Interagency Operations Advisory Group
Optical Link Study Group

Optical Link Study Group
Addendum to Final Report

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Executive Summary

This addendum addresses specific topics beyond the Optical Link Study Group (OLSG) Final Report, as requested at Interagency Operations Advisory Group-15b (IOAG-15b). The IOAG also provided the OLSG with additional direction regarding specific topics to address in the standardization guidance portion of this addendum. During the past year the OLSG studied these topics and in the course of performing its investigations, identified additional issues and collected further information relevant to its initial findings. Section 2 of this document details the work performed to address these topics. Based on this work, the OLSG developed a set of recommendations (detailed in section 3 of this addendum), which will be delivered as an input to IOAG-16 in December 2012. These recommendations are summarized in the three tables below.

Recommended Actions for All Space Agencies	Priority
The OLSG recommends that space agencies coordinate with their respective civil aviation authorities to support optical space communications within ICAO.	1
The space agencies should conduct a rigorous detailed study independent of the CCSDS to determine if there are ways of accomplishing beaconless PAT, as this would also facilitate a solution to the eye safety issues.	2

Recommended Actions for the OLSG	Priority
The OLSG should continue the dialogue with ICAO, with the goal of accommodating optical space communications within the ICAO laser safety standard for all types of aircraft passing through the uplink optical laser beam.	1
The OLSG should continue the dialog with the NASA JSC Space Medicine Office to discuss the implications of the revised eye safety calculations performed by the OLSG for ground-to-spacecraft, LEO spacecraft-to-ground, and satellite-to-satellite cases, and for atmospheric scintillation effects.	1

Recommended Standardization Guidance for the Consultative Committee for Space Data Systems (CCSDS)	Priority
The CCSDS should study the possibility of dual wavelength ground terminals in the event that a single wavelength is not achievable, assuming that dual wavelength onboard terminals are not recommended. Best practices for a common optical interface should be defined that would allow one agency's back-end equipment to be connected to another agency's optical front-end.	2
The CCSDS should standardize the uplink beacons and associated acquisition sequence.	1
The CCSDS should develop two sets of standards for modulation and coding for return links to deal with the low and high photon density domains.	1
The CCSDS should develop standards for combinations of modulation and coding for channel-dependent effects (e.g., those caused by elevation angle and standard atmospheric conditions). The CCSDS should develop Variable Coding and Modulation (VCM) standards.	3
The CCSDS should develop standards for combinations of modulation and coding for channel-dependent effects (e.g., those caused by elevation angle and actual atmospheric conditions). The CCSDS should develop Adaptive Coding and Modulation (ACM) standards.	4
The CCSDS should develop two sets of standards for modulation and coding for forward links to deal with the low and high photon density domains.	2
The CCSDS should conduct a study to confirm that IOAG Service Catalog 1 and IOAG Service Catalog 2 can be used, and recommend an association of the optical physical modulation and coding layers with the existing higher protocol layers. If the existing protocols are considered insufficient, then CCSDS should develop optical communication-specific protocols.	1
The CCSDS should develop data exchange standards for optical communication forecasts and meteorological data from ground sites. The CCSDS should reuse existing standards (e.g., BUFR, GRIB, NETCDF) from the meteorological community when possible.	1
The CCSDS should develop standard practices for each scenario (e.g., LEO, GEO, Lunar, L1/L2, deep space) that will enable automatic retransmission.	2
The CCSDS should review the service management standard and identify areas that must be modified to accommodate optical communications and develop the necessary amendments.	2

Recommended Standardization Guidance for the Consultative Committee for Space Data Systems (CCSDS)	Priority
The CCSDS should develop best practices for the systems engineering of optical communication links for missions, including practices for meteorological information and predictive weather, mission and eye safety link budgets, compatibility testing, and terminology/system decomposition.	2

1 Introduction

1.1 Purpose

The Optical Link Study Group (OLSG) was formed by the Interagency Operations Advisory Group (IOAG) in November 2010 to determine if there is a business case for cross support of optical communication links, and if so, to provide guidance for standardization. The OLSG reported its findings to the IOAG in an intermediate report in December 2011 and in a final report in June 2012. The OLSG Final Report recommended that the OLSG continue its work, and provide additional guidance regarding the standards required to realize interagency optical communications cross-support capability. This guidance was to be incorporated in an addendum to the final report. The IOAG accepted the OLSG recommendations and tasked the OLSG with developing such an addendum, and also provided the OLSG with a list of topics to explore further (sections of this addendum containing OLSG findings relevant to these topics are indicated in *italics*):

- Investigate astronaut eye safety and Low Earth Orbit (LEO) satellite uplink safety (including accommodations for Laser Clearing House [LCH]), as well as contacting International Civil Aviation Organization (ICAO). *(section 2.1)*
- Explore the ground station coordination and operations concept for optical communication missions further including long-term and short-term scheduling, inter-station weather information flow, etc. *(section 2.2)*
- Include uplink data as part of the standardization guidance (develop short scenarios for uplink communication) (*section 2.3)*
- Investigate if adaptive modulation/coding should be included as part of standardization guidance *(section 2.4*)
- Converge on standardization of modulation schemes for deep space *(section 2.5)*

The IOAG also provided the OLSG with additional direction regarding specific topics to address in the standardization guidance portion of this addendum.

During the past year the OLSG studied these topics, and in the course of performing its investigations, identified additional issues and collected further information relevant to its initial findings. Throughout its extended work period, the OLSG periodically briefed the IOAG on its progress.

This report is an addendum to the final OLSG report delivered to the IOAG in June 2012 and provides the technical details to address each topic posed by the IOAG for additional research, any other additional relevant information the OLSG has gathered during its investigations, as well as updated guidance for standardization. If approved by IOAG-16 in December 2012, the final OLSG report (including the addendum) will provide the basis of the optical communication topic to be presented to Interagency Operations Panel-3 (IOP-3), as well as serve as guidance to the Consultative Committee for Space Data Systems (CCSDS) for development of optical communication cross-support standards.

1.2 *Scope*

The scope of this document is limited to the technical questions presented by the IOAG, as well as any new issues uncovered during deliberations of the OLSG during the past year.

1.3 *Methodology*

Following the Terms of Reference provided in the OLSG Charter (see section 1.1 of the OLSG Final Report) the agencies participating in the OLSG addressed the questions posed by the IOAG. The team used various methodologies, depending on the topic area. The OLSG refined link budgets to address specific eye safety questions, and made initial contacts with the International Civil Aviation Organization (ICAO) and the NASA Johnson Space Center (JSC) Space Medicine Office to help interpret regulations for civil aviation and astronaut eye safety. The OLSG further refined weather data to address availability questions. Additional analysis addressed questions regarding use of optical communication in the various scenarios, including extension of the weather-based visibility analysis done for the original report.

2 OLSG Additional Research

The subsections below contain material developed by the OLSG since publication of the OLSG Final Report in June 2012. This material augments the information on specific topics addressed in the OLSG Final Report and addresses topics the IOAG posed to the OLSG for additional research.

2.1 Uplink Eye Safety

Section 2.1 and its subsections describe the research the OLSG conducted to address the following topic suggested for further investigation by the IOAG:

- Investigate astronaut eye safety and LEO satellite uplink safety (including accommodations for LCH), as well as contacting ICAO

To address these issues, OLSG contacted the International Civil Aviation Organization (ICAO) to begin a dialogue concerning uplink eye safety and future implications that ICAO standards may have on laser communications for all space agencies. OLSG also sought advice and recommendations from human spaceflight safety staff to determine the restrictions (if any) currently in place for laser communications and operations on the International Space Station (ISS).

The OLSG did not study eye safety related to LEO-to-Earth or satellite-to-satellite beams that would affect human spaceflight. The OLSG also did not consider atmospheric scintillation effects.

This section also provides additional information on one example of a LEO uplink design using 1064 nm.

2.1.1 Additional Low Earth Orbit Uplink Design Using 1064 nm (RUAG, ESA/TESLA)

The Terminal for Small Satellite LEO Application (TESLA) project targets the development of an Optel-μ engineering model of the space terminal and of a prototype of the ground terminal. The activity is being executed by a European consortium, led by RUAG Switzerland.

The Optel-μ terminal is described in the OLSG report, section 3.1.2, as an example of LEO space terminal. The ground terminal is equipped with an uplink beacon at 1064 nm that provides a reference for the space terminal during acquisition and pointing, and works as a pulsed system that delivers Automatic-Repeat Request (ARQ) information. Key features of the ground laser are:

- Wavelength: 1064nm
- Beams: 4 incoherent beams, with an average power of 3 W per laser source
- Laser: Pulsed laser, with a pulse repetition frequency of 20 kHz and a pulse duration of 30 ns

To assess the laser hazard for repetitively pulsed and modulated lasers, the most restrictive condition among the following three must be considered:

1. The exposure from any single pulse in a train of pulses shall not exceed the maximum permissible exposure (MPE) for a single pulse
2. The average power for a pulse train of duration T (exposure time to be considered for the assessment) shall not exceed the MPE for an exposure of duration T
3. The exposure for any single pulse or group of pulses in the train during the time T shall not exceed the MPE for a single pulse multiplied by a multiple-pulse correction factor, which accounts for the number of pulses in the time T

The limiting condition for the TESLA uplink laser is condition number 3, above. The energy density at the TESLA telescope aperture is designed to be smaller than the MPE value of condition 3 (2.36 mJ/m^2). Therefore, the beacon can be considered eye-safe at any distance, starting from the aperture. Due to the incoherence and the divergence of the beams, the peak emittance further decreases when the distance from the aperture increases.

The laser of the TESLA beacon/uplink system has been measured and certified by an internationally certified evaluator, following the International Electrotechnical Commission standard (IEC 60825-1)[1]. It has been classified as Class 1M laser—i.e., not harmful to the unaided human eye (only harmful if directly viewed through magnifying optical instruments).

The communication subsystem ensures reliable transmission of the data with 2.5 Gbps raw/2 Gbps user data rate over two optical channels (1 Gbps each) at bit error rate (BER) $>10^{-9}$ over link distances up to 1000 km. Both optical channels can be used simultaneously. The direct detection system has to cope with variations in space loss, atmospheric scintillation effects, background noise, and varying link distances. Uplink beacon channel information is used for optimal data rate adjustment during a downlink, and data rate is scaled for optimal exploitation of channel transmission characteristics.

[1] International Electrotechnical Commission (2007), *Safety of laser products – Part 1: Equipment classification and requirements*, IEC 60825-1, Geneva, Switzerland.

