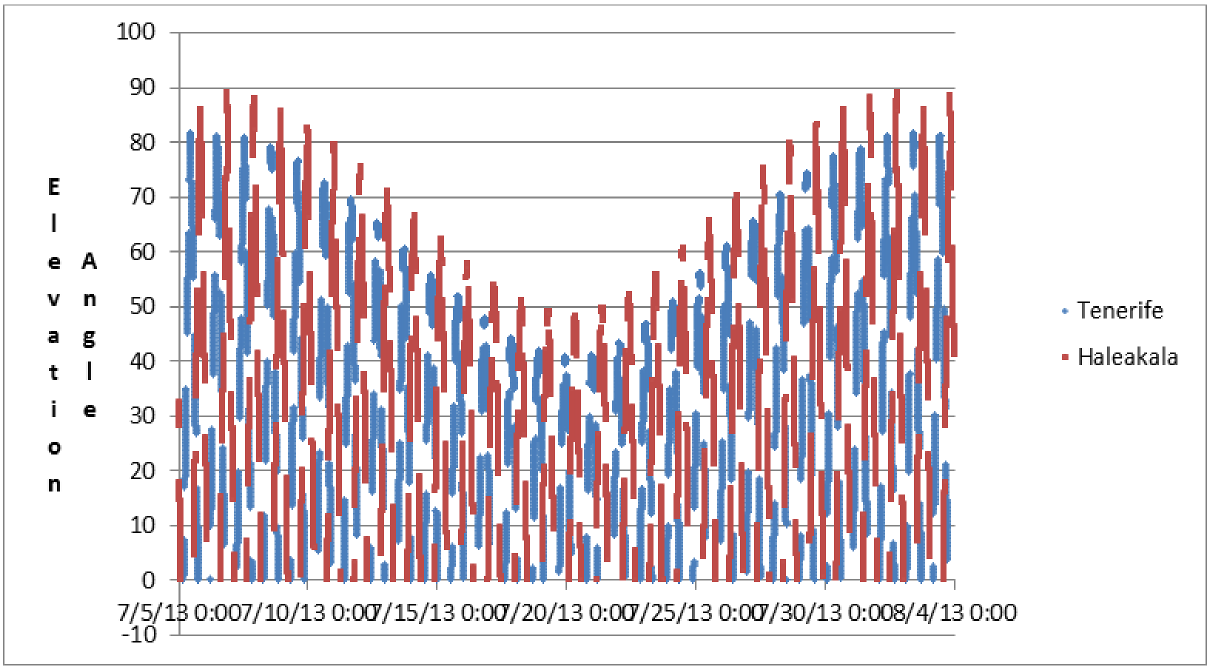


Figure 29: Geometric Access from LLST to hypothetical ground terminals at Haleakala and Tenerife (from July 5 – August 4, 2013).

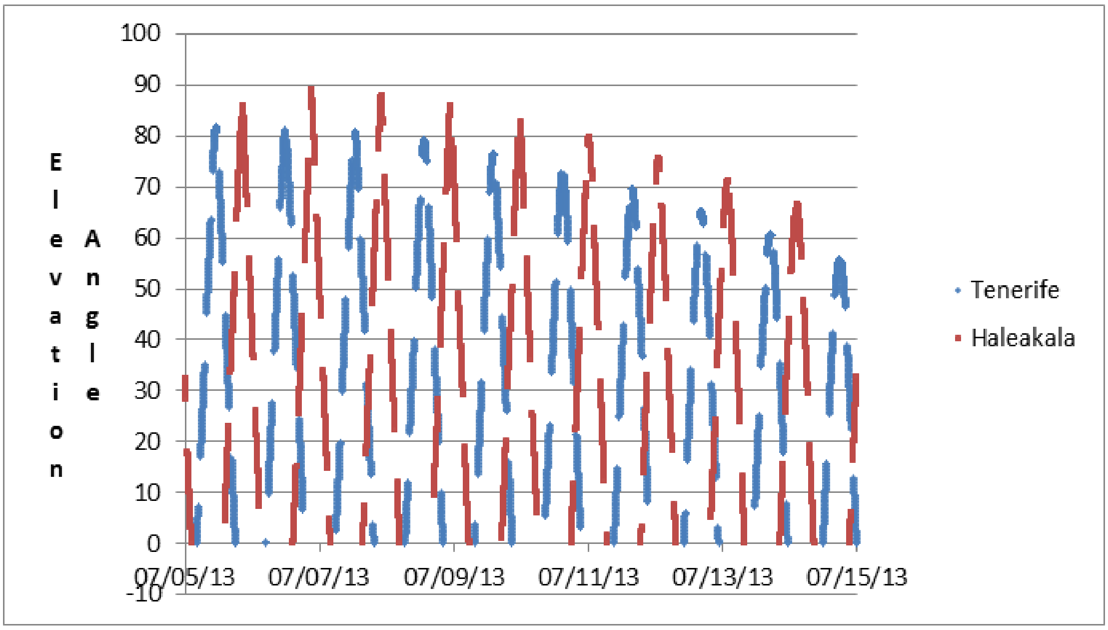


Figure 30: Geometric Access from LLST to hypothetical ground terminals at Haleakala and Tenerife (from July 5 – 15, 2013).

3.4.1 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 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 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 appropriate, 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 a potential data volume ConOps. 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.

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 Lunar Laser Communications Demonstration project made implementation decisions relevant to the lunar scenario, and the onboard segment will be briefly described in this section. While this example represents a mature and well-studied design, the choices should be considered a potential, but not required solution for the lunar scenario.

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 storage and/or distribution of 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 LLCD project made implementation decisions relevant to the lunar scenario, and the ground terminal will be briefly described in this section. While this example represents a mature and well-studied design, the choices should be considered a potential, but not required solution for the lunar scenario.

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 lunar scenario similar to that of NASA's LLCD project. To show the value of interoperability between the United States and European assets, two sets of site configurations were evaluated. The first 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 assumption in Section 3.4.1, Table 7 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 jumps 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 31 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 7: PDT (%) for Lunar Scenario for the 2005-2010 period.

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

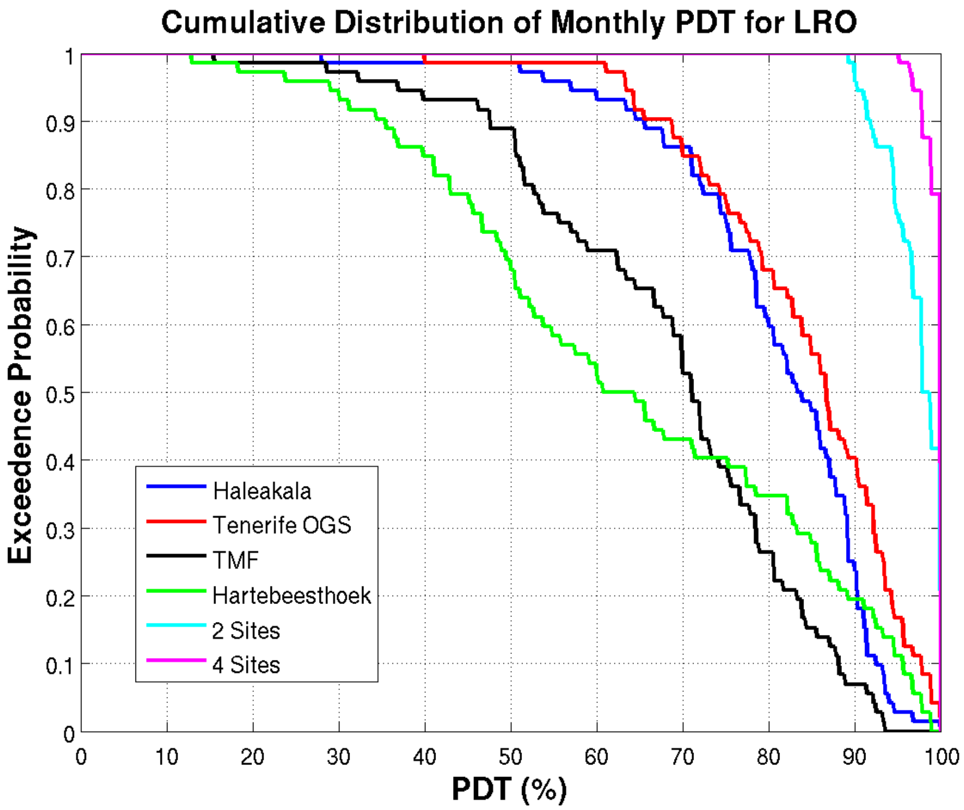


Figure 31: CDF of PDT for the four individual sites and the two- and four-site networks for the Lunar (LRO) scenario.

3.4.5 Link Budget

Figure 32 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
Uncoded Slot Rate	5.0E+09	s^{-1}
Bits Per Word	4.00	
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
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
Required Photons / Pulse	3.74	
Code Rate	0.50	

LINK BUDGET	
Tx Ave Power	**26.99 dBm**
Tx Photons / Pulse	6.27E+09
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
Total Optical Path Loss	**-88.80 dB**
Ave Power at Rx Detector	**-61.81 dBm**
Photons / Pulse at Rx Detector	**8.26**
Required Photons / Pulse	3.74
Link Margin	**3.44 dB**

Figure 32: Sample LLCD downlink budget. The 622 Mbps data rate is expected during benign atmospheric conditions.

3.4.6 Ground Terminal Cost

There are a number of costs that must be considered for the ground terminal. There are costs directly associated with the equipment for the optical communications link (as described in section 3.4.3). By developing the LLGT, the LLCD is demonstrating a transportable optical ground segment with equipment costs on the order of 7.5 M€. There are also costs associated with maintaining the physical infrastructure of a site, including personnel and infrastructure not directly related to the communications system. These infrastructure costs should ultimately be included, but are not included in this estimate of LLGT's cost.

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

For the L2 scenario, the Euclid mission has been adopted as the model case, as it 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.

3.5.1 Concept of Operations

As previously described, the optical communication link is used primarily for high-rate data downlinking. There will be an optical uplink for pointing, acquisition and tracking (PAT) in the ground terminal with the potential added feature of uplinking data, but the optical uplink will not be used for spacecraft commanding. Since the uplink/beacon must adopt an eye-safe design (using proper wavelength and the minimum necessary brightness), there is no further safety layer beyond the first-layer safety system (i.e., local occupational health and safety regulations designed for unattended remote operations). There will also be a ranging function.

3.5.1.1 Basic ConOps

Euclid's daily ConOps calls for science observations for 21 hours, followed by a "burst-mode" downlink of the acquired data during the remaining 3 hours. To quantify the data return in the different analyses, the following input assumptions were adopted:

- Downlink data rate: 700 Mbps (a 10-fold increase over the planned RF downlink for Euclid)
- Onboard storage capacity: corresponding to 3 days of science observations
- The entire 3 hours are necessary to downlink 100% of one day's mission data

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.