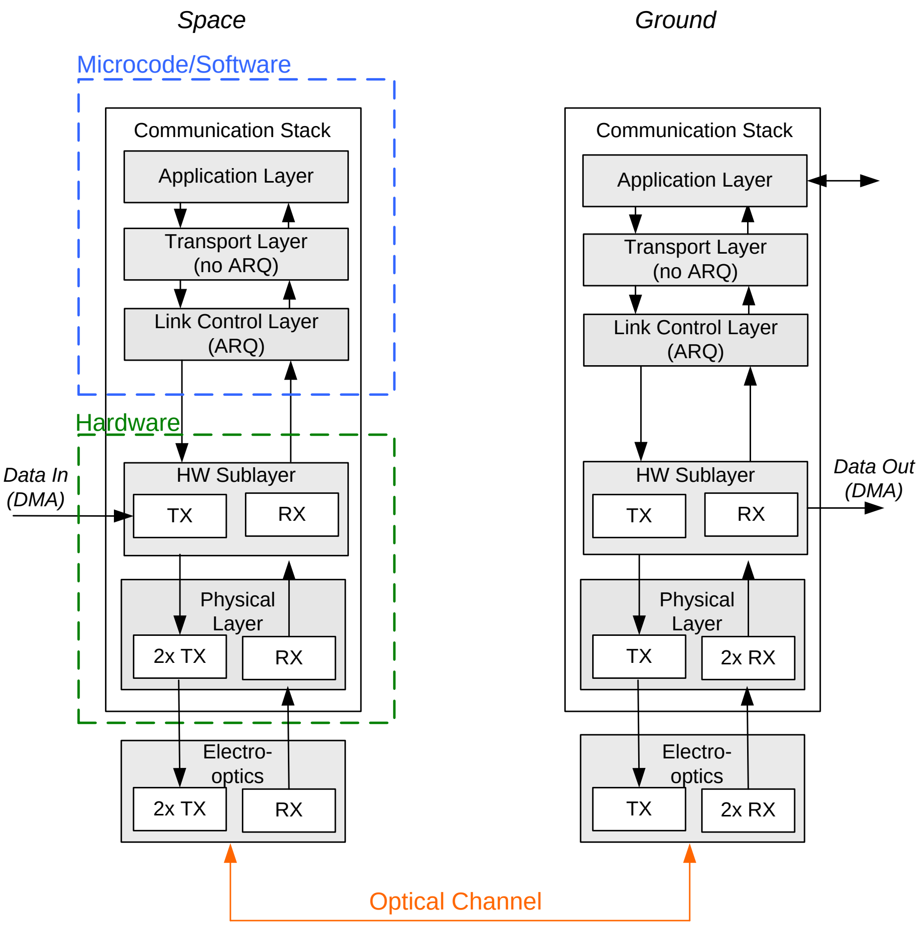

Figure 2-1. Block diagram OPTEL-μ Link Layer Architecture

The block diagram in Figure 2-1 shows the link layer architecture of the OPTEL-μ communications subsystem. The link to the mass memory (MM) of the host spacecraft is handled by an adaptable interface, which can be customized to address the expected variety of spacecraft interfaces. The interface is designed for a BER of 10^{-12} for the basic link to the MM. A BER better than 10^{-14} can be achieved if the link to the MM is protected by a higher level error detection protocol.

The payload data source provides the communication stack (CS) with data payload to be transmitted over the optical link to the ground station. The payload may be a mass storage device or any data source that can be interfaced. The payload data is buffered before transmission. When the downlink channel is available, the data is passed to the protocol stack on the communication controller, co-running in soft- and hardware. There, the data is grouped into packets to be able to synchronize, identify, and validate the data at the receiver. A low speed optical feedback service channel (ARQ) is necessary to request erroneous packets for retransmission. To achieve this, an intensity modulated optical uplink beacon is used, both as spatial reference and for ARQ purposes. The BER is designed to 1 bit error per 10^{15} bits, assuming that data is stored in the buffer no longer than five days before readout.

2.1.2 Discussion with International Civil Aviation Organization

The OLSG has engaged several members of the International Civil Aviation Organization (ICAO) to determine the impacts of eye safety guidelines on each operational scenario listed in the OLSG Final Report (June 2012).

The OLSG began the analysis by reviewing the formulas and calculations for maximum permissible exposure (MPE) in the ICAO Manual on Laser Emitters and Flight Safety (Doc. 9815)[2] relative to the uplink laser at the ground terminal aperture. The current OLSG calculations use infrared light, which is not visible. This issue raised some uncertainty as to the validity of some of the assumptions supporting the requirements in the ICAO manual (Doc. 9815). The OLSG also noted that given the narrow beam width and the speed of the aircraft, it was unlikely that any exposure would exceed the 10 second figure used in ICAO Doc. 9815. After modifying the calculations to include both near-field considerations and time spent in the beam, as discussed below, the OLSG presented its calculations to ICAO staff for concurrence on the OLSG's application of the formula in the ICAO manual. During the discussion, ICAO noted that a distinction should be made for each scenario between the use of a few high-powered ground stations and the possible use of many lower-powered mobile ground stations, when considering the application of laser safety as laid out in the ICAO manual and potential future airspace restrictions. The OLSG explained that various space agencies may have plans to deploy such facilities in the next few years; hence clear standards and guidance are necessary. The OLSG is still engaging with ICAO staff, and has asked that ICAO consider providing direction to the OLSG regarding the best way forward to ensure that the OLSG's proposed installations are within the eye safety limits set forth by the ICAO. In the ensuing discussion between OLSG and ICAO, the following action plan was agreed:

a) ICAO to determine whether the proposed LEO and Geostationary Earth Orbit (GEO) installations meet the safety requirements of Doc 9815. This effort will require an examination of the previous analysis done by the OLSG.
b) If the proposed LEO and GEO installations meet the safety requirements of Doc 9815, then effort shall be directed towards guidance regarding the assignment of restricted airspace for high power facilities. Even if the LEO/GEO installations are compliant with Doc. 9815, the document may need to be amended to directly deal with this new application of laser technology.
c) If the proposed LEO and GEO installations do <u>not</u> meet the safety requirements of Doc 9815, then work should begin on guidance regarding the assignment of restricted airspace now. ICAO explained that this issue would first need to be introduced to the ICAO work program for standards development.

Simply applying the current ICAO formula yields non-eye-safe uplinks in all OLSG scenarios. However, applying physical near-field calculations yields eye-safe conditions in the LEO and GEO scenarios for the 1550 nm wavelength. Applying a shorter duration for time spent in the beam potentially yields an additional eye-safe scenario (Lunar). Therefore, OLSG recommends that conversations with ICAO continue, with the goal of revising the current

[2] International Civil Aviation Organization (2003), *Manual on Laser Emitters and Flight Safety-First Edition*, ICAO Doc. 9815, Montreal, Canada.

ICAO standard formula to consider near-field propagation and time spent in the beam for use in fixed ground stations (non-moving). Note that the wavelengths under consideration for optical communications (infrared wavelengths 1064 and 1550 nm) are not visible, thereby mitigating issues such as distraction and dazzling.

The OLSG recommends that space agencies coordinate with their respective civil aviation authorities to support optical space communications in the ICAO.

2.1.2.1 Near Field Considerations

In the laser hazard assessment, the Nominal Ocular Hazard Distance (NOHD) (i.e., distance along the axis of the laser beam beyond which the applicable MPE is not exceeded) shall be determined. Toward this purpose, the irradiance or the radiant exposure of the laser beam from the transmit aperture onwards must be estimated.

The NOHD formulas reported in Appendix A of the ICAO Manual on Laser Emitters and Safety are derived from Appendix B6 of the American National Standards Institute (ANSI) standard Z136.1[3] and represent the far-field approximation, where the initial beam diameter can be neglected due to the large distance of the observation point from the source. However, as explained in the OLSG Final Report, this approximation (see Table 3, line 9 in the OLSG Final Report, now updated in Table 2-1, line 10 in this document) is not accurate for all the scenarios of interest. The general procedure for NOHD calculation described in ANSI Z136.1, which also accounts for the near-field distribution (see results in Table 3, line 10 in the OLSG Final Report, now updated in Table 2-1, line 11 in this document) is discussed below.

The average irradiance, *E*, in the direct beam at a range, *r*, for a circular beam and under the assumption of no atmospheric losses (worst case), can be computed as follows:

$$E(r) = \frac{\Phi}{\pi\left[\frac{D_L(r)}{2}\right]^2} \qquad \text{(Eq. B42, ANSI Z136.1)}$$

Where Φ is the radiant power and D_L is the beam diameter at the range *r*:

$$D_L = \sqrt{a^2 + r^2\phi^2} \qquad \text{(Eq. B39, ANSI Z136.1)}$$

where a and ϕ are the initial beam diameter and beam divergence, respectively. The formula for the beam diameter is valid for a Gaussian beam, where the waist occurs at or near the exit port of the laser.

If the average irradiance in the formula above is replaced with the applicable MPE and the formula is solved for *r*, the NOHD results:

$$r_{NOHD} = \frac{1}{\phi}\sqrt{\frac{1.27\Phi}{MPE} - a^2} \qquad \text{(Eq. B50, ANSI Z136.1)}$$

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[3] American National Standards Institute, Inc. (March 2007), *American National Standard for Safe Use of Lasers*, ANSI Z136.1—2007, Laser Institute of America, Orlando, FL.

The NOHD computed from the average irradiance refers to Continuous Wave (CW) lasers. The same formulas can be derived from the radiant exposure and applied to pulsed systems.

The OLSG proposes that this calculation be included in an updated ICAO Manual on Laser Emitters and Safety. Modifying the near-field calculation as proposed above would yield a less restrictive MPE threshold, which could potentially make the LEO and GEO scenarios eye-safe.

2.1.2.2 Time Spent in Beam

To minimize the required complexity of the laser safety system (radar/visual) and the operational constraints, it would be beneficial if the time spent in the beam could be reduced, while still meeting human eye safety requirements. Due to the narrow beams that are typical of laser communication ground stations and the speed at which most aircraft would move through the beam, there would be negligible chance of exposure approaching 10 seconds. Therefore, a smaller set of aircraft (such as helicopters and balloons) should be considered for eye safety concerns.

For a laser hazard assessment, an exposure duration must be defined. Such a time interval depends on the wavelength and on the operation mode of the system, according to the laser safety standards.

In the case of CW lasers at the infrared wavelengths, the exposure duration for unintentional viewing is 10 seconds (see ICAO Manual on Laser Emitters and Safety).

For pulsed systems, the duration of the single pulse must be considered.

In the case of a repetitive-pulse system, the portion of the pulse train corresponding to the exposure duration is relevant to the assessment. At 1064 nm and 1550 nm, for small beam divergence angles, the exposure duration is also 10 seconds for repetitive-pulse lasers.

OLSG has begun a discussion with ICAO to verify whether a radiation exposure of 10 seconds is realistic, or whether the exposure time can be reduced for the ground beacon system under consideration. Defining a shorter unintentional viewing duration would likely yield a less restrictive MPE threshold, which could potentially make the Lunar scenario eye-safe.

2.1.3 Human Spaceflight Concerns

For optical communication human spaceflight concerns, the OLSG used the guidance for laser operations on the International Space Station (ISS), which contains binding agreements on standards and protocols with the European Space Agency, Russian Federal Space Agency, Italian Space Agency (Agenzia Spaziale Italiana, or ASI), Canadian Space Agency (CSA), and NASA. The guidance reports key areas of concern and parameters for laser operations on ISS, as identified by the medical experts at Johnson Space Center.

The Payload Safety Policy and Requirements for the International Space Station (SSP 51700)[4] indicates the requirements for payloads on ISS to limit exposure of the crew to radiation in general. In particular, for optical systems with wavelengths (λ) between 385 and 1400 nm, the spectral radiance shall satisfy the following condition, which prevents retinal thermal hazard injury:

$$0.2\sum_{\lambda}\{L_{\lambda}R(\lambda)\Delta\lambda\} \leq \frac{5}{\alpha t^{1/4}}$$

where
L_{λ} is the source spectral radiance in W/(cm^2·sr·nm),
$R(\lambda)$ is the Retinal Thermal Hazard Function, given in the American Conference of Industrial Hygienists (ACGIH) standards,
$\Delta\lambda$ is the wavelength range in nm,
t is the exposure duration in seconds, and
α is the angular subtense of the source in radians (which we understand to mean solid angle in steradians).

In addition, thermal injury due to exposure to every type of infrared radiation (wavelengths between 770 and 3000 nm) shall be prevented:

$$0.2\sum_{\lambda}\{E_{\lambda}\Delta\lambda\} \leq 1.8t^{-3/4} \qquad [\text{W/cm}^2]$$

where E_{λ} is the spectral irradiance and all the other terms are defined as above.

This requirement is intended to prevent ocular injury caused by overexposure to infrared radiation, including delayed effects to the lens (such as cataract genesis). These Threshold Limit Values (TLV) apply to an environment with an ambient temperature of 37 °C, and can be increased by 0.8 mW/cm^2 for every whole degree below 37 °C. However, the OLSG calculations do not assume a lower temperature.

Any exposure evaluation must consider the entire pathway of the incident radiation prior to its interaction with a crewmember's body, including any concentration, diffusion, or filtering.

In Table 2-1, the two conditions are applied to the uplink scenarios of interest in lines 16 and 17 respectively (the retinal thermal hazard limit is only relevant to the 1064 nm case). If the ISS is flying at 330 km above the Earth surface (minimum altitude) at a velocity of 7.7 km/s, and the largest beam divergence of the uplink beacons is considered, the astronaut would spend approximately 2 milliseconds in the beam. The calculation shows that the irradiance at the ISS range (line 19) is always below these limits of at least a factor of 10^4.

The formulas reported here from the ISS regulations are not specific to laser beams, but consider generic optical radiation to which the crew could be exposed. Therefore, the OLSG also considered the standard regulation on laser hazard, by deriving the proper MPE value from the ANSI Standard Z136.1, for an exposure time of 2 milliseconds, in the case of the

[4] National Aeronautics and Space Administration, International Space Station Program (April 2010), *Payload Safety Policy and Requirements for the International Space Station*, SSP 51700, Johnson Space Center, Houston, TX.

unaided eye (see line 18). The estimated irradiance at the ISS (line 19) is also not harmful for the astronauts using this method.

In summary, application of both ISS regulations on crew exposure to optical radiation and the more general conditions for laser hazard evaluation proves that all the considered scenarios are eye-safe for astronauts, with sufficient margin to also allow for viewing with binoculars (100-fold amplification).

Furthermore, in the case of optical communication to the ISS, which would follow a similar design as communication to a LEO spacecraft, the uplink can be designed to be eye-safe at the exit of the ground terminal aperture.

The OLSG recommends that it should continue the dialog with the NASA JSC Space Medicine Office to discuss the implications of the revised eye safety calculations performed by the OLSG for ground-to-spacecraft, LEO spacecraft-to-ground, and satellite-to-satellite cases, and for atmospheric scintillation effects.

Table 2-1. Laser safety calculation for the uplink beacon beams at 1550 nm and 1064 nm.

NOTES:

This table updates Table 3 in the OLSG Final Report by including the laser safety calculations for the astronauts working on the ISS (lines 13-19).

Values highlighted in red indicate that a scenario is calculated not to be eye safe at the aperture according to a particular formula, and values highlighted in green indicate that a scenario is calculated to be eye safe at the aperture according to a particular formula.

Eye-safety calculations have been performed on one single radiating sub-aperture for each scenario. The distance at which the individual sub-beams start to overlap is reported in line 8. For the scenarios highlighted in yellow, the overlap occurs before the NOHD for a single sub-aperture is reached. In such cases, the NOHD has been re-evaluated considering the total power available for the uplink (lines 10 and 11).

(*) The LEO case reports the design parameters described in section 3.1 of the OLSG report. As discussed in section 2.1.1 of this document, the design of an eye-safe LEO system operating at 1064 nm is possible.

	Inputs	**LEO**	**LEO (*)**	**MOON**	**MOON**	**L1**	**L1**	**L2**	**L2**	**MARS**	**MARS**	**GEO relay**	**GEO relay**
1	Mode of operations	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW	CW
2	Power [W]	0.125	0.125	10	40	560	560	50	400	5000	5000	2.5	2.5
3	**Wavelength [nm]**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**	**1550**	**1064**
4	Number of apertures	4	4	4	4	8	8	8	8	9	9	4	4
5	Aperture diameter [m]	0.05	0.05	0.15	0.15	0.15	0.15	0.15	0.15	0.07	0.07	0.15	0.15
6	Beam divergence, 1/e points [mrad]	2.79E-02	1.92E-02	9.30E-03	6.39E-03	9.30E-03	6.39E-03	9.30E-03	6.39E-03	1.99E-02	1.37E-02	9.30E-03	6.39E-03
7	Tx efficiency [%]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	**Beam Overlap Distance [m]**	**17,828**	**25,971**	**51,277**	**74,698**	**39,864**	**58,073**	**39,864**	**58,073**	**16,692**	**24,316**	**51,277**	**74,698**
	Laser hazard evaluation												
9	**MPE [W/cm^2]**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**	**0.1**	**0.005**
	ICAO Formulation												
10	**NOHD slant range [m]**	**451**	**2,940**	**12,111**	**157,799**	**90,628**	**590,431**	**27,080**	**499,006**	**126,375**	**823,317**	**6,055**	**39,450**
	Formulation including near field												
11	**NOHD slant range [m]**	**0**	**2,290**	**4,093**	**156,942**	**89,919**	**590,266**	**24,568**	**498,787**	**126,366**	**823,405**	**0**	**35,789**
	Irradiance at Aperture (Gauss)												
12	**[W/cm^2]**	**0.0127**	**0.0127**	**0.1132**	**0.1132**	**0.7922**	**0.7922**	**0.5659**	**0.5659**	**28.8716**	**28.8716**	**0.0283**	**0.0283**
	ISS crew hazard												
13	ISS minimum orbital altitude [km]	330	330	330	330	330	330	330	330	330	330	330	330
14	Exposure time [s]	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
15	Retinal Thermal Hazard Function	n/a	0.2	n/a	0.2	n/a	0.2	n/a	0.2	n/a	0.2	n/a	0.2
16	**Retinal Thermal Rad. limit [W/cm^2]**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**	n/a	**591.09**
17	**Thermal Radiation limit [W/cm^2]**	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63	**951.63**	951.63
18	**MPE [W/cm^2]**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**	**500**	**0.0426**
19	**irradiance at ISS [W/cm^2]**	**1.87E-07**	**3.97E-07**	**1.34E-04**	**1.14E-03**	**7.53E-03**	**1.59E-02**	**6.72E-04**	**1.14E-02**	**1.47E-02**	**3.11E-02**	**3.36E-05**	**7.11E-05**

2.2 *Operational Considerations*

Section 2.2 and its subsections describe the research the OLSG conducted to address the following topic suggested for further investigation by the IOAG:

- Explore the ground station coordination and operations concept for optical communication missions further including long-term and short-term scheduling, inter-station weather information flow, etc.

An optical communications system in space will most likely communicate with a network of ground stations. For example, a LEO spacecraft may transmit to a series of ground stations, or a relay in GEO may need to be supported by more than one ground station to provide higher availability in the presence of clouds. It is anticipated that a network of ground stations will be selected for a mission based primarily on the climatological occurrence of clouds, expected atmospheric effects, and level of access of terrestrial fiber links. Selection of ground sites will also favor a combination of sites whose degrees of cloudiness are uncorrelated or nearly uncorrelated from each other. However, climatology only seeks to maximize the availability of an optical communication system over the long term. Under operational situations, it is suggested that a variety of predictive weather technologies will be required to choose the most optimal ground site on a minute-by-minute basis.

Once a network of ground stations has been selected to support a spacecraft, those ground stations must be coordinated. The OLSG anticipates that an agency's optical communications ground stations will be coordinated by an optical communications Network Operations Center (NOC), and that the NOC will coordinate with the spacecraft's Mission Operations Center (MOC).

The OLSG assumes that agencies will be willing to share meteorological information including current weather conditions, cloud forecasts, and station resource allocation information. The Agency NOCs will coordinate with each other to arrange systematic backup services for routine operations. During optical communication service provision, the NOC requesting backup services will consider the near real-time meteorological status and schedule (dependent on the concept of operations) of backup stations prior to making a request to move the communication service to the backup station. Upon identifying an available backup station, the requesting agency NOC will request support from the supporting agency NOC controlling the backup ground station, as well as inform the mission operations center to command the handover from the nominal station to the backup. The handover process could be accomplished either via direct command or by pre-programmed conditional command.

To facilitate interoperability, standards for information exchange should be employed. For instance, there should be a standard information model used at each ground station covering:

- Real-time cloud coverage
- Real-time atmospheric conditions
- Forecast of cloud coverage
- Forecast of atmosphere conditions
- Current station assignments

- All resource availability info exchanged today for radio frequency (RF) ground stations (e.g., see the CCSDS Blue book Space Communications Cross Support—Service Management—Service Specification[5])

The OLSG recommends that the CCSDS investigate reuse of World Meteorological Organization (WMO) standards for exchange of meteorological data. In addition to the network operations concept there are other factors that need to be considered, such as predictive weather, aircraft avoidance, spacecraft interference, and retransmission protocols, which are discussed in the following subsections.

2.2.1 Multi-agency Operations Model

The OLSG envisions that in the mission formulation stage, before a new mission with an optical communications link is launched, an assessment will be made to determine how to support the mission communications. Selection of optical ground stations for a specific mission will be based upon certain criteria that will drive the number of stations needed and station locations. The criteria will include factors such as the data throughput required over a mission period (e.g., data throughput per 24 hours), Cloud Free Line of Sight (CFLOS) statistics, station availability, and other factors, such as the level of supporting terrestrial communications at the station, etc. It is likely an agency will choose a set of its own ground stations to support its mission. If this option is not feasible, the agency would then pursue use of other space agencies' available ground stations, per an interagency cooperative agreement. Below are some example scenarios showing how a mission using optical communications could be supported for routine operations:

- A single space agency's optical communications ground stations
- A single space agency's optical communications ground stations with one or two "backup stations" from another agency
- A mixture of ground stations from different space agencies with all ground stations considered "equal"

In all of these scenarios, the first step is to develop a long-term plan to determine the ground stations to be used to support the mission. Necessary negotiations and cross-support commitments should be in place before the mission begins. The mission is then supported by execution of the long-term plan. During mission execution, real-time changes consistent with the long-term plan may be needed, based on predictive weather (see section 2.2.2). For example, at a specific point in its orbit, a mission may have the ability to transmit to either a ground station in Flagstaff, Arizona or in White Sands, New Mexico, based on its long-term plan. While the mission is flying, predictive weather is used to determine which station to schedule for a specific pass ahead of time. In addition, the spacecraft could start transmitting to Flagstaff, and then due to cloud cover, perform a handover to White Sands. Thus predictive weather can be used in advance to schedule stations, and also in real time to support handovers.