3.5.1.2 Scenario ConOps

The L2 scenario was the first mission scenario tackled 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) was available on the fourth day.

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 in a link budget calculation, the transmitter diameter and the link distance, scale with the square 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 Mio. 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 10Mbps 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 (LCT) with these parameters is under development by Tesat Spacecom for the European Data Relay Satellite (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 a laser communication terminal (LCT) from the Lagrange point (L2) could be based upon the lunar laser communication demonstrator (LLCD) design or upon the Tesat LCT design for EDRS. In case of the latter, the downlink would use pulse position modulation, a wavelength of 1064 nm and a data rate of 700 Mbps. The seed laser, modulator, and 5 Watt power amplifier of the transmitter are already space-qualified components. The LCT would track a modulated optical beacon signal from the Earth-based receiver terminal at 1550 nm, which combines the advantage of eye-safety (a wavelength above 1400 nm cannot pass the human eye), with lowest possible beacon transmission power from ground, as the space-based receiver would use a lock-in technique to track the modulated beacon signal. Onboard vibration isolation is performed by high-speed tip/tilt tracking of the beacon signal. Solar radiance blocking is performed by a band-pass filter at 1550 nm.

The onboard LCT would have the following technical parameters:

- Aperture diameter: 135 mm
- Transmit wavelength: 1064 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 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 either 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 1m-class telescope (as indicated in the link budget) is deemed suitable for distances up to the Lagrangian points (including Lunar missions). 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 meter 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 1m clear aperture with sufficient optical quality (need not be diffraction limited) with tip-tilt control of received beam. Adaptive optics, while beneficial, is 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 our 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 wavelengths at 1m, 1.5m and 2m, incorporating narrow-band spectral filtering against sky background and stray light, as well as uplink and receive beam separation. [TRL 7]
- 20 W laser beacon system at 1.5m or 2m eye-safe wavelengths [TRL 7]
- Incoherent beacon emission from 4-8 sub-apertures (as defined by the spider of the secondary mirror) of the main telescope. The diameter of the transmit beacon beams would be such that the operation is eye-safe (direct viewing into the transmit beam at any distance is eye-safe). 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 1m-class telescope and commercial high-performance charge-coupled device (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

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 33 and Table 8 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.

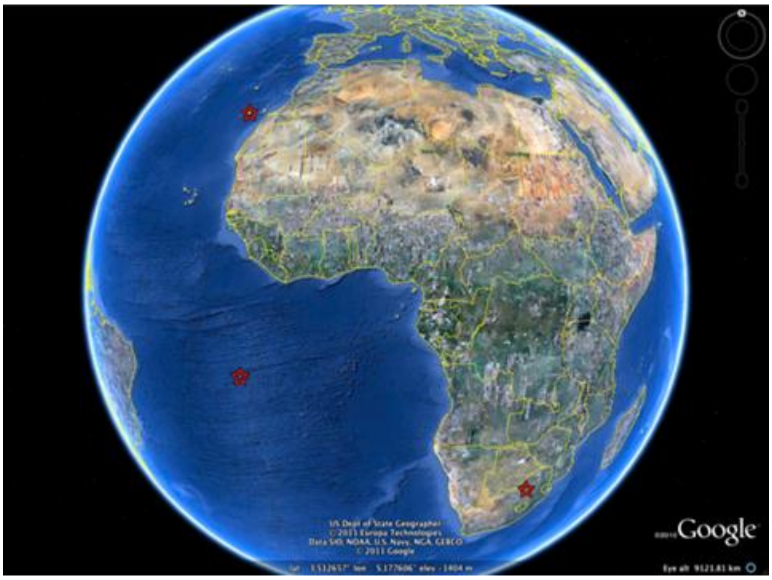


Figure 33: Location of ground sites in the L2 scenario

Table 8: PDT (%) for L2 Scenario over the 2005-2010 period.

Tenerife OGS	Ascension Is.	Hartebeesthoek	Tenerife OGS + Ascension Is.	Tenerife OGS + Hartebeesthoek
96.29	89.56	85.21	99.84	99.89

Figure 34 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.

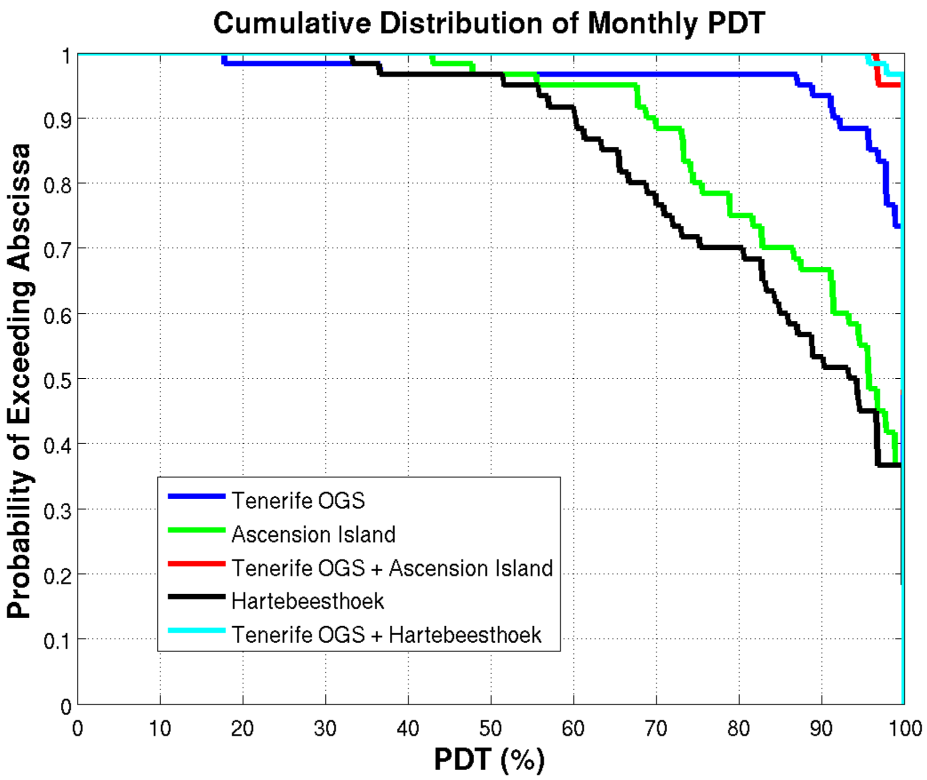


Figure 34: The cumulative distribution of the monthly PDT for the period 2005-2010 for the L2 Scenario.

3.5.5 Link Budget

For any orbit around L2, the SEP is always greater than 150 degrees, and therefore will never pose a problem. Figure 35 shows the L2 downlink budget.

L2 DOWNLINK BUDGET

INPUT PARAMETERS		
Range	2.0E+06	km
Elevation	20	deg
TRANSMITTER		
Modulation Type	64-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	1.0	W
Tx Word Rate	50.0E+06	Hz
Uncoded Slot Rate	1.1E+09	s^{-1}
Bits Per Word	6.00	
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
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	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	3.74	
Code Rate	0.50	

LINK BUDGET	
Tx Ave Power	**30.00 dBm**
Tx Photons / Pulse	1.56E+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	-2.65 dB
Rx Antenna Gain	126.14 dBi
Rx Array Gain	0.00 dB
Rx Transmission Loss	-4.56 dB
Rx Pointing Loss	0.00 dB
Total Optical Path Loss	**-101.16 dB**
Ave Power at Rx Detector	**-71.16 dBm**
Photons / Pulse at Rx Detector	**11.95**
Required Photons / Pulse	3.74
Link Margin	**5.04 dB**

Figure 35: L2 Downlink Budget

3.5.6 Ground Terminal Cost

The overall ground terminal investment cost is estimated for the baseline 1 m-class terminal (suitable up to Lagrangian point distances) considering the following break-down:

1m Telescope, including Mount	5 M€
Telescope Housing (Calotte type dome)	1 M€
Detector + Receiver Signal Chain	0.5 M€
High-power Laser Beacon	0.5 M€
Environmental (weather, etc..) monitoring & safety system	0.5 M€
Site Installation and Validation	0.5 M€

The analysis yields a total cost of 8 M€. This figure is also commensurate to 7.5 M€ stated for the Lunar case.

The above represents only an estimate (while reasonably realistic, it is without margin); the final cost will depend on the complexity of the system (e.g., it will be driven by a potential need for adaptive optics, local regulatory compliance requirements for the uplink, etc.) and the accessibility and difficulty of implementing the site infrastructure.

The cost of the site infrastructure of a new site can vary to the extreme depending on accessibility, any existing infrastructure, as well as the political/contractual situation governing the host agreement. It is therefore not useful to provide a figure for these costs; rather, it is assumed that the terminals are set up at existing sites with infrastructure – consistent with the sites considered in the CFLOS analyses.

The operating costs can safely be assumed to be virtually identical to existing RF stations (pending regulatory eye-safety requirements for the uplink/beacon demanding permanent human presence during operations).

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 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

The adopted ConOps and analysis methodology are identical to the L2 case described in detail in section3.5.1.

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 1m-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 having a clear advantage over other designs)
- A heat transport and management system of the telescope tube (baffles in particular), as well as suitable air-conditioning system of 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 1m (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 9 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 9: PDT (%) for L1 Scenario over the 2005-2010 period.

Tenerife OGS	Ascension Is.	Hartebeesthoek	Tenerife OGS + Ascension Is.	Tenerife OGS + Hartebeesthoek

92.17	79.90	85.16	98.87	98.52

The cumulative distributions of the monthly PDT are shown in Figure 36. 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.