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[5] Consultative Committee for Space Data Standards (August 2009), *Space Communication Cross Support—Service Management—Service Specification*, CCSDS 910.11-B-1.

2.2.1.1 Single Space Agency

In the first scenario, a single space agency uses its own optical communications ground stations to support its mission. Its NOC can determine ahead of time which of its ground stations will be used to support the mission in general. For example, a space agency might have seven ground stations located around the world and decide that four of those seven stations will be made available to support the new mission. Long-term CFLOS statistics could be used to help determine which four of the seven stations will be used. During the mission, predictive weather (see section 2.2.2) is used in real time to determine how the four ground stations will be used to support the mission, and as one of the parameters to determine when a handover should be performed from one ground station to the next.

2.2.1.2 Primary Single Agency with Limited Cross Support

In the second scenario, a single space agency primarily uses its own optical communications ground stations to support its mission, plus it negotiates ahead of time with another space agency to use one or two of the other agency's ground stations as backup stations. For instance, ESA could plan on using four of its eight ground stations around the world to support a mission. To increase availability, ESA could negotiate ahead of time to use two of NASA's ground stations as backups to be used only if necessary. For example, ESA could decide that it is only necessary to use the backup NASA ground stations when the spacecraft is executing a mission-critical operation in space. Predictive weather could be used to plan ahead of time how ESA's four ground stations are used. In this example ESA would attempt to support the mission using only its four ground stations, and would employ the NASA ground stations only when absolutely necessary. For instance, in the event that one or two of ESA's ground stations are covered by clouds, ESA's NOC could have the spacecraft do a handover to a predetermined NASA backup ground station to avoid loss of mission data.

In this second scenario, the NASA ground stations might be free and available during the specific time they are designated to act as backup terminals. In this case there is no impact to another mission should ESA actually require a NASA ground station. However, it could also be the case that the NASA ground stations are scheduled to support another NASA mission during that time. If ESA asks for real-time support from a NASA ground station that is already scheduled to support a NASA mission, then a decision must be made in real time regarding which mission to support. This decision would be based on individual mission priorities that are negotiated ahead of time. For example, NASA and ESA could negotiate that the ESA mission has a higher priority than NASA Mission A, but a lower priority than NASA Mission B. If ESA's NOC requests support for the ESA mission when the NASA ground station is supporting NASA Mission A, then the request is granted; if the request is made while the NASA ground station is supporting NASA Mission B, then the request is denied. Again, in this scenario the NASA ground stations are only used when absolutely necessary and not on a routine basis.

2.2.1.3 Multi-agency Cooperative Scenario

In the third scenario (e.g., a cooperative mission among three agencies), a mission is supported by a combination of ground stations from multiple space agencies, and all stations are considered “equals.” In other words, there are no “primary” and no “backup” stations. Each space agency involved would agree to make one or more of its ground stations available for the mission. For example, NASA could provide two ground stations, ESA could provide two ground stations, and JAXA could provide one station. All five stations are considered “equal,” and predictive weather would be used to determine how the stations are used ahead of time. The OLSG envisions that in this scenario one space agency’s NOC would be responsible for supporting the mission and managing the scheduling of the individual ground stations to support the mission. In this example, ESA’s NOC is responsible for coordinating with the spacecraft MOC. ESA’s NOC would schedule NASA’s ground stations through NASA’s NOC and JAXA’s ground station through JAXA’s NOC. The method by which ESA would schedule and coordinate the other agencies’ ground stations would be negotiated ahead of time.

2.2.2 Predictive Weather

Operation concepts outlined in this study are taken directly from the OLSG Final Report. For each scenario, the term *handover* refers to the process of “moving” the optical link from one ground station to another. The number of space optical terminals assumed for all of the scenarios is one. This makes each scenario very interesting, since a “*break-before-make*” handover is required to repoint the communication links between ground sites. A “break-before-make” handover requires that the current communication link be terminated, the terminal pointed to another site, and a new acquisition be accomplished prior to establishment of further communications. It is desired that the ground site terminal is then pointed to have a cloud-free line-of-sight. To maximize the probability of a cloud-free line-of-sight, an accurate cloud prediction is required. *Forecast lead-time* refers to the amount of time required to make the decision during operations regarding which site to choose for optical communications. Generally, the forecast lead-time will be shorter for near-space scenarios (seconds to minutes) than for deep space (minutes to hours). The term *predictive weather requirements* refers to those atmospheric monitoring sensors and models required to provide the necessary forecast lead-time to achieve a successful handover. Each ground station is expected to have the following instrumentation:

- Ground-based cloud monitoring
- Turbulence monitoring (Differential Imaging Motion Monitor [DIMM] or equivalent)
- Atmospheric transmission measurement

Information from these instruments will be communicated to a NOC. The NOC will also obtain meteorological satellite imagery from international weather services (e.g., National Environmental Satellite, Data, and Information Service [NESDIS], European Organisation for the Exploitation of Meteorological Satellites [EUMETSAT]). The NOC will then employ yet to be developed forecasting algorithms to produce its recommendations for the most desirable sites to select for communications. Below are some types of methodologies that could be utilized for cloud predictive weather:

- Satellite-based cloud detection
- Cloud advection forecast, based on either ground-based or satellite-based cloud detection
- Numerical weather prediction (NWP)

The optical communication forecasts and the meteorological data from the ground sites will be shared among all NOCs (see Figure 2-2).

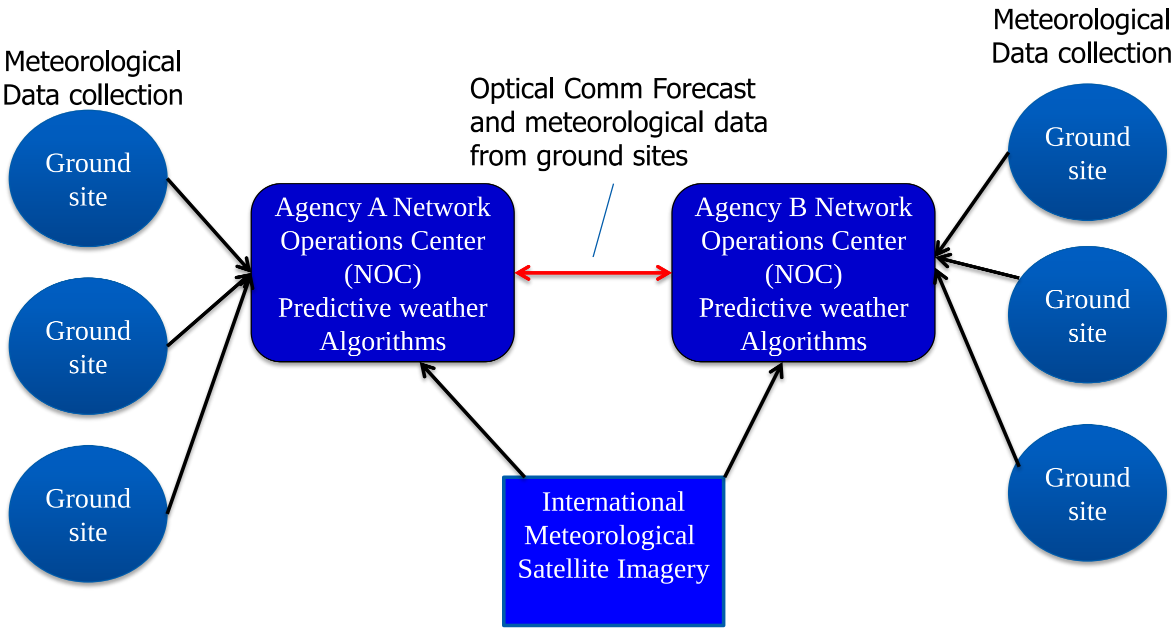


Figure 2-2. Conceptual depiction of interagency exchange of ground site meteorological data and optical communication forecasts.

Several of these ground station requirements are discussed below.

Ideally, each site would have a local ground instrument that is designed to image clouds. A combination of visible and infrared sensors may be utilized. This instrumentation would provide a local account of the current cloud conditions within the skydome at a high spatial and temporal resolution (Figure 2-3). In general, however, these instruments are currently of research grade and are not sufficiently developed in quality to be relied upon to support an operational system. They must be developed to be highly reliable, work in all weather conditions, work at all hours of the day, and operate with little maintenance. In addition, accurate algorithms are required to quantitatively interpret the raw imagery into the cloud products required to make handover decisions.

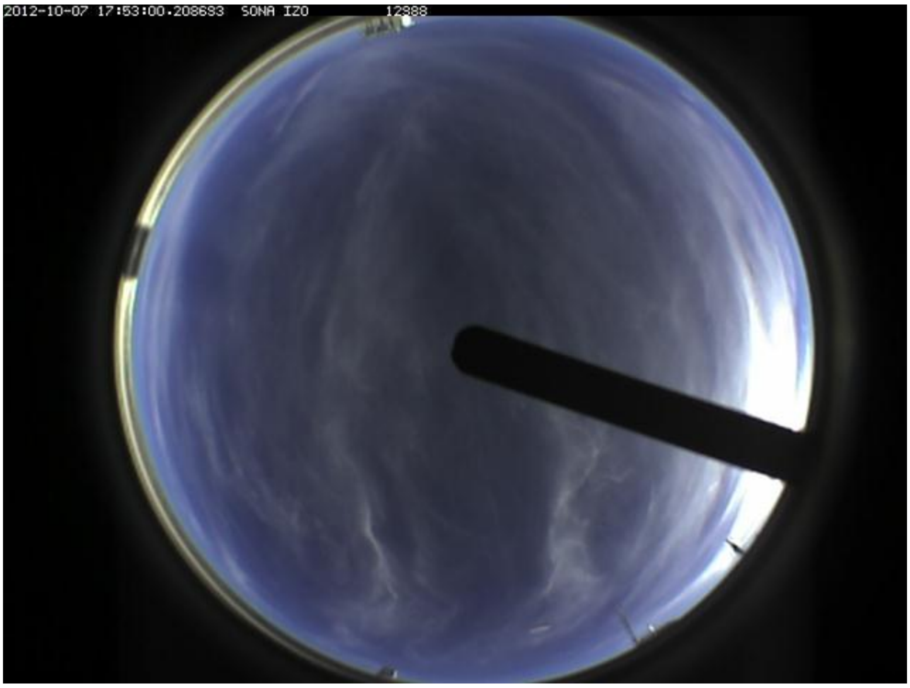


Figure 2-3. Whole Sky Imager depiction of cirrus clouds in a skydome over Tenerife.

A seeing monitor, such as a Differential Imaging Motion Monitor (DIMM), is desirable to monitor local seeing conditions, including the Fried parameter (r_0). Aerosol monitoring may also be helpful, particularly at sites that have frequent aerosol loading events that may cause undesirable fades in the optical signal. The aerosol monitoring can also be accomplished by a whole sky imager, by meteorological satellites, or by a sun photometer.

Cloud monitoring from geostationary satellites will also be desirable since they provide a larger areal coverage of regional cloud conditions. This cloud monitoring analysis will take place at the NOC. This extended coverage is important for longer range forecasts (minutes to hours) (see Figure 2-4). Although these satellites do not provide the high resolution in space and time that a local sensor can provide, they do provide a more regional perspective and depiction of clouds. In addition, the satellites have routine schedules and can be relied upon to provide consistent information at regular intervals (e.g., less than, or equal to 15 minutes). Sophisticated and validated cloud algorithms that produce an accurate account of current cloud conditions have also been developed and matured over the last decade. Figure 2-4 below shows a detailed cloud analysis derived for four potential optical communication sites: Haleakala, Hawaii; White Sands, New Mexico; Table Mountain Facility (TMF), California; and Tenerife, Canary Islands in support of the upcoming Lunar Laser Communications Demonstration (LLCD).

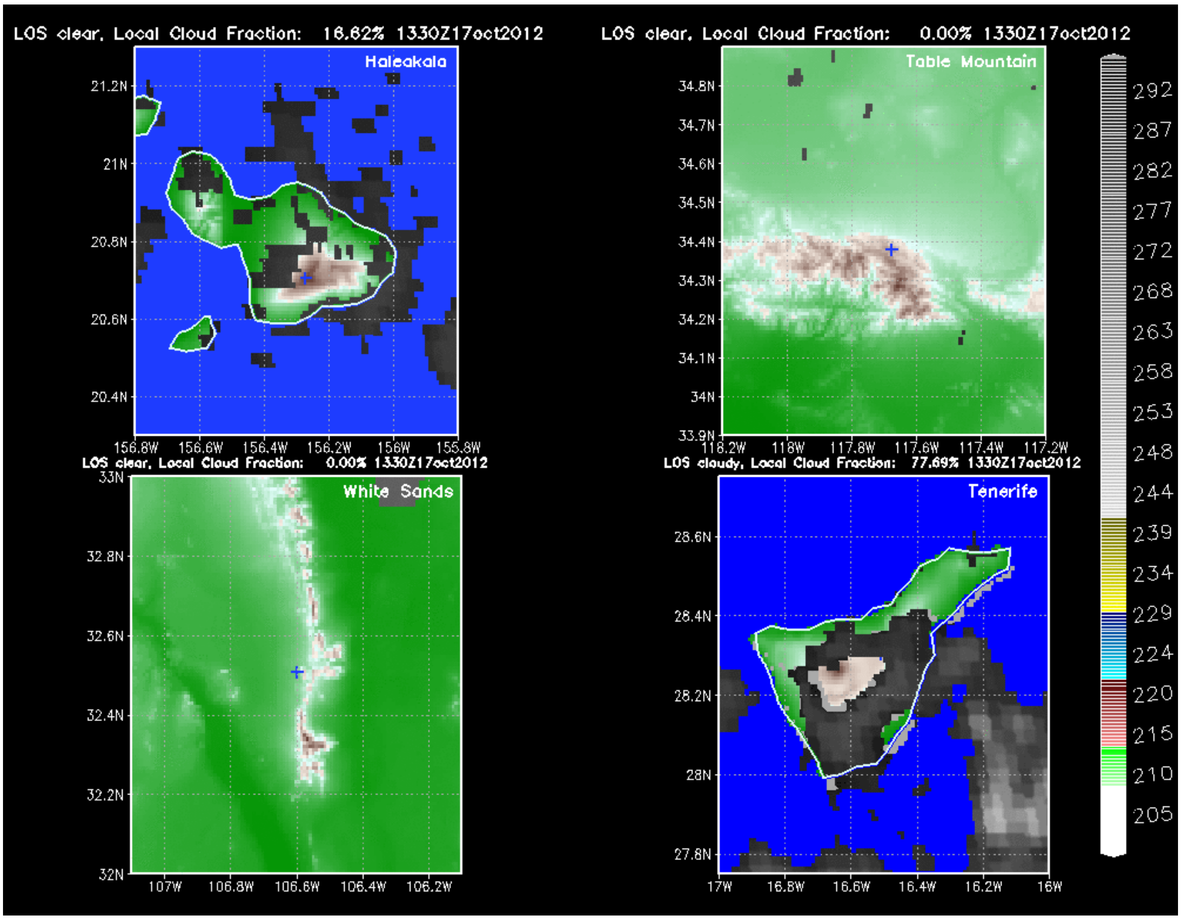


Figure 2-4. Real-time cloud analysis derived from Geostationary meteorological satellites. These analyses provide regional coverage of clouds around a site so that short-term predictions can be made for handover. The gray areas in each analysis indicate that a cloud exists and the shade of gray indicates the cloud height in terms of its temperature.

Forecasting will, in general, be based on a combination of cloud advection algorithms and NWP. All forecasting activities take place at the NOC. Cloud advection algorithms use recent cloud motion to propagate cloud positions forward in time, thus producing a prediction of the positions of the clouds in the future. These algorithms work well in most cases out to a few hours.

If longer range forecasts of cloud positions are desired, then reliance on a physical model of the atmosphere will be required. NWP has been used to provide predictions of clouds from a few hours, out to as many as several days. The Weather Research and Forecasting (WRF) model has been used to provide such predictions. In addition, a collection of forecasts can be used to minimize the uncertainty. These forecasts are referred to as an ensemble forecast because they are made up of multiple sets of nearly independent forecasts. In Figure 2-5, below, a short-term ensemble forecast of cloud amount is shown out to four days. The cloud forecasts are broken down by cloud height. An empty circle implies a cloud-free forecast, while a filled-in circle means the site is forecast to be overcast and therefore not available.

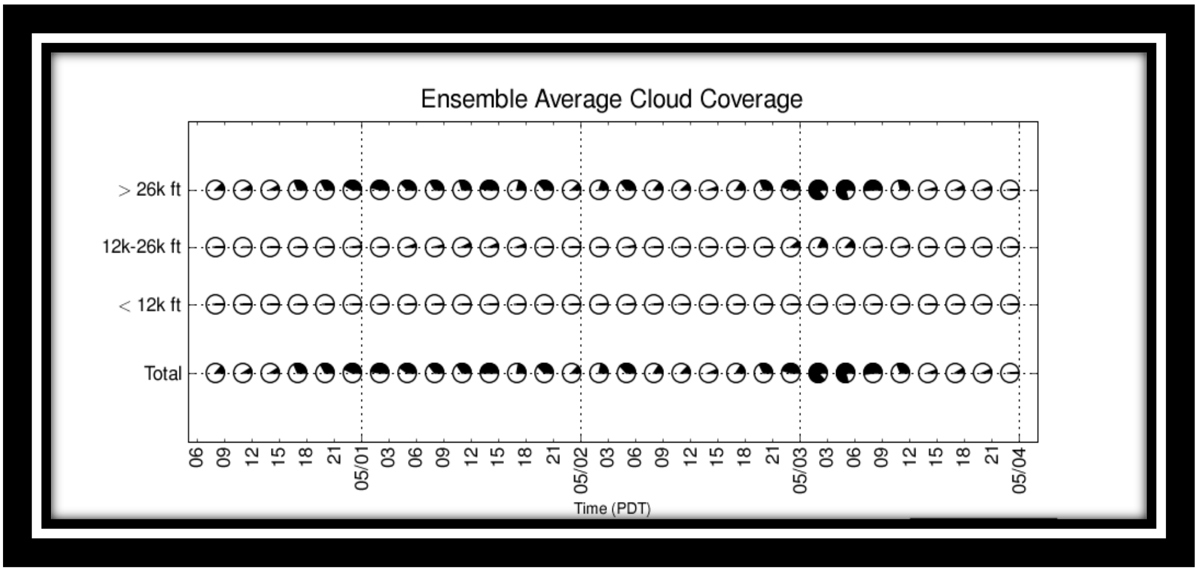


Figure 2-5. Example of a cloud forecast derived from a numerical weather prediction model for an optical ground site.

It is important to remember, however, that any predictive weather system is highly dependent on the concept of operations and scenario in question, and will need to be specifically tailored to meet the objectives of the mission. An example is the predictive weather decision-making tool currently being developed for NASA's LLCD (Figure 2-6). The decision aid takes into account current cloud conditions at each site, each site's respective elevation angle to the satellite (must be above 20 degrees), and each site's expected cloud conditions (from a short-term, satellite-based, cloud forecasting algorithm) for subsequent orbits out to 14 hours. This type of graphic provides a ranking of the sites for each orbital pass so that planners can make decisions regarding the site to use for communications.

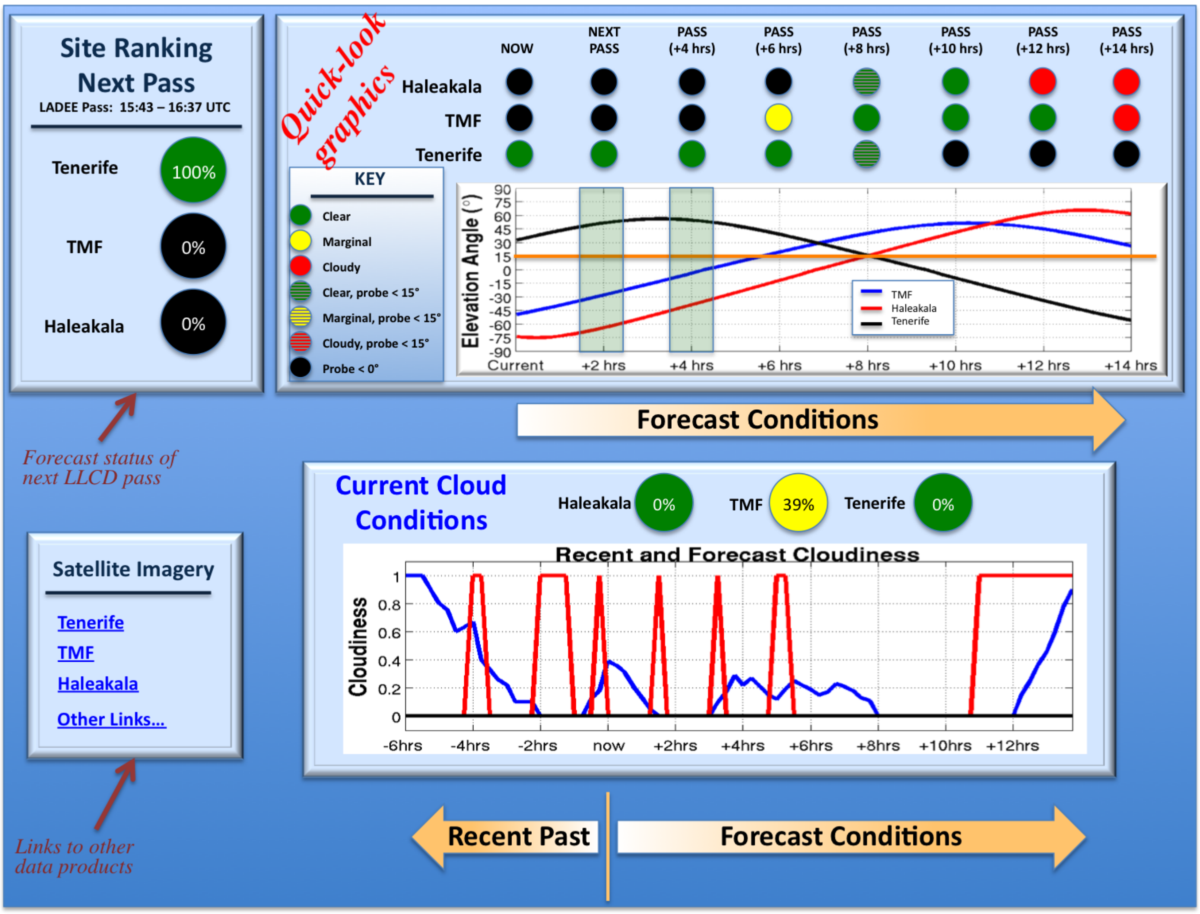


Figure 2-6. A conceptual predictive weather system developed for NASA's LLCD mission.