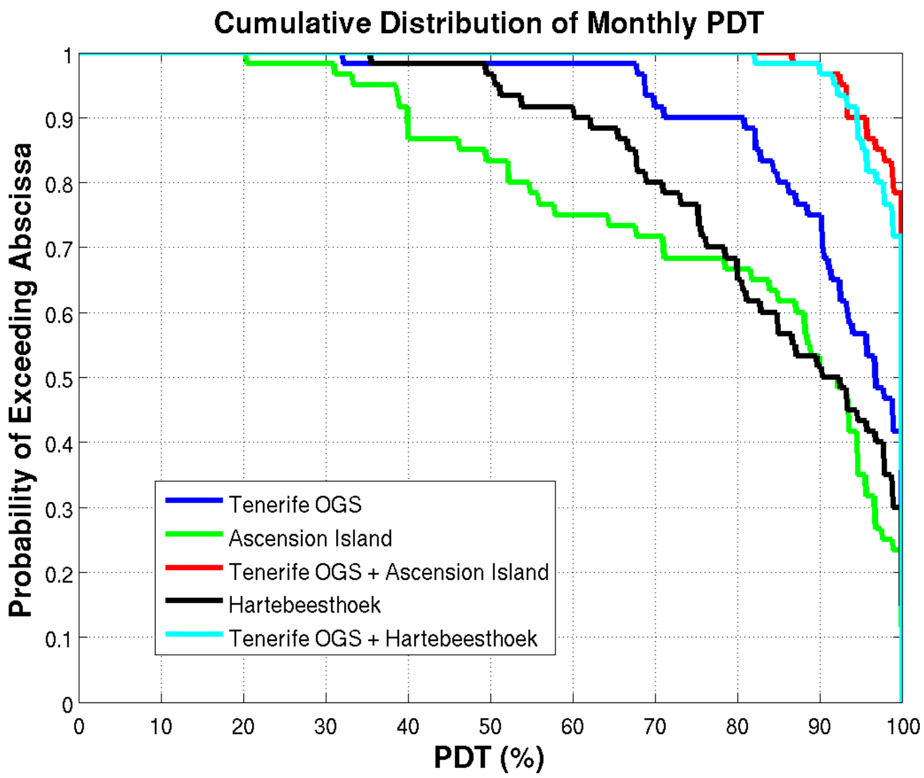


Figure 36: Cumulative distributions of the monthly PDT for the L1 scenario.

3.6.5 Link 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 37 shows the downlink budget for the L1 scenario.

L1 DOWNLINK BUDGET

INPUT PARAMETERS		
Range	2.0E+06	km
Elevation	20	deg
TRANSMITTER		
Modulation Type	64-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	1.0	W
Tx Word Rate	20.0E+06	Hz
Uncoded Slot Rate	426.7E+06	s^{-1}
Bits Per Word	6.00	
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
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	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	3.74	
Code Rate	0.50	

LINK BUDGET	
Tx Ave Power	**30.00 dBm**
Tx Photons / Pulse	3.90E+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	-2.65 dB
Rx Antenna Gain	126.14 dBi
Rx Array Gain	0.00 dB
Rx Transmission Loss	-4.56 dB
Rx Pointing Loss	0.00 dB
Total Optical Path Loss	**-101.16 dB**
Ave Power at Rx Detector	**-71.16 dBm**
Photons / Pulse at Rx Detector	**29.87**
Required Photons / Pulse	12.20
Link Margin	**3.89 dB**

Figure 37: L1 Downlink Budget

3.6.6 Ground Terminal Cost

Given the added complexity to deal with operations at small SEP angles with respect to the L2 scenario as discussed in section 3.6.3.1, the ground terminal cost is estimated to increase by 1 M€ to a total of 9 M€.

The same caveats and assumptions apply as in the L2 case.

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

Deep Space refers to distances beyond two 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 (Sun-Probe-Earth [SPE] Angle) and between the Sun and spacecraft as seen from Earth (Sun-Earth-Probe [SEP] angle)

The above characteristics are both functions of the celestial dynamics of the destination body relative to Earth. Because of the large distances involved in deep space scenarios (and hence week 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 Terminal (DOT), a 12-meter diameter receiving telescope and a 1-m transmit telescope. The variation in Mars range over the July 29, 2018 to October 29, 2020 period is 0.42 AU (63 million km) to 2.7 AU (405 million km), as shown below in Figure 38, with commensurate round trip time delays of 7 minutes and 45 minutes. Note that this scenario also implies a point-ahead angle of up to 400 microradians.

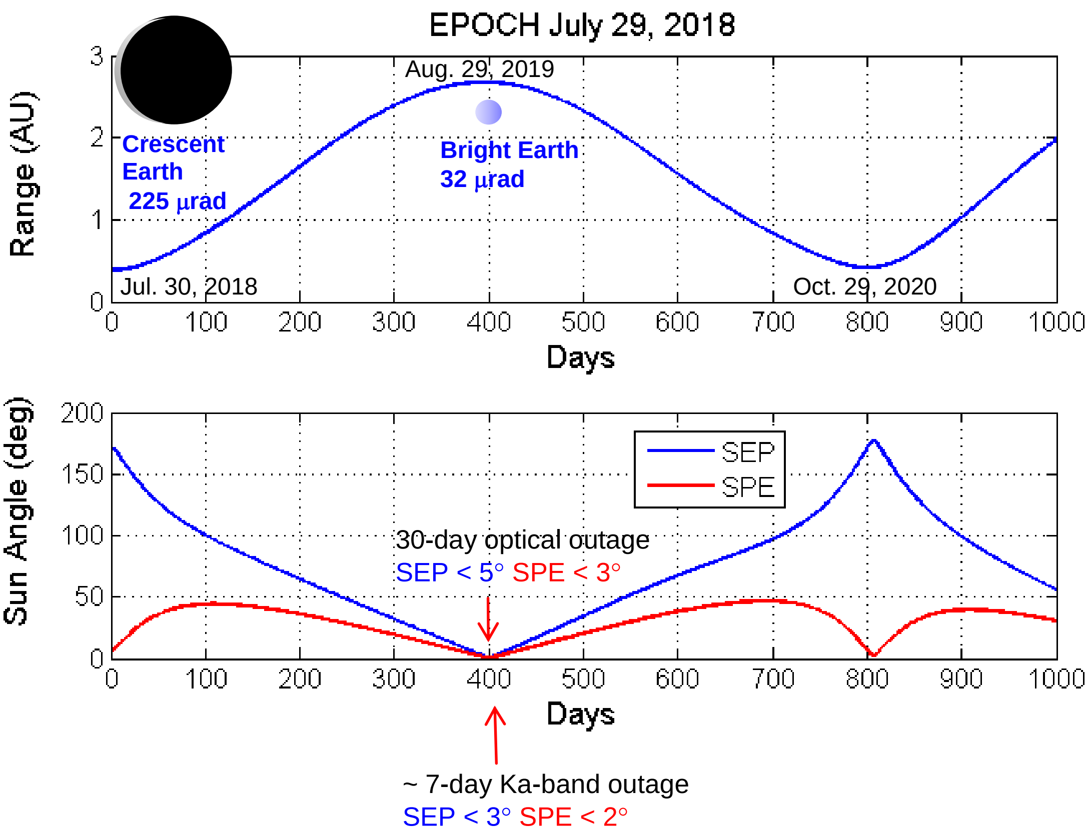


Figure 38: Range and Sun angle variations for Mars

3.7.1 Concept of Operations (ConOps)

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 pointing, acquisition and tracking (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.

3.7.1.1 Basic ConOps

The basic ConOps assumes that the spacecraft has onboard storage of 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 that under geometric and CFLOS conditions, 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 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, receiving the uplink, and processing the uplink data and ranging. 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 scenario, Figure 39 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 the epoch considered.

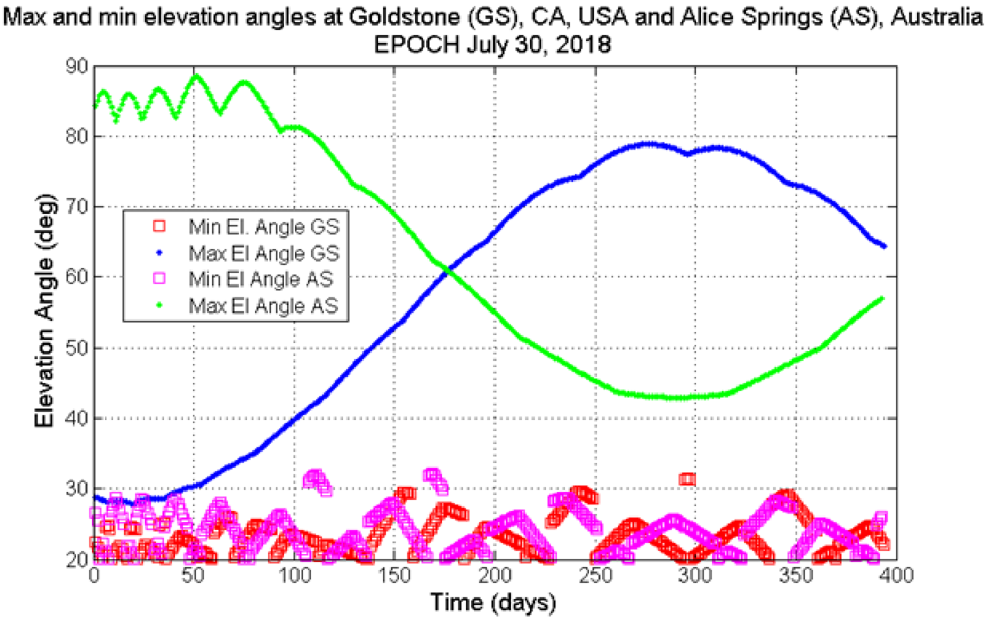


Figure 39: Elevation angles of a Mars-orbiting spacecraft relative to GDSCC and Alice Springs

Figure 40 also shows the contact times at GDSCC and Alice Springs strictly based upon geometric line of sight and for elevation angles above 20 degrees.

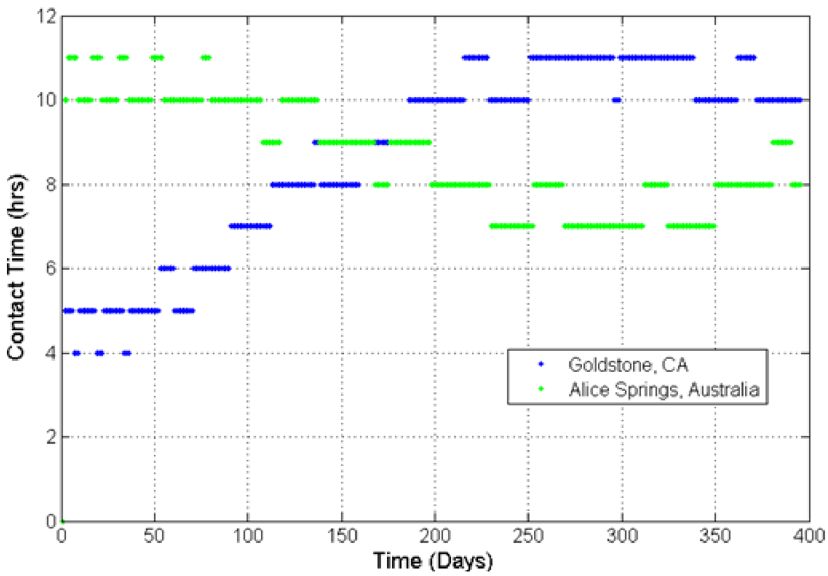


Figure 40: Contact times at GDSCC and Alice Springs

The importance of a good geographically diverse cross support is shown Figure 41 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.

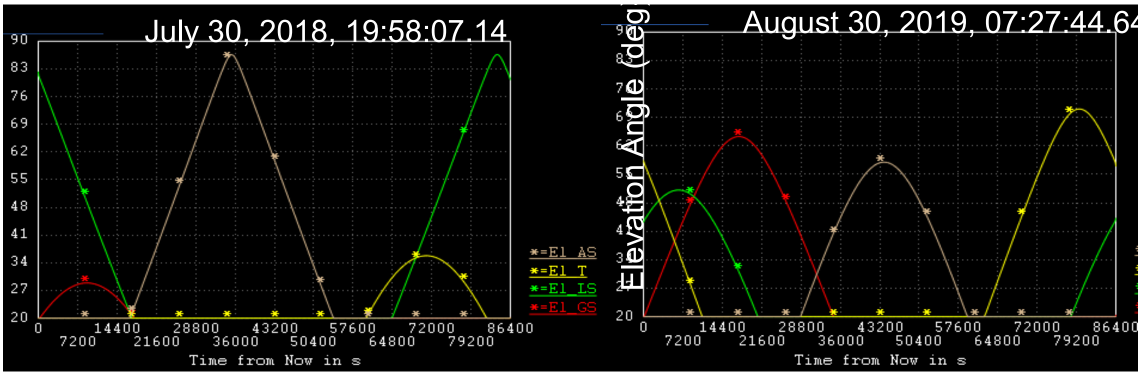


Figure 41: Elevation angles to four potential receive stations

The link budgets (see Section 3.7.5 below) for the proposed 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 42 shows the data rate versus distance for GDSCC. The performance of the MRO Ka-band telecom system with 90% weather and a 34m 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 43. 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. When combined with the CFLOS analysis and multiple receive stations as discussed above, this data return can be increased substantially.

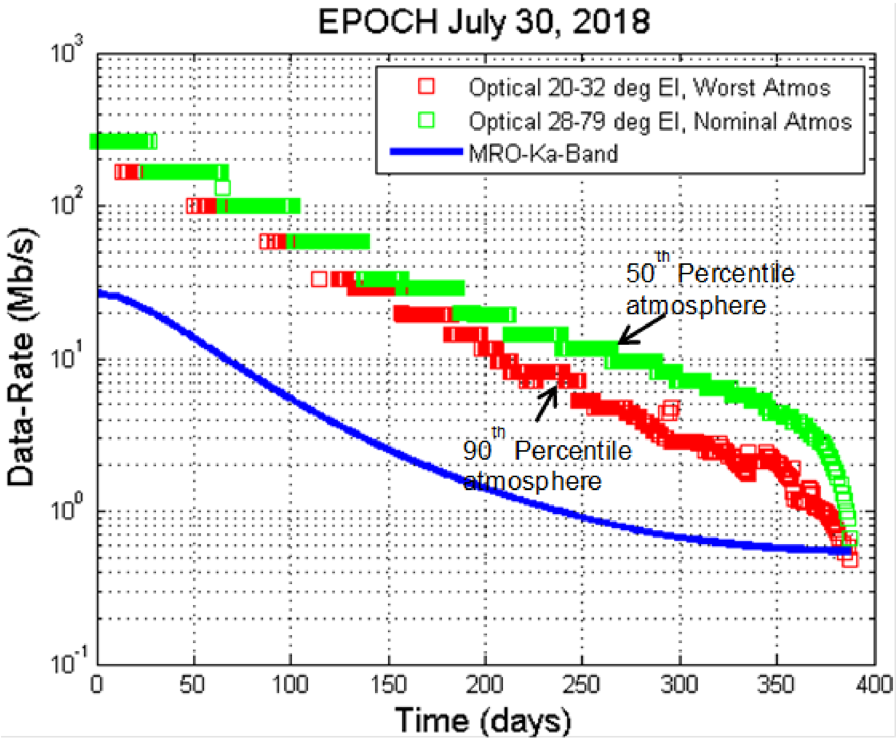


Figure 42: Data rate vs. distance at GDSCC

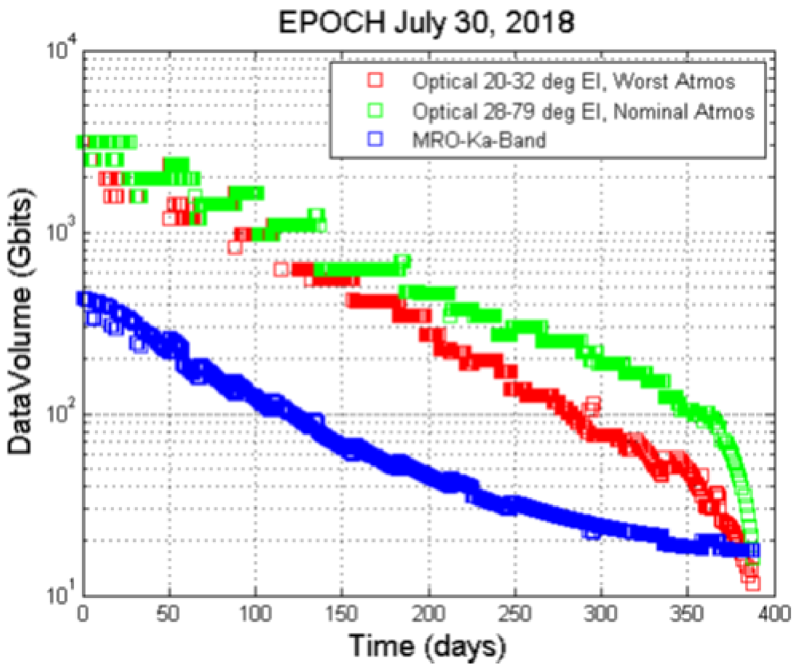


Figure 43: Data volume versus distance for GDSCC

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 44 and Figure 45.

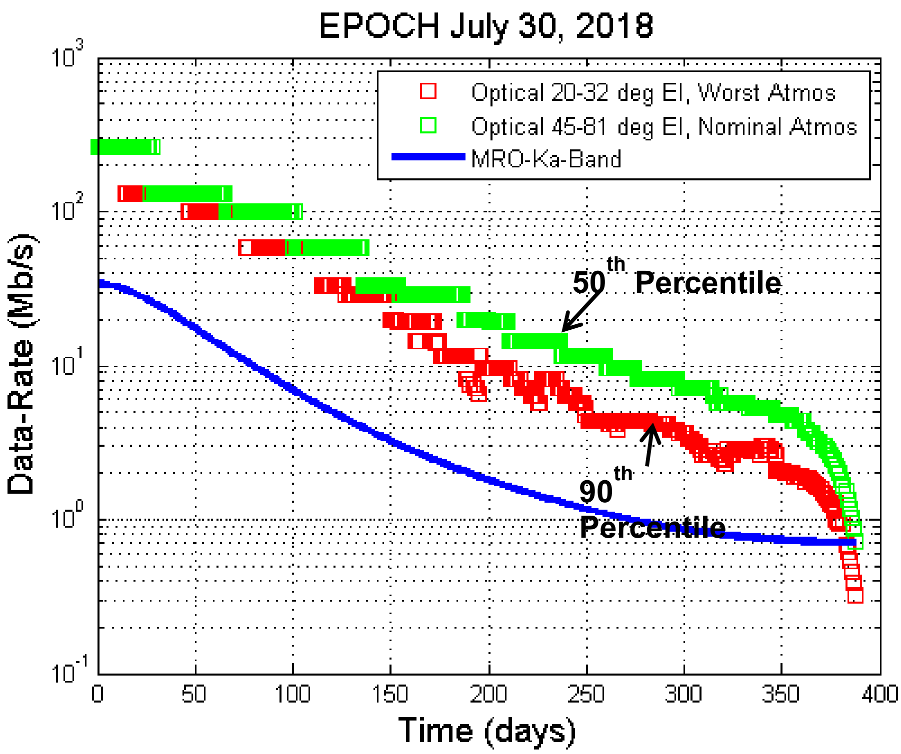


Figure 44: Data rate versus distance for Alice Springs

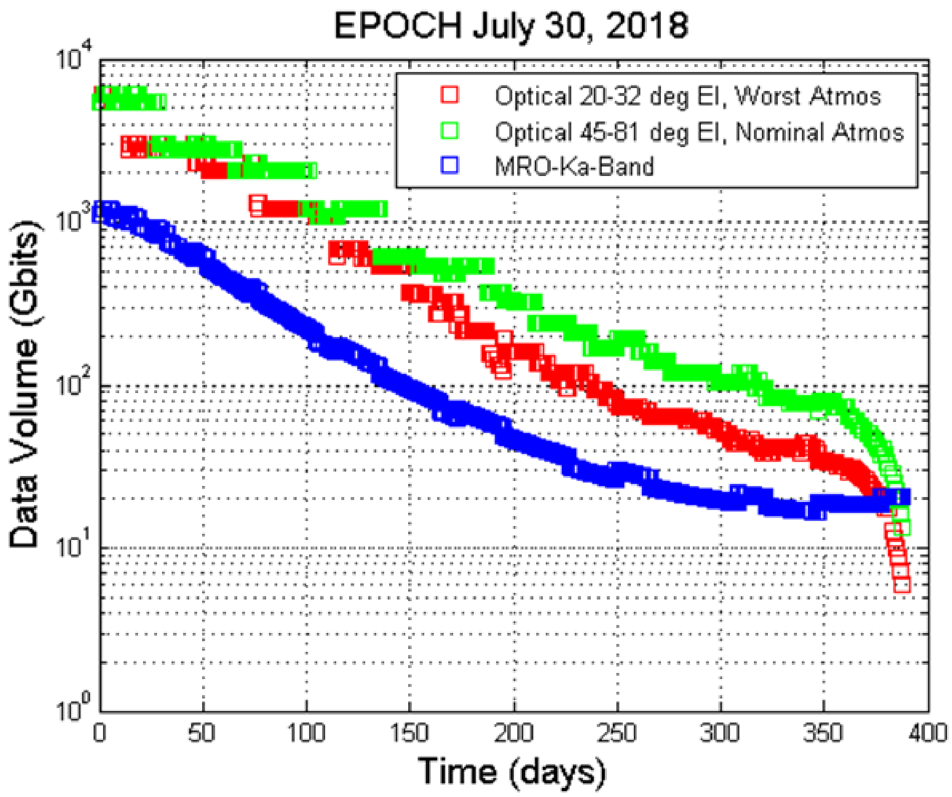


Figure 45: Data volume versus distance for Alice Springs

3.7.2 Space Terminal

The space terminal must provide the functions described in the 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 formatting, 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 46) 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 is 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 Mars Reconnaissance Orbiter (MRO) Ka-band telecom system. It is also assumed that there is 1.1 Tb of data storage onboard—10 times larger than current MRO capability.