2.2.3 Aircraft Avoidance—Optical Communication Telescope Laboratory Analysis

Laser beam transmissions from an optical ground station are required for the purpose of pointing, acquisition, and tracking for the spacecraft optical terminal and potentially for uplinking data. This laser transmission must be controlled to avoid illumination of overflying aircraft. NASA JPL carried out a study to assess the effect that aircraft avoidance would have for an uplink from the Optical Communication Telescope Laboratory (OCTL) at Table Mountain, CA, to the Lunar Lasercomm Space Terminal (LLST) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft[6]. To accomplish this study, aircraft flight path data was obtained from the Federal Aviation Administration (FAA) for November 5, 2012 to November 14, 2012. This data included all aircraft with transponders and any aircraft that were visible to the FAA radar in the Los Angeles basin. The data were sampled every 4-11 seconds. The data were converted to show locations relative to OCTL. Figure 2-7a shows the

[6] Biswas, A., W. T. Roberts, J. M. Kovalik and M. W. Wright (to be published), OCTL Laser Beam Transmission Interruptions Due to Aircraft and Predictive Avoidance, *InterPlanetary Network Progress Report*, NASA JPL, Pasadena, CA.

integrated time history for November 10, 2011 between 0848 and 2123 Pacific Standard Time, which was the busiest day in the records and the busiest time of the day. Note that the majority of the flights are at low elevation angles relative to OCTL. Ninety-seven per cent (97%) are below 10 degrees and 99% are below 20 degrees. Figure 2-7b shows example trajectories of the LADEE spacecraft at the Moon relative to OCTL during August 1-17, 2013 (i.e., Figure 2-7b shows where the OCTL laser would point). Breaks in the tracks occur when the spacecraft is behind the Moon.

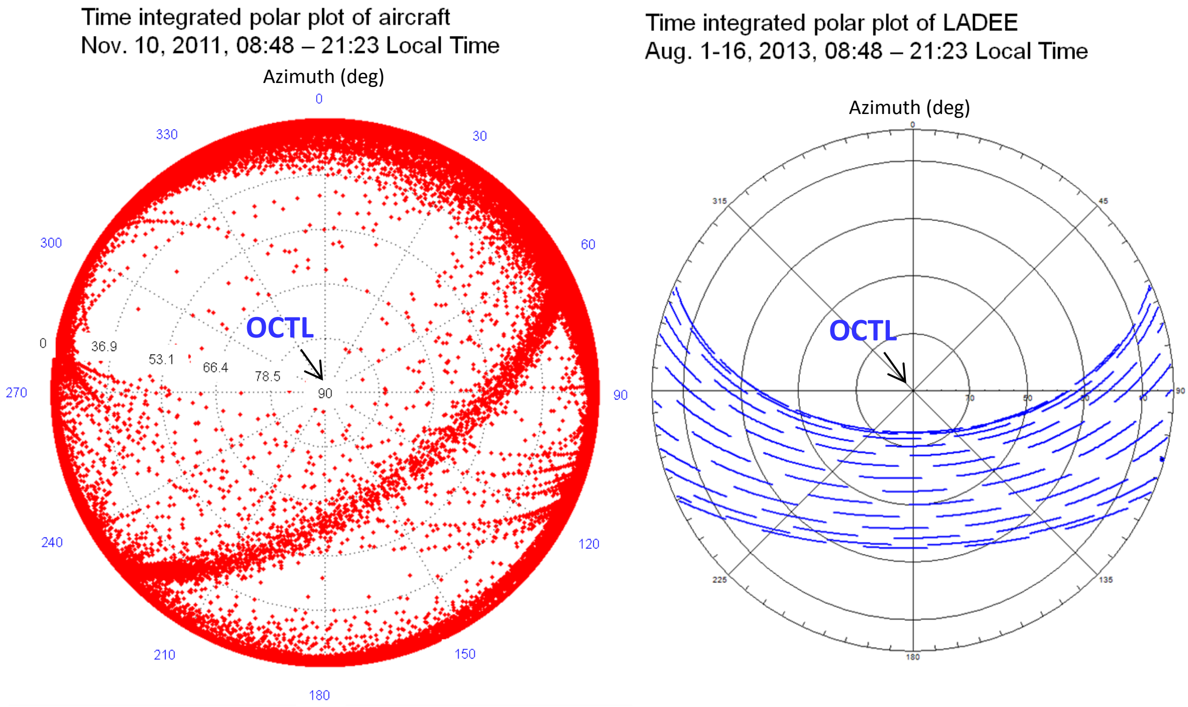


Figure 2-7. (a) Time integrated polar plot of the azimuth (radii) and elevation (concentric circles) for aircraft on Nov 10, 2011; (b) Time integrated polar plot of the azimuth and elevation for LADEE for August 1-16, 2013.

To determine the interruptions caused by the aircraft, the characteristics of the OCTL three-tier safety system [ref. OLSG Final Report] were used. If an aircraft intercepts a +/- 3.5 degree cone along the OCTL-to-LADEE line-of-sight, it is assumed that there is a one-minute interruption in the uplink. It should be pointed out that this is a conservative approach, because the aircraft generally traverse this cone in 5-10 seconds and the actual cone is +/- 2.5 degrees. However, even a one-second disruption could, in some circumstances, be enough to require resynchronization of the link. The number of interruptions for each track shown in Figure 2-7b and the aircraft data in Figure 2-7a are shown in Figure 2-8. On some days there were no interruptions, while on one day there were 15 interruptions. The total number of interruptions in the month of August was 56, or 0.7% of the total time.

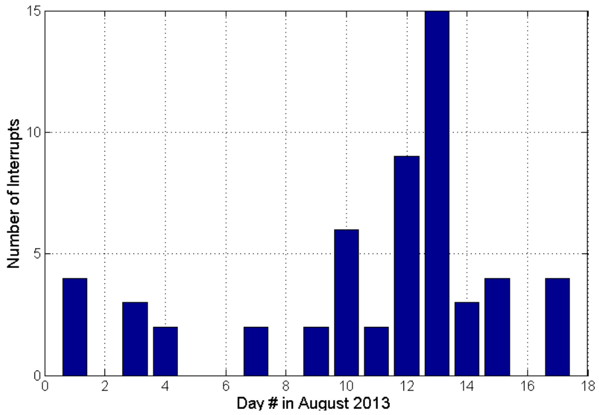


Figure 2-8. Number of interruptions of the OCTL-LADEE uplink August 1-17, 2013.

It should be noted that this is a small statistical sample giving an initial indication of the severity of the problem. Every interruption has the potential for loss of signal synchronization; therefore, the system should be designed with the potential for fly-wheeling through such interruptions. Additionally, there is the potential for data drops during these interruptions, which suggests the need for retransmission protocols to mitigate this problem.

2.2.4 Spacecraft Interference

Some satellites have sensitive detectors that can be damaged by intense light sources originating from Earth. In the United States, all Department of Defense (DoD) outdoor laser activities that have the potential to adversely affect a satellite or humans in space must be coordinated with the United States Strategic Command (USSTRATCOM) Laser Clearinghouse under Chairman of the Joint Chiefs of Staff Instruction 3225.01[7]. As a federal government agency, NASA also coordinates its outdoor laser activities with the Laser Clearinghouse. The ANSI standard for outdoor laser propagation (ANSI Z136.6) recommends that lasers that meet certain criteria also coordinate with the Laser Clearinghouse. There is, however, no international standard or requirement specifying that space agencies other than NASA must coordinate with the Laser Clearinghouse.

The Laser Clearinghouse provides predictive avoidance analysis and deconfliction with U.S., allies', and other space operations with the potential to affect satellites (which includes human space flight). The Laser Clearinghouse can determine whether a laser has the potential for interference or damage to particular satellites. Lasers with very high peak powers and very small beam divergences (10 microradians or less) probably have the greatest potential for producing damage to these very expensive systems in space. Rather than give detailed guidance on the levels that could produce damage to satellites, criteria are provided as a starting place to indicate where coordination with the Laser Clearinghouse is desirable. Lasers that can produce an instantaneous irradiance exceeding 1 mW/cm^2 at an

[7] Chairman of the Joint Chiefs of Staff (2008), *Illumination of Objects in Space by Lasers*, CJCSI 3225.01, United States Government.

elevation of 60,000 feet (18 km), even for 1 ns or less, should contact the Laser Clearinghouse.

Safe laser beam propagation from the United States into space requires that the laser and its site be registered with the Laser Clearinghouse. The registration information includes:

- Specification of the peak and average laser outputs
- Laser site location
- Laser wavelength
- Laser track across the sky and duration of propagation

Based on the laser propagation details, the Laser Clearinghouse can either issue a blanket approval of transmission at the time of registration or require coordination of all laser beam propagation activity.

The Laser Clearinghouse will consider non-DoD, civil, and international requests to review proposed laser illumination at or above the horizon or in space, and perform predictive avoidance as necessary.

2.2.5 Retransmission Protocols

The transmission of data from space to ground via an optical link presents more challenges than a traditional radio frequency (RF) link. Atmospheric effects like turbulence can cause multi-gigabit-length dropouts, and clouds can bring an end to a pass. Other sources of disruption like aircraft or LCH blackouts cause short-term dropouts, but effects like outages caused by clouds or handovers can cause long-term dropouts. The end-to-end information system (EEIS) design becomes more complex as a mission deals with information that was not successfully transmitted to ground as planned. Retransmission protocols/methods are one of the factors in this design that may help ameliorate these outages.

There are many trades to consider in EEIS design: science data acquisition strategy (how much, how often, and what priority), number of downlink passes, pass length, bit rate, error-correction coding, size of data storage on the spacecraft, data latency, data quality (e.g., data compression ratio) and priority, as well as whether or not to use a retransmission strategy.

In the simplest case, a retransmission strategy is a manual process whereby the ground data system engineer evaluates the information received, determines what is missing, and decides what needs to be retransmitted or what does not need to be retransmitted (e.g., data that was not important or can be collected again at another time). A command is then sent to the spacecraft to retransmit the needed data on a subsequent pass and to remove the data that has been successfully received on the ground from the spacecraft’s onboard storage to free up space for collecting new data.