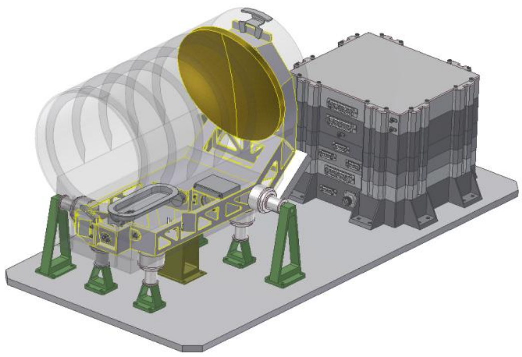


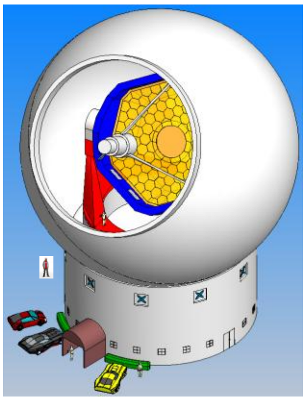
Figure 46: 22 cm DOT Flight Terminal with Vibration Isolation and Opto-Electronics Box

3.7.3 Ground Terminal

The ground terminal must provide the functions described in the ConOps. The ground terminal performs transmit and receive functions for data and ranging, weather and atmospheric measurements, and provides interfaces to 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 47) and a 1 m diameter transmit telescope (see Figure 48). 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.



New 12-m Telescope

Figure 47: 12 m segmented spherical primary receive telescope

Figure 48: 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 2005-2010. The deep space scenario differs from the other scenarios (e.g., L1 and L2) in that the distance of the satellite from Earth varies considerable through time. This factor impacts the data rate, since the data rate is proportional to $1/r^2$. 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 two of the main performance drivers—the number of ground stations and the data rate. 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 issue of variable data rate is simplified for this analysis by showing six cases. These represent the extremes of a very high data rate of 250 Mb/s (closest range to satellite) and low data rate of 10 Mb/s (farthest range) along with four intermediate data rates.

The nine example candidate ground sites for the Deep Space scenario are displayed on a map in Figure 49. 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, Perth Observatory 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 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.

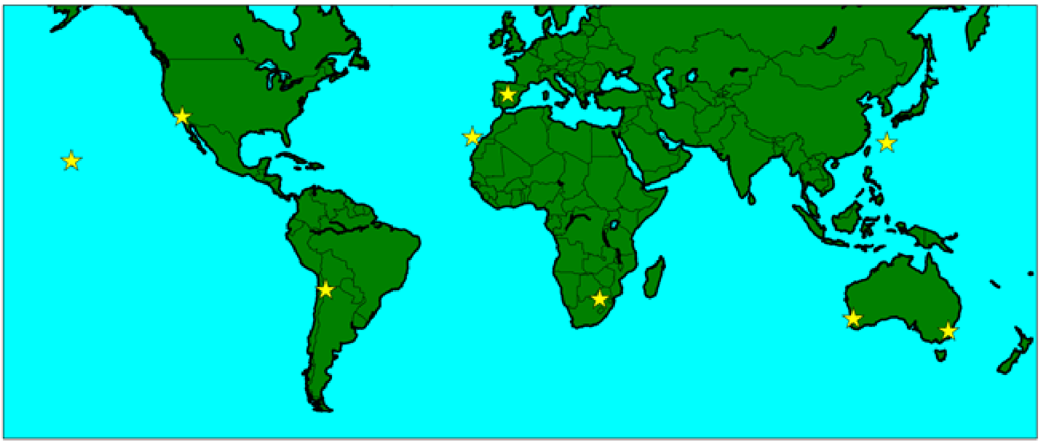


Figure 49: Candidate ground stations used for the deep space scenario.

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 Perth (116.1 East). Figure 50 shows the PDT of each network size for six different data rates. The blue line shows the PDT for the 250 Mb/s scenario, where the satellite is at its closest range. In this case, a single site (the Tenerife OGS) achieves 90% PDT, and only two ground stations (Haleakala and the Tenerife OGS) are required to achieve 99% PDT. However, the PDT drops for lower data rates when the daily data volume remains constant. For example, the green curve for 25 Mb/s could be considered to represent the "average" distance to the satellite over the mission lifetime. For this case, nine sites are required to achieve 99% PDT.

Note that for this analysis, the daily data volume is not decreased proportionately with the increased range to the satellite. The PDT is calculated based on a daily data volume of 1.1 Tb in all cases. With this in mind, consider the case when the satellite is at maximum range with a data rate of 10 Mb/s. While nine sites produce a PDT of "only" 66%, this translates to an average of 728 Gb per day from deep space (at 10 Mb/s). Similarly, using this same scenario (10 Mb/s), an average of 660 Gb per day can be sent to Earth with six ground stations (PDT = 60%). This analysis indicates that the cloud and longitudinal diversity made possible by international cross support makes transferring large data volumes via optical communications from deep space an attractive option.

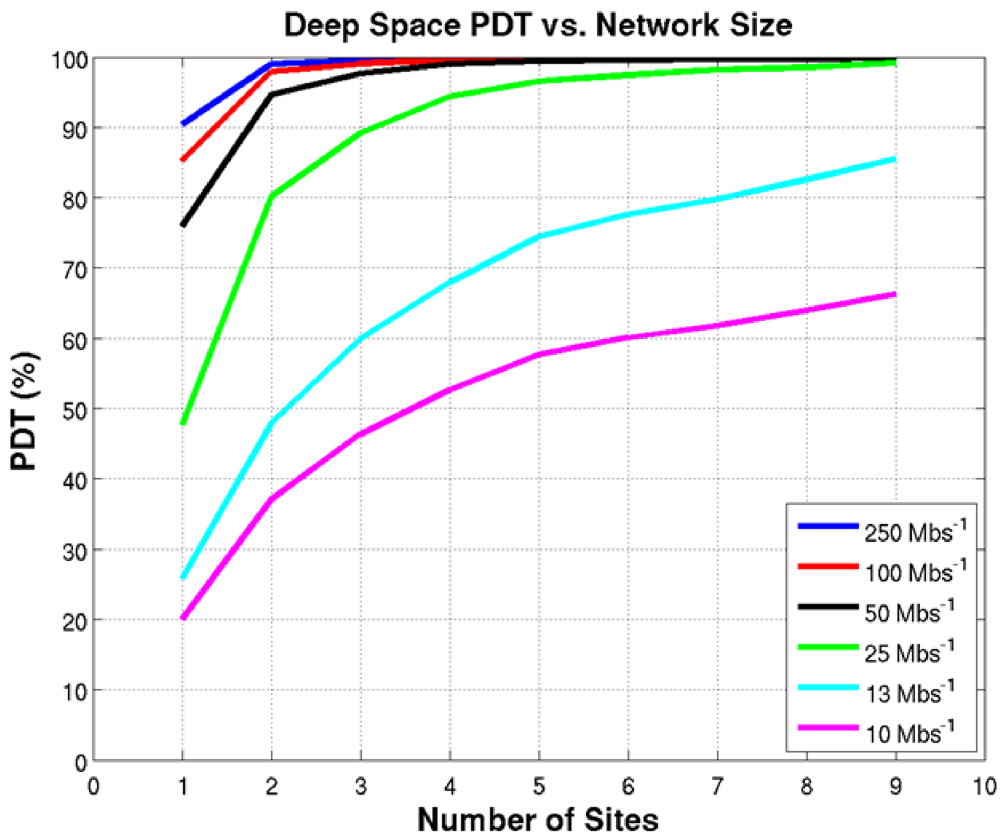


Figure 50: Overall Percent Data Transferred (PDT) for the Deep Space scenario for 1-9 site networks of ground stations for six different data rates.

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 51 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.

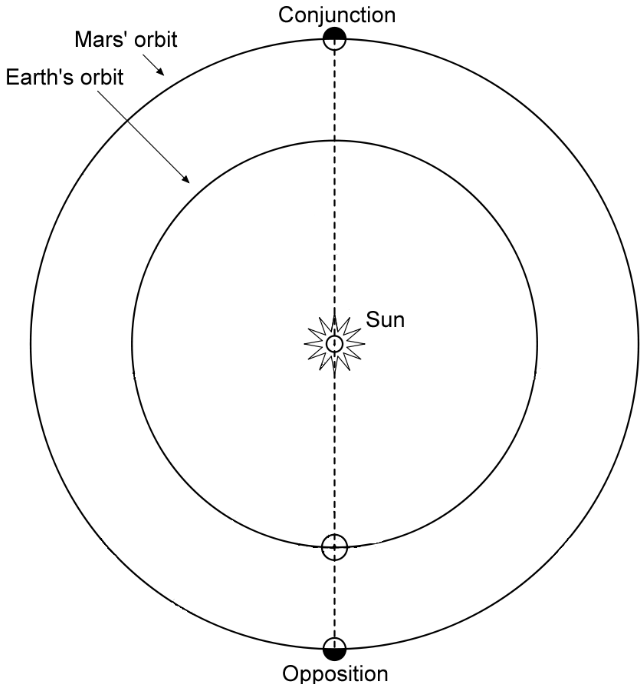


Figure 51: Schematic of the orbits of Earth and Mars

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.

Following below are sample link budgets for a near range (around opposition, see Figure 52) and a far range (around conjunction, see Figure 53) scenario. At far range, the space loss is more than 15 dB greater than at near range. Simultaneously, the presence of copious amounts of solar stray light in the atmosphere during the daytime communication opportunities when Mars is near conjunction increases the number of signal photons per pulse required to achieve an adequate signal-to-noise ratio for detection.