For systems using data units such as packets or frames, the retransmission can be implemented by automatically monitoring each unit for correct reception, and then automatically requesting retransmission of elements not received correctly—Automatic Repeat Request (ARQ). There are a variety of ARQ techniques such as Stop-and-Wait, Go-back-N and Selective Repeat to notify the sender which units were or were not received, and hence which need retransmission. The CCSDS Communication Operation Procedure-1 (COP-1) and Proximity-1 (COP-P: Communication Operation Procedure for Proximity links) use a Go-Back-N ARQ method. Protocols have been extended to large data units, such as files, using techniques like CCSDS File Delivery Protocol (CFDP) and Disruption Tolerant Networking (DTN) with its underlying Bundle Protocol and Licklider Transport Protocol. Note that CFDP uses a selective repeat approach underlying the file transfer. It should be possible to use any of these techniques over optical links, though some may be more effective than others. The parameters of the protocols, e.g., data unit size, time-outs, etc., will need to be tuned to be commensurate with expected bit rates and outage durations.

Note that the common factor among these methods is a communication channel back to the spacecraft. In all cases, this return channel (optical or RF) must be able to handle the bit rate associated with the retransmission requests. This factor will drive selection of the size of the data elements for a given return bit rate.

The use of retransmission protocols will be very scenario-specific. A LEO satellite with a very short pass duration, limited downlinking opportunities, and limited onboard storage for data that is continuously updated may choose to maximize transmission success by adding significant margin to the link and/or using a very simple ARQ scheme that is matched to the short pass and the capability of the uplink. Any data not downlinked would be dumped to allow collection of new data. At the other end of the spectrum would be a deep space scenario, where retransmission protocols operating at a file level—CFDP or DTN—would be perfectly matched to short or long outages and long time delays.

Future work is needed to develop specific mission scenarios, evaluate existing protocols, and tweak parameters where necessary to match the characteristics of optical links. If it is found that such tweaking still will not fit the protocol to the scenario, then new protocols may have to be developed.

2.3 Data Uplink

Section 2.3 describes the research the OLSG conducted to address the following topic suggested for further investigation by the IOAG:

- Include uplink data as part of the standardization guidance (develop short scenarios for uplink communication)

Data included on an optical uplink is likely to be very similar to that on an RF uplink; however, the optical uplink data can be potentially transferred at a higher data rate. Optical uplink could be used for the following:

- Support for pointing, acquisition, and tracking (PAT) (ground measurements)
    - Received optical power from the satellite (irradiance); the irradiance is a measure of the optical communication channel and can also be used to improve onboard alignment (e.g., point-ahead angle)
- In-band commanding of the optical terminal
    - More immediate command of the onboard terminal (e.g., for handover)

- Support for adaptive coding and modulation (ACM) (ground measurements) (See section 2.4)
- Data (e.g., time stamps) related to a ranging process
- Network protocol acknowledgements
    - Acknowledgement of correct data reception in case the data are being transmitted in packets (blocks); packets that are distorted too much by atmospheric turbulence and outages such that they cannot be error-corrected at the ground receiver are requested to be resent
- Software uploads
    - The trend is for more frequent software uploads consisting of large files; thus, the increased data rate of optical links is advantageous over that of RF links

Therefore, the OLSG has identified a need for optical uplink standardization. The OLSG decided not to consider telecommunication satellite optical feeder uplinks for cross support.

2.4 Variable Downlink Data Rates

Section 2.4 describes the research the OLSG conducted to address the following topic suggested for further investigation by the IOAG:

- Investigate if adaptive modulation/coding should be included as part of standardization guidance

The communication channels associated with up- and downlinks are affected by several factors (e.g., link distance, varying atmospheric conditions, Doppler shift, and background noise) that are highly dependent on the satellite elevation angle seen from the ground terminal, as discussed in section 3.1.1.1 of the OLSG Final Report. Since transmitting data at lower elevations is more difficult, a fixed-data-rate system should be designed for operability down to a certain minimum elevation. In that case, there is a compromise between lowering the minimum elevation above which the link can be established and maintaining a high data rate. Under specific conditions, there exists a sizable improvement in data rate when using variable coding and modulation (VCM) and adaptive coding and modulation (ACM) [8]. Indeed, the increased complexity of an adaptive transmission should be counterbalanced by a significant performance enhancement.

VCM refers to the process whereby different levels of error protection are provided to different components within the service. VCM accomplishes this process by allowing different combinations of modulation and forward error correction (FEC) rate to be applied to different parts of the data stream using standard atmospheric conditions. ACM extends VCM by providing a feedback path from the receiver to the transmitter to allow the level of error protection to be varied dynamically using actual measurements in accordance with varying propagation conditions.

[8] Perlot, N., T. de Cola (2012), Throughput Maximization of Optical LEO-Ground Links, *Free-Space Laser Communication Technologies XXIV*. Proc. of SPIE Vol. 8246, 82460V.

For a fixed-data-rate system, the minimum elevation that maximizes the throughput is mainly a simple function of the clear-sky attenuation at zenith, and therefore can be estimated knowing the wavelength and the local atmosphere at the ground station. When the turbulence loss is significant, it has been shown that there is an increase in the optimal minimum elevation.

The implementation of an ideally adaptive data rate provides a throughput improvement that depends essentially on the satellite altitude. For example, in the case where H_{sat} = 700 km, the throughput can be as much as three times higher than that for a fixed-data-rate system (see Figure 2-9)[8]. This improvement may be too little compared to the higher complexity of the adaptive solution. However, allowing the data rate (or the coding rate) to vary has an important advantage: it increases data throughput per pass.

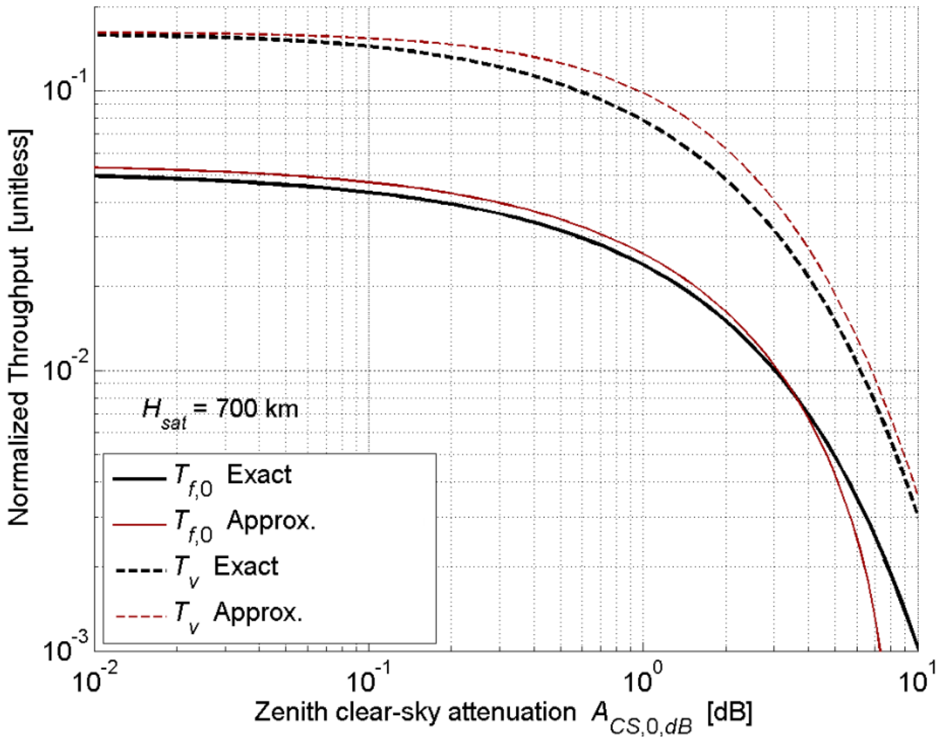


Figure 2-9. Normalized throughputs for fixed ($T_{f,0}$) and variable (T_v) data rates as a function of zenith clear-sky attenuation ($A_{CS,0,dB}$). Exact computations are compared to approximate formulas. Satellite altitude is set to H_{sat} = 700 km.[8]

Ideally, the application of VCM or ACM will take place onboard the satellite in real time, since the primary concern is the more transient effect of atmospheric attenuation. This process requires a constant beacon signal from the ground station, from which the satellite can determine atmospheric attenuation. Based on the beacon received power, the satellite can then adapt the data link accordingly, while the ground station detects the change and acts in a corresponding fashion. From the satellite perspective, this implementation requires little in the way of additional hardware, but does require more sophisticated software.

This ideal case is considered a long-term goal in the development of optical links. In the nearer term, a more straightforward approach is to have the ground station make measurements of the atmospheric attenuation and signal the satellite to act appropriately.

While simpler in its implementation, this approach requires more overhead on the data link, since more control messages are exchanged between the satellite and the ground station.

Unlike the effects of attenuation, the effects of scintillation for a given ground station vary seasonally and can be predicted with reasonable accuracy ahead of time. For that reason, a certain level of adaptation can be preprogrammed prior to the satellite acquisition.

2.5 Modulation and Coding Considerations

Section 2.5 and its subsections describe the research the OLSG conducted to address the following topic suggested for further investigation by the IOAG:

- Converge on standardization of modulation schemes for deep space

While there are many modulation schemes applicable to free space optical communications, the OLSG Final Report scenarios refer almost exclusively to two: pulse position modulation (PPM) and phase shift keying (PSK). PSK examples include both binary phase shift keying (BPSK) and differential phase shift keying (DPSK). In addition, binary on-off keying (OOK) is also a potential selection due to its simplicity in implementation. This section will briefly describe the modulations. As detailed in section 3.1.3, PPM is recommended as the superior modulation format for low photon flux links (such as deep space links) and PSK is recommended as an attractive modulation for higher photon flux links, where high data throughput is desired.

2.5.1 Pulse Position Modulation

Pulse Position Modulation, together with single photon receivers, is the recommended solution for photon-starved channels with modest data throughput requirements (i.e., below 1 Gbps). For this reason, PPM was assumed in the scenario descriptions for Lunar distances, Lagrange point missions, and deep space links. In addition, PPM is desirable for shorter distance links (such as LEO-to-GEO inter-satellite links) if the link emphasis is on low size and power terminals, rather than on maximizing data throughput. Deploying photon counting PPM in low photon density links, such as space-to-space links and for uplinks from the ground, requires the development of space-qualified single photon receivers, an area of continuing research emphasis.

PPM with single photon detectors is a specific instance of the general class of intensity modulation direct detection (IMDD) receivers. PPM encodes information in the time of arrival of a signal pulse. A transmit symbol consists of M time intervals of duration, T. The transmitter places the signal in exactly one of the M slots; the receiver’s task is to detect which slot contained the signal pulse, and hence which $\log_2 M$ bits were transmitted.

The virtue of PPM for optical communications is its potential for extreme photon efficiency. By employing single photon detectors in the receiver and advanced error correcting codes, PPM systems can transmit multiple bits of information for each received photon. With sensitive receivers, use of PPM can reduce the link budget requirements on other portions of the system, such as aperture sizes and laser transmit power. For this reason, PPM is often the technology of choice for photon-starved links, with the principal example being deep space links. It should be noted that background light and detector dark counts affect the system performance.

It is important to note that the high photon efficiency arises from the combination of both PPM and single photon detectors. When combined with more standard photo-detectors or in optically pre-amplified receivers, PPM modulation has similar photon efficiency to other modulation formats. Significant investments are being made in single photon receivers for ground applications and in detectors that can be flown in space to leverage the best sensitivity.

PPM achieves photon efficiency at the cost of bandwidth efficiency. For every MT units of time, $\log_2 M$ channel bits of information are transmitted. In addition, forward error correction (FEC) with a rate on the order of 0.5 is necessary to maximize sensitivity, further increasing the bandwidth. To maximize the photon sensitivity, PPM-specific codes and/or decoding methods may be required due to the orthogonal nature of the PPM symbol constellation. An example is the serially concatenated PPM (SC-PPM) code developed for the Mars Laser Communications Demonstration and to be deployed on LLCD. Another option is the development of PPM-specific decoding of existing standardized codes. Since components (particularly single photon detectors) place a practical limitation on the bandwidth, there is a corresponding practical limit on the achievable data rate. As an example, the LLCD has a 5 GHz clock rate and a maximum data rate of 622 Mbps. Thus, while PPM and photon counting receivers are enabling technology for high throughput in photon-starved channels, other optical modulations and receivers are preferred to maximize the data throughput in higher flux channels.

2.5.2 Phase Shift Keying (PSK)

Phase shift keying is an attractive option to achieve high data throughput. For this reason, the telecommunications industry has invested extensively in phase shift keying systems for terrestrial fiber optic communications. Much of the deployed infrastructure implements DPSK, and significant research and development emphasis is currently placed on coherent phase shift keying (including BPSK). The OLSG selected PSK as the example modulation for the near-Earth scenarios in the OLSG Final Report due to the technology's maturity and achievable data throughput. Phase shift keying is recommended for scenarios that require high data throughput. This is particularly relevant to near-Earth links, in both inter-satellite and space-to-ground scenarios.

In phase shift keying, the information content is carried in the phase of the waveform. In binary DPSK, the phase difference between consecutive pulses encodes the information (e.g., a "0" is sent by maintaining the same phase, and a "1" is sent by a 180 degree phase shift). In BPSK, an absolute phase (relative to some reference tone) is maintained (e.g., a "0" is sent by a +90° phase shift, and "1" is sent by a -90° phase shift from the reference). In contrast to PPM, the channel information rate is the same as the channel slot rate, so there is no intrinsic bandwidth expansion. This feature enables the very high data throughputs achievable with PSK.

A typical DPSK receiver employs an optical pre-amplifier and a delay-line interferometer, comparing the phase of consecutive symbols. A coherent receiver mixes the received signal with a strong, stable local oscillator, providing the reference phase and the mechanism to measure the signal phase directly. Coherent receivers (for BPSK) are theoretically more photon efficient than delay-line DPSK receivers; the additional sensitivity has also been demonstrated in practice. However, the phase stability requirements for DPSK are more lenient, enabling practical implementations that nearly achieve the ideal receiver characteristics. It should also be noted that both types of PSK receivers are relatively insensitive to background light, especially in contrast with PPM. Adaptive optics may be necessary to correct for atmosphere induced wavefront distortions for space-to-ground links (see section 2.8).

BPSK with coherent detection was demonstrated on the inter-satellite link between TerraSAR-X and the Near Field Infrared Experiment (NFIRE). It will be deployed on the Alphasat, European Data Relay System (EDRS) A and C Geo Spacecraft, and on the Sentinel-1A and B and the Sentinel-2A and B LEO spacecraft with user data rates of 1.8 Gbps.

NASA’s Laser Communications Relay Demonstration (LCRD) will deploy a pre-amplified DPSK receiver. This experimental system will operate in geosynchronous orbit at data rates up to 1.25 Gbps. LCRD is described in detail in the OLSG Final Report section 4.1.2.2.2.2.

2.5.3 Binary On-Off Keying (OOK)

One of the simplest modulation options is binary on-off keying (OOK), where a channel bit’s value is indicated by the presence (“1”) or absence (“0”) of a pulse. Combined with a simple optical power measurement, OOK is another example of intensity modulation direct detection (IMDD). In general, binary OOK is not as photon sensitive as PPM or phase shift keying, but it has the advantage of simple implementations, especially on the receiver. In addition, it does not have the data throughput limitations of PPM. Like PPM, OOK has performance sensitivity to background light. For these reasons, binary OOK is a potential selection for links that are constrained most by complexity considerations and in links that can tolerate the reduced photon sensitivity and background light.

2.6 Pointing, Acquisition, and Tracking Schemes

The OLSG conducted research on this topic to support development of the related standardization guidance in section 3.

Pointing, Acquisition, and Tracking (PAT) refers to the methods and/or mechanisms that two optical terminals use to point at each other, acquire signals, and maintain a link over a period of time. As discussed in section 2.2.2 of the OLSG Final Report, this process can be divided into two classes: with beacon or without beacon.

The primary methods in use today require a beacon. “Beacon” is a general term that refers to the need for a signal from one or both of the terminals that is used as a means of locating the other terminal. These beacon signals can be:

1. A different wavelength, separate from the communication signals and strictly for PAT purposes
2. The communication signals, themselves

In general, the beacon can be modulated with a sine wave or pseudorandom sequence to increase the signal-to-noise ratio (SNR) on the link for ease of detection by the other terminal. It can also be modulated with a unique identification sequence such that the communication link is only established and data only sent by one terminal upon positive identification of the other terminal. This modulation may be in addition to any data modulation as in case (2) above.

Case (1) is illustrated—as discussed in the OLSG Final Report in section 3.4.1.2—by the LLCD, which starts off with an uplink beacon from the ground to the lunar terminal. Once pointing has been established, LLCD will establish the uplink data signal on a slightly different wavelength and use this wavelength for fine tracking, while continuing to monitor the uplink acquisition beacon.

Case (2) is illustrated by the DLR/Tesat-Spacecom Laser Communication Terminal (LCT), which is discussed in the OLSG Final Report in section 3.1.2.1.2. The LCT uses high-rate bidirectional communication signals for the PAT process—all on one wavelength. A spatial search is implemented to resolve the unknown initial pointing offsets. It should be noted that Tesat refers to this system as “beaconless,” since it does not have a separate beacon signal. In terms of control theory this can be defined as a closed-loop beaconless PAT, since the communication channel is used as a continuous control feedback.

A second example of case (2) is the Deep space Optical Terminal (DOT), which is discussed in the OLSG Final Report in sections 3.7.2 and 3.7.3. For this case, the ground terminal blind-points to the location of the space terminal (e.g., at Mars) and sends up the “acquisition signal.” This signal is acquired by the flight terminal, which then begins transmitting data to the ground. Data is then modulated upon the same uplink signal (i.e., same wavelength) that was used for acquisition, once the downlink is received. The acquisition/tracking modulation and data are nested.

A second category of PAT is often referred to as “beaconless.” In our parlance, this implies that both optical terminals can blind-point without the use of any optical signals from either end (e.g., for a deep space scenario). This arrangement is not currently being used and is an ongoing research topic.

Besides the need for a beacon signal, accurate knowledge of the laser terminal’s attitude with respect to its surroundings plays a critical role in an efficient PAT system. In the case of space terminals, such as the ones discussed above, this attitude determination is performed with the use of star trackers, inertial measurement units (IMU), or by detecting the Earth limb.

Star field calibration is also used for fixed ground stations that, by virtue of being permanently located, have the luxury of supporting regular night operations to conduct position and attitude alignments. However, when considering mobile ground stations, such as the Transportable Optical Ground Station (TOGS) under development at DLR in Oberpfaffenhofen, operational requirements may exclude star tracking as an option (e.g., rapid deployment or relocation during daylight hours). In this case, ground terminals obtain reliable position and attitude information through the use of differential Global Positioning System (GPS) and an Inertial Navigation System (INS), which, in turn, determine attitude from gravity and magnetic field measurements.

2.7 Dual Wavelength Ground Terminals, Optical Interface Points for Cross Support

The OLSG conducted research on this topic to support development of the related standardization guidance in section 3.

As noted in the OLSG Final Report and discussed further in section 3.1.1, there are two wavelength bands being operationally pursued for optical communications: 1064 nm and 1550 nm. Since compatible wavelengths are a prerequisite for cross support, terminals that support both wavelengths are desirable.

It is technically possible to develop a dual wavelength compatible ground station. This capability will be especially important for deep space optical communications, where the ground stations on Earth will most likely employ very large telescopes. Since large telescopes are expensive to build, maintain, and operate, the ability to support multiple wavelengths in an international interoperable environment will be extremely valuable.

A practical approach to achieve dual wavelength ground terminals is exemplified by the OCTL terminal (described in the OLSG Final Report, section 7.1.3). In this case, the large optics part of the telescope (a seven-mirror reflective path) has no spectral dependence in the band between 400 and 2000 nm, and thus supports both wavelengths. The final mirror in the path, however, is mechanically addressable to one of four optical tables. The mechanical addressing is repeatable to within the necessary addressing accuracy, so that each table can represent a separate terminal back end with minimal time (on the order of minutes) required for switching. It is the back-end receiver that has single-band wavelength dependence and contains the receiver hardware to support the specific optical communications link. Each addressed table will require small optics that match the focal characteristics of the large optics to couple the received light into the desired receiver. A similar interface approach is likely feasible with other large telescopes where the large telescope optics and the receiver back end are physically separated. For smaller ground terminals, this multiple back-end approach may not prove cost effective, in which case it may be advisable for cross support to consist of sites that host small terminals corresponding to each wavelength used.

2.8 Adaptive Optics

The OLSG conducted research on this topic to support development of the standardization guidance in section 3 and concluded that it is not necessary to standardize adaptive optics.

2.8.1 Adaptive Optics for Near-Earth Links

Adaptive optics (AO) were originally proposed in the 1950s, but the technology was not matured until the 1970s, when it was developed for military imaging applications. Widespread use of AO in astronomy started in the early 1990s, when adaptive optics technology became affordable and computers achieved sufficient computational speeds. Astronomers using large-aperture telescopes have always been frustrated by the fact that their image resolution does not exceed that obtained by small star gazing amateur telescopes (due to the size of the atmospheric turbulence cells, also called the Fried parameter, r_0). This situation changed with use of adaptive optics, where the wavefront (phase) deformations of the received light are measured and corrected by applying the inverse deformation (e.g., by a deformable mirror).

AO is only required in ground stations where the receive aperture is larger than the Fried parameter (r_0). The atmosphere distorts the wavefront quality of a beam passing through, but the asymmetry (also called the shower curtain effect) has a different effect, depending on distance. A ground station in the atmosphere will experience beam distortions and beam wander, while a satellite in orbit will only experience changes in received optical power caused by beam spreading