MARS (NEAR RANGE) DOWNLINK BUDGET

INPUT PARAMETERS		
Range	68.82E+06	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
Uncoded Slot Rate	2.1E+09	s^{-1}
Bits Per Word	4.00	
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
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.00	
Atm Transmission Along LOS	95.0	%
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	1.0	apertures
Required Photons / Pulse	1.89	
Code Rate	0.50	

LINK BUDGET		
Tx Ave Power	**36.02**	**dBm**
Tx Photons / Pulse	1.20E+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	-0.42	dB
Rx Antenna Gain	147.72	dBi
Rx Array Gain	0.00	dB
Rx Transmission Loss	-4.90	dB
Rx Pointing Loss	0.00	dB
Total Optical Path Loss	**-104.79**	**dB**
Ave Power at Rx Detector	**-68.77**	**dBm**
Photons / Pulse at Rx Detector	**3.98**	
Required Photons / Pulse	1.89	
Link Margin	**3.25**	**dB**

Figure 52: Near-range Mars Downlink Budget

MARS (FAR RANGE) DOWNLINK BUDGET

INPUT PARAMETERS		
Range	400.0E+06	km
Elevation	30	deg
TRANSMITTER		
Modulation Type	128-PPM	
Tx Wavelength	1.55	µm
Tx Ave Power	4.0	W
Tx Data Rate	764.0E+03	Hz
Uncoded Slot Rate	27.9E+06	s^{-1}
Bits Per Word	7.00	
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
ATMOSPHERIC LOSSES		
Atm Zenith Transmittance	95.0	%
Relative Airmass	1.00	
Atm Transmission Along LOS	95.0	%
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	1.0	apertures
Required Photons / Pulse	6.15	
Code Rate	0.50	

LINK BUDGET	
Tx Ave Power	**36.02 dBm**
Tx Photons / Pulse	4.09E+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	-0.42 dB
Rx Antenna Gain	147.72 dBi
Rx Array Gain	0.00 dB
Rx Transmission Loss	-4.90 dB
Rx Pointing Loss	0.00 dB
Total Optical Path Loss	**-120.08 dB**
Ave Power at Rx Detector	**-84.06 dBm**
Photons / Pulse at Rx Detector	**40.13**
Required Photons / Pulse	24.61
Link Margin	**2.12 dB**

Figure 53: Far-range Mars Downlink Budget

3.7.6 Ground Terminal Cost

There are a number of costs that must be considered in the assessment. Initial cost for the site preparation and implementation of the receive and transmit telescopes and associated electronics, and provision of infrastructure (roads, facilities, communications, etc.).

The largest entry cost for the deep space ground terminal is the estimated 30 M€ - 45 M€ cost of the 12 m receive terminal.

The estimated cost for a 1 meter transmit station is 3 M€ - 4.5 M€, for a total of 50 M€ for transmit and receive.

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

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, which otherwise could not communicate at all or could not 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 low Earth orbit (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. No need for coordination and licensing of optical inter-satellite link frequencies and interference free operation.

Generally speaking, based on NASA's Tracking and Data Relay Satellite (TDRS) system, each Earth relay 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.

The European Data Relay Satellite (EDRS) system is currently being developed and will initially be a constellation of two GEO satellites intended to relay information between user spacecraft and Earth.

EDRS supports 600 and 1800 Mbps optical communications inter-satellite links. Downlink (Feeder Link) is via Ka-band to the ground at a maximum rate of 600 Mbps.

EDRS will provide data relay services for the Sentinel 1a and Sentinel 2a Earth observation satellites of the Global Monitoring for Environment and Security (GMES) initiative, led by the European Union (EU). The sentinels, Sentinel 1 being a synthetic aperture radar satellite and Sentinel 2 a multi-spectral imager, can generate data rates of up to 600 Mbps and 500 Mbps respectively.

EDRS will initially consist of two GEO satellites (EDRS-A and EDRS-C) very closely spaced (3° East and 8° East) to enable downlinks to ground stations all over Europe, as shown in Figure 54.

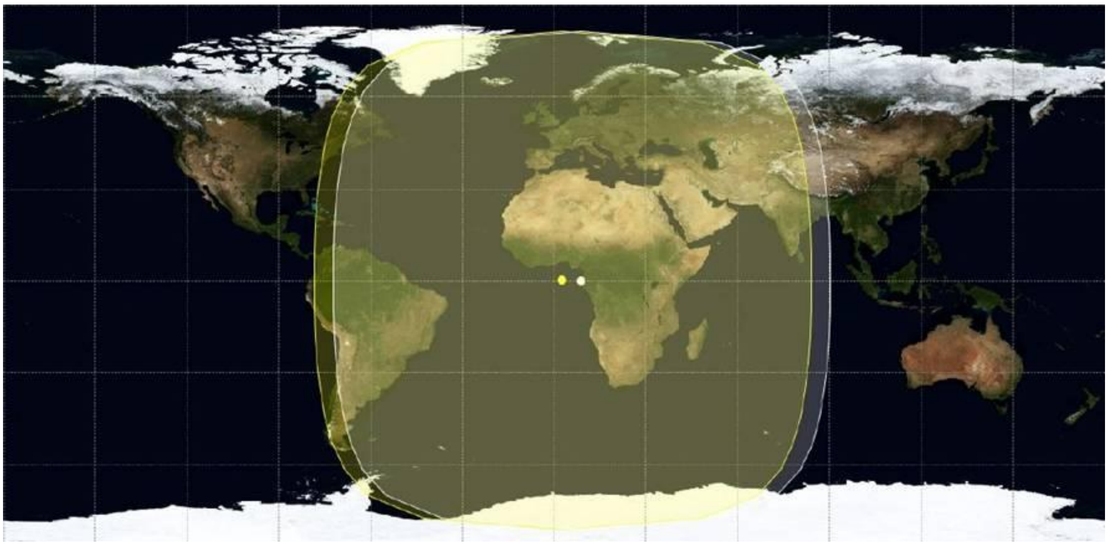


Figure 54: Planned orbital locations and Earth coverage of the first two EDRS satellites EDRS-A (9° East) and EDRS-C (3° East, TBC)

The EDRS system will also provide data relay services for the follow-on Sentinel 1b and Sentinel 2b satellites. The optical inter-satellite link between the Sentinel and EDRS spacecraft is based on binary phase shift keying (BPSK) of neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers at 1064 nm wavelength. This is a coherent phase modulation scheme developed and space-qualified by Tesat Spacecom and funded by the German Space Agency (DLR). BPSK modulation was chosen because of its high sensitivity (in terms of required photons per bit).

The laser communication terminals (LCT) on the Sentinel and the EDRS spacecraft are identical and Table 10 shows the key parameters of the LCT.

Table 10: Key parameters of the laser communication terminals used for the Sentinel and EDRS spacecraft.

Antenna diameter:	135 mm
Transmit power:	<3000 mW
Data rate:	1.8 Gb/s
Wavelength:	1064 nm
Modulation scheme:	BPSK
Maximum link distance:	<45000 km
Power consumption:	160 W
Mass:	54 kg

Figure 55 shows a previous version of the laser communication terminal mounted on a spacecraft with the hemispherical coarse pointing periscope actuated. The launch lock and park position is shown as the oval “black hole” on the left hand side of Figure 55.

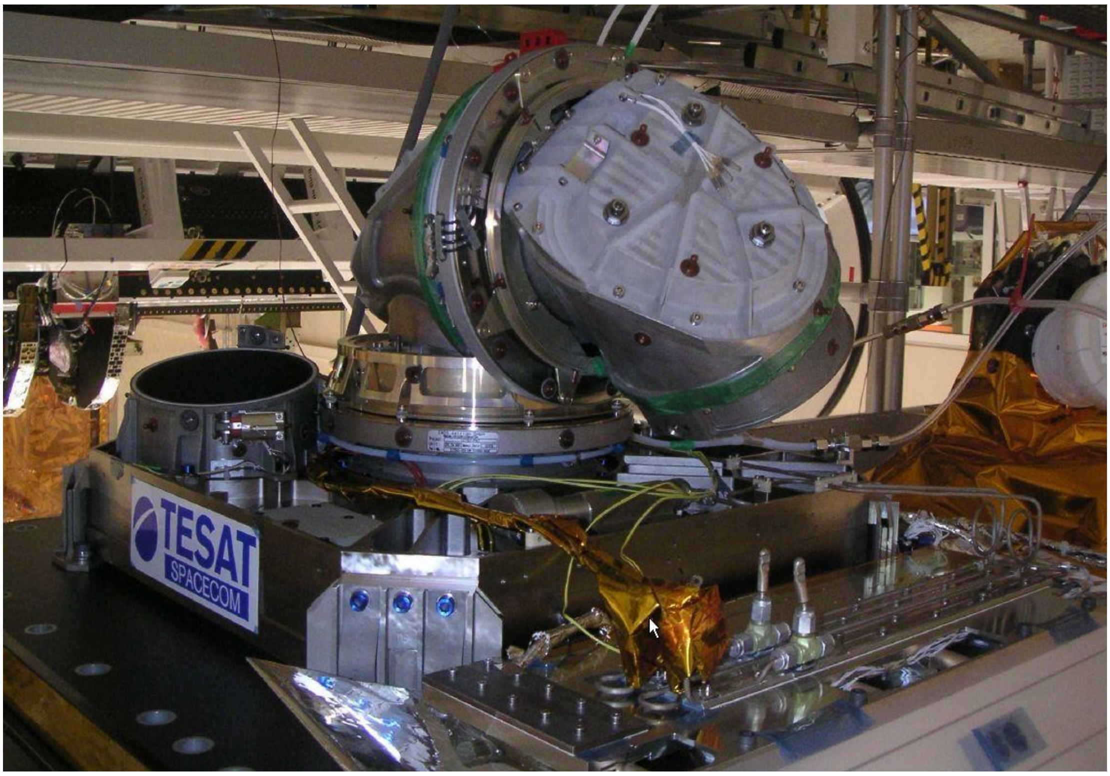


Figure 55: Laser communication terminal with hemispherical coarse pointing periscope actuated

Two precursor LCT were implemented in 2008 on two LEO satellites (NFIRE and TerraSAR-X) and are demonstrating data rates of 5.6 Gb/s over link distances of up to 6000 km, after which the line of sight is interrupted by the Earth’s atmosphere.

The LCT on the two LEO satellites are also used to demonstrate space-to-ground links, which are feasible in good seeing conditions. For commissioning the LCTs onboard the EDRS system, ground stations will be equipped either with adaptive optics, or utilize incoherent differential phase shift keying (DPSK) reception. Both systems are currently being tested at ESA’s Tenerife OGS.

NASA’s Goddard Space Flight Center is currently developing the Laser Communications Relay Demonstration (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.

4.1.1 Scenario Description

For the purposes of this report, the following scenario is being used for the corresponding analysis and business case development.

The Earth relay 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. The Earth relay will use differential phase shift keying (DPSK) at 1.8 Gb/s for the inter-satellite optical communications links. The Earth relay will 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 optical link or an RF link and the availability requirement on the relay.

In this scenario, 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.

4.1.2 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 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, that means 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 would allow more user spacecraft to be supported and/or act as a backup to the first relay satellite.

4.1.3 Earth Relay RF Feeder Link

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 studied transmitting this data rate via RF in various studies over the past decade and the technology and spectrum (via Ka-Band) 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.

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 (26 GHz) is limited.

4.1.4 Earth Relay Optical Feeder Link

Instead of relying on an RF feeder link, an optical feeder link could be employed instead. This option is particular 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 would 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 many optical communication ground terminals to support the feeder link.

A previous DLR study concluded that 11 optical communication ground terminals scattered throughout Europe to a GEO satellite would provide 99.67% availability. 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 quick study by NASA showed that 5 ground terminals carefully located over southern Europe, Africa, and Saudi Arabia would result in 99.26% availability.

As briefly mentioned, 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 link with a maximum data rate of 2 Gb/s and an optical 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 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. As more optical ground terminals are added to support the optical feeder link, the capacity of the overall Earth relay would increase.

4.1.5 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, however, 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, thus allowing the feeder links to downlink data from another Earth relay satellite from time to time.

4.1.6 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 24 hours a day /7 days a week optical communications service, 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, no strong case appears to exist for cross support. However, if the same GEO terminal serves the same communications with the LEO and with the ground (feeder link), further study is required.

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 Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) satellite in geostationary Earth orbit (GEO) 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 Tracking, Telemetry and Command (TTC) of the spacecraft (i.e., the optical communication system is considered an additional system with a dedicated space terminal and associated ground terminals).

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 a must in order to distribute the global capabilities and cost over multiple space agencies.

5.1 Space-Earth Scenarios Business Case Recommendation

Table 11 provides an overview of the likelihood of optical space communication to be applied in future mission scenarios and the corresponding potential need for cross support. A prioritization of the various scenarios will be attempted in OLSG Phase 2.

Table 11: Space Earth Scenarios Business Case Assessment

Scenario Class	Orbit	Distance [km]	Cross Support Practice for RF operations	Cross Support / interoperability Potential for Optical routine operations	Potential future Missions	OLSG Example taken from:	Realisation: Space	Realisation: Ground
Space-Earth								
< GEO	LEO	800	Cross Support often used for high data rate telemetry	high	ESA: ISS ACES ELT (Time Transfer) confirmed	1. Tesat LCT Product	Terminal is flight qualified, coherent detection through earth atmosphere is under test with ground adaptive optics	Ground terminal ESA 1m Tenerife used for tests
						2. DLR-IKN OSIRIS Prototype	Space terminal under development	Ground terminal DLR 40cm Oberpfaffenhofen developed
						3. ESA RUAG Optel-mu Engineering Model	Space Terminal Engineering Model under development	Ground terminal under development
						4. NASA/JPL 10 Gbps LEO prototype	Space terminal prototype developed	
	MEO	22,000	traditionally not used	low		-	-	-
	GEO	36,000	traditionally not used, commercial sector	see below: Earth Relay Feeder Optical Link and Telecom Mission Optical Feeder Uplink		-	-	-
> GEO	HEO	140,000	routine based on mission MoU (e.g. Cluster, Integral), LEOP, Emergency	high	ESA: CV M3 STE-QUEST (Time Transfer) study		descoped from study	descoped from study
	Moon	370,000	routine no, mainly LEOP, Orbit Insertion, Entry Descent Landing (EDL), Emergency	high	NASA: Ladee LLCD technolgy demonstration, ESA: Lumetto study	NASA Ladee LLCD Example	Space terminal technology demonstrator will be flight qualilfied for Ladee/LLCD	Ground terminal developed for Ladee/LLCD technology demonstration
	L2	1,500,000	routine no, mainly LEOP, Emergency	high			Space terminal assumed to be derivable from a Moon Terminal	Ground terminal assumed to be derivable from a ground station for the Moon scenario
	L1	1,500,000	routine no, mainly LEOP, Emergency	high			Space terminal assumed to be derivable from a Moon Terminal	Ground terminal assumed to be derivable from a ground station for the Moon scenario
	Deep Space (e.g. Mars, Jupiter)	405,000,000	routine no, mainly LEOP, Orbit Insertion, Entry Descent Landing (EDL), Emergency	high	NASA: Deep Space Optical Terminal, study	NASA/JPL DOT Study Example	Space terminal highest complexity	Ground terminal largest size, further cost optimised designs needed

While realizable technical solutions in terms of space terminal technology and ground terminal cost containment seem to exist for the LEO, Moon, L1, and L2 scenarios, the deep space scenario is considered less mature, both in terms of space terminal technology readiness (due to the inherently higher complexity) and the very high ground terminal cost.

This requires a technical standardization process for optical space-Earth communication to be started to avoid incompatible realizations.

5.2 *Earth Relay Business Case Recommendation*

Table 12 provides an overview of the likelihood of optical space communication to be applied in future earth relay scenarios and the corresponding potential need for cross support.

Table 12: Relay Scenarios Business Case Assessment

Scenario Class	Orbit	Distance [km]	Cross Support Practice for RF operations	Cross Support / interoperability Potential for Optical routine operations	Potential future Missions	OLSG Example taken from:	Realisation: Space	Realisation: Ground
Earth Inter-Satellite Link (ISL)								
Earth ISL, Space-Ground RF	LEO to GEO		traditionally not used, ATV only	high	ESA: Artemis operational, DLR: TerraSar-X / NFire demo operational, ESA: EDRS confirmed, Sentinel confirmed	1. ISL: ESA: Tesat LCT Product	Space terminal is flight qualified	not applicable as based on RF solution
						2. ISL: NASA: LCRD Example	Space terminal technology demonstrator will be flight qualilfied on commercial hosting satellite in LCRD project	
	GEO-GEO Crosslinks			low	-	-	descoped from study	descoped from study
Earth ISL, Space-Ground Optical	GEO to Earth			low		NASA: LCRD Example	Space terminal technology demonstrator will be flight qualilfied on commercial hosting satellite in LCRD project	Ground terminal will be developed in LCRD project
Moon Inter-Satellite Link (ISL)								
Moon ISL	Surface to Orbiter		no example	low due to Moon dust	NASA: Constellation study, ESA: Lumetto		descoped from study	descoped from study
Mars Inter-Satellite Link (ISL)								
Mars ISL	Surface to Orbiter		routine no, mainly Entry Descent Landing (EDL), Emergency, cross support demo	low due to Mars dust and wind		NASA/JPL Study "Future Planetary Optical Access Links" Example	descoped from study	descoped from study
Telecom Mission Optical Feeder Uplink								
Telecom Mission Optical Feeder Uplink	GEO		traditionally not used	low, as in the commercial domain		ESA: Study	descoped from study	descoped from study

While technical solutions in terms of space terminal technology exist for the Earth Relay LEO-GEO scenario, this is not the case for relay scenarios around Moon or Mars, which were therefore de-scoped from the study. In the Earth Relay scenario, GEO-GEO crosslinks were also not considered further as they would be needed only for very high availability requirements. While the GEO-Earth optical feeder links could provide a much higher data return from an Earth Relay no strong case for cross support could be identified.

There is a requirement to start a technical standardization process for the Earth Relay LEO-GEO scenario in order to avoid incompatible realizations.

5.3 Ground Station Cost

Conceptually, the ground station cost is split into one-off investment cost and yearly running cost. The ground station investment cost is decomposed into the site facilities, wide area communication and the terminal investment cost. The annual running cost is decomposed into the site and terminal running cost and the wide are communication running cost.

Table 13 shows typical terminal investment cost in support of the space-Earth scenarios and the total terminal investment cost per scenario. The site facilities and wide area communication investment costs are highly location-dependent and are not estimated here. Similarly, the annual running cost of a site with its terminals and the wide area communication running cost are not estimated here as they are also highly location dependent.

The ground terminal costs vary between 800 k€ for a 50cm terminal for LEO applications, 8-9 M€ for a 1m terminal for Moon/L1/L2 applications, to 50 M€ for a 12m terminal for deep space applications (see Table 13).

Table 13: Ground Station Cost

	Space-Earth Scenario				
	LEO	Moon	L1	L2	Mars
Terminal Size [m]	0.5	1	1	1	12
Terminal Investment Cost [M€]	**0.8**	**8**	**9**	**8**	**50**
Number of Terminals in Scenario	9	2	2	2	2
Total Terminal Investment Cost for Scenario [M€]	**7.2**	**16**	**18**	**16**	**100**
Site Facilities Investment Cost (Buildings, Power, Cooling) [M€]	site dependent	site dependent	site dependent	site dependent	site dependent
Wide Area Communication Investment Cost [M€]	site dependent	site dependent	site dependent	site dependent	site dependent
Site and Terminal Running Cost [€/y]	site dependent	site dependent	site dependent	site dependent	site dependent
Wide Area Communication Running Cost [€/y]	site dependent	site dependent	site dependent	site dependent	site dependent

While incompatible spacelink implementations for support of LEO scenarios might be conceivable (e.g., nine proprietary terminals of 800 k€ each) this approach is not recommended, as it is not economical for the space agencies. Incompatible spacelink implementations for larger distances requiring larger terminals are considered prohibitive in cost, therefore, internationally standardized solutions are considered mandatory.

In summary, the cost analysis for the needed ground terminals demands standardized technical solutions to allow interoperability and thereby economical investments and operations.

5.3.1 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. Prospective sites for future ground stations should apply if possible 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.

5.3.1.1 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 grow out of these pre-existing sites. Additional sites would then be added as needed for particular missions.

5.3.1.2 Other Existing Sites

When selecting the first sites to augment this initial set, there is a potential for cost sharing of support facilities at existing tracking stations, astronomical observatories, or laser ranging sites that would be willing to host optical terminals. These sites would operate under the assumption that the space communication terminal operations (particularly the uplink) do not disturb their nominal observations. This arrangement would possibly allow the ground terminal to benefit from the existing site infrastructure (buildings, power, cooling) and available terrestrial telecommunication networks needed for high volume data transfers. In the case of existing astronomical observatory sites, there is also the potential for re-use of decommissioned optical telescopes that could possibly be refurbished for space communication applications.

5.3.1.3 Future Collaborative Sites

The establishment of altogether 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. As noted above, several terminals might be sited in 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.

5.3.2 Recommendations and Preliminary 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.

The OLSG identified several additional issues that require further analysis. It is proposed to extend the OLSG into a phase 2 in the first and second quarters of 2012 to address the following additional topics and update the final report accordingly:

1. Assess a LEO scenario that includes high latitude stations, based on improved meteorological measurements, e.g., Svalbard, Alaska, Troll, McMurdo
2. Establish contact with the International Civil Aviation Organization (ICAO) with regard to aircraft global laser safety, and continue analysis of eye safety issues.
3. Investigate hosting of optical terminals at existing astronomical observatory sites
4. Investigate re-use of decommissioned optical telescopes as optical terminals at existing astronomical observatory sites
5. Investigate hosting of optical terminals at existing satellite laser ranging sites
6. Investigate re-use of satellite laser ranging terminals at existing laser ranging sites
7. Develop uplink beacon link budget for all scenarios to assess eye safety and backscattering
8. Refine cost estimates for consistency for all scenarios
9. Investigate shared use of optical relay terminals for both inter-satellite GEO-LEO links and GEO-ground feeder links.
10. Investigate how IOAG Service Catalog 1 needs to be amended to include optical communications

Optical space communication would benefit from technical standards that would facilitate cross support between space agencies during routine mission phases for payload data return. However, the OLSG phase 2 effort should be completed first to provide proper guidance for the development of the standards. The following steps are envisioned after conclusion of the OLSG phase 2 study:

1. In-situ meteorological measurements and associated data exchange format
2. Space Earth wavelength, modulation and detection, and pointing, acquisition, and tracking
3. Inter-satellite link wavelength, modulation and detection, and pointing, acquisition, and tracking
4. Investigate existing protocol standards to determine applicability to optical communication

6 Standardization Requirements

Table 14 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 14: Parameters to be defined to ensure compatibility in an optical cross-support scenario.

Functional breakdown	Cross support interface parameters[1]	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[2] range + stability d. Modulation 3. Receive Signal (S/C "beacon"): a. Wavelength + linewidth b. Polarization + purity c. Radiant Intensity[3] 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

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

		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… 7. Link protocol + control a. Sync pattern b. Data (frame) structure (CCSDS packet TM, etc.) c. DTN d. …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) 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 15 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 15: 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[4] 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…

6.1 *Issues of Interoperability*

6.1.1 Wavelength

Two wavelengths should be considered for optical communications—1064nm and 1550nm. Uplinks from the ground should be 1550nm to take advantage of possibly less restrictive eye safety limits. Eye safety limits should be defined according to ICAO recommendations, which are yet to be developed. 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 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 1550nm technology may be advantageous because of its synergy with terrestrial fiber-optic

[4] 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.

components, however the performance of both the 1064nm and 1550nm wavelengths should be considered. The availability of space-qualified or qualifiable parts should also be considered.

6.1.2 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 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.

7 Annex

7.1 Existing and Prospective Space Agency Optical Assets and Sites

These sites include existing and prospective space agency optical assets in:

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

7.1.1 DLR's OGS (Oberpfaffenhofen)

Figure 56 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 56: Optical ground station at DLR Oberpfaffenhofen.

7.1.2 ESA's OGS (Tenerife)

ESA's optical ground station (Tenerife OGS) is shown in Figure 57. 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 57: 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 58) 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

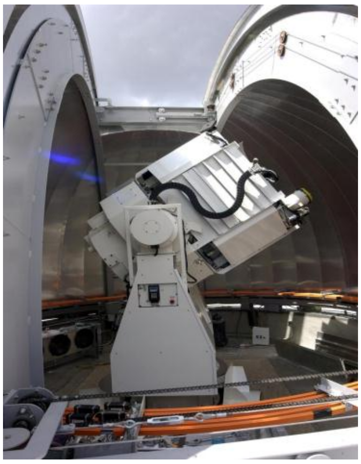
Figure 58: 1-meter Zeiss telescope and English mount of the ESA Tenerife OGS.

7.1.3 NASA's OGS (Table Mountain)

The NASA/JPL Optical Communications Telescope Laboratory (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 59).


Figure 59: 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 60: The OCTL telescope and parameters

For laser propagation out of the facility, OCTL is equipped with a three-tier safety system (see Figure 61).

- 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 FAA to automate this process based on sensors and data from the LCH and the FAA.

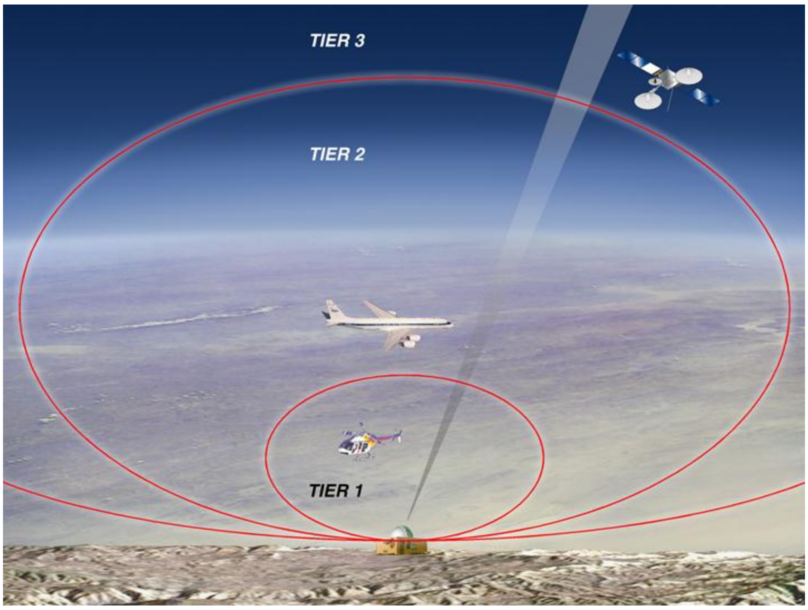


Figure 61: OCTL's Three-tiered safety system

7.1.4 NICT's OGS (Tokyo)

NICT's optical ground station (shown in Figure 62) 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.

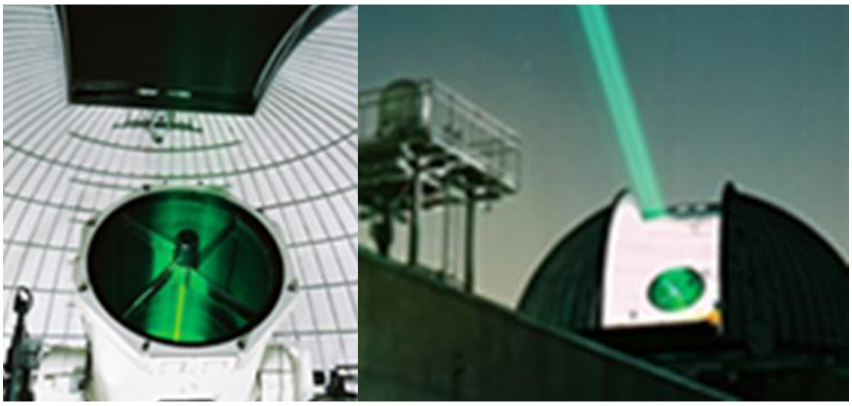


Figure 62: Koganei, Tokyo, 1.5m telescope (left) and OGS (right)

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 63, the site is located at an altitude of 114.4m, close to Chofu airport in Tokyo, 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	114.4m
Height above ground	7m
Dome	11m Sliding Roof
Telescope type	1.5m Nasmyth/Bent Cassegrain/Cude

Figure 63: 1.5 meter Contraves (Currently Brasher LP)

7.2 *Laser Ranging Sites*

These sites might be of interest for LEO space-to-Earth communication.

International Satellite Laser Ranging Network possible sites:

- 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

7.3 List of Astronomical Observatory Sites

Table 16: 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
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

Designator (a.k.a.)	Location	Dia. (m)
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:

1) This is not an exhaustive list and does not include the many decommissioned telescopes around the world.

2) Most astronomical telescopes are for night use only and may need significant modification for day use.

3) The 1.0-2.0 m class telescopes shown are just examples, since there are many in this class.

4) The telescopes above 5 m are in heavy use by astronomers.

Appendix A. List of Acronyms

2-PSK	2-Phase Shift Keying
ANSI	American National Standards Institute
AS	Alice Springs
APD	Avalanche photodiodes
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

ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon’s Interaction with the Sun
ASI	Agenzia Spaziale Italiane
BSI	British Standards Institution
BLS	Boundary layer scintillometer
BPSK	Binary phase shift keying
CCD	Charge-coupled device
CFLOS	Cloud-free line of sight
CNES	Centre National d'Études Spatiales
COTS	Commercial off the shelf
CWDM	Coarse wavelength division multiplexed
DFS	Deutsche Flugsicherung
DIMM	Differential Image Motion Monitor
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOT	Deep Space Optical Terminal
DPSK	Differential phase shift keying
DSN	Deep Space Network
EDFA	Erbium-doped fiber amplifier
EDRS	European Data Relay Satellite
EO	Earth-observation
ESA	European Space Agency
FAA	Federal Aviation Administration
FPGA	Field-programmable gate array
Gb/s	Gigabit per second
GDSCC	Goldstone Deep Space Communications Complex
GEO	Geostationary Earth Orbit
GMES	Global Monitoring for Environment and Security

HQ	Headquarters
ICAO	International Civil Aviation Organization
IDA	Institute for Defense Analyses
IKN	Institut für Kommunikation und Navigation
IOAG	Interagency Operations Advisory Group
ISL	Inter-satellite link
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KARI	Korea Aerospace Research Institute
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCH	Laser Clearinghouse
LCRD	Laser Communications Relay Demonstration
LCT	Laser communication terminal
LEO	Low Earth Orbit
LIDAR	Light detection and ranging
LLCD	Lunar Laser Communication Demonstration
LLGT	Lunar Lasercomm Ground Terminal
LLST	Lunar Lasercomm Space Terminal
LNOT	Laser Communications Network Optimization Tool
LOS	Line of sight
LS	La Silla
M-ary PPM	M-ary Pulse Position Modulation, where M is the number of possible symbols
Mb/s	Megabits per second
MDEG	Milli-degree or 1/1,000 of one degree, s. “ARCSEC”
MetOP	Meteorological Operational Satellite
MIR	Middle infrared
MIT	Massachusetts Institute of Technology
MODIS	Moderate Resolution Imaging Spectroradiometer European
µRAD	Micro-radian or 1/1,000,000 of one radian, s. “ARCSEC”
MOPA	Master-oscillator power amplifier
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
NICT	National Institute of Information and Communications Technology
OCTL	Optical Communications. Telescope Laboratory
OGS	Optical Ground Station
OICETS	Optical Inter-Orbit Communications Engineering Test Satellite
OLSG	Optical Link Study Group
OOK	On-Off Keying
OSIRIS	Optical Space Infrared Downlink System
PAT	Pointing, acquisition, and tracking
PDT	Percent data transferred
PPM	Pulse position modulation
RF	Radio Frequency
SCPPM	Serially Concatenated Pulse Position Modulation
SEP	Sun-Earth-Probe angle
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal-to-noise ratio
SNSPD	Superconducting nano-wire single photon detectors
SPE	Sun-Probe-Earth angle
SWIR	Short-wave infrared

T	Teide
TDRS	Tracking and Data Relay Satellite
TMF	Table Mountain Facility
TTC	Telemetry, tracking, and command
WSI	Whole sky imager

Appendix B. References

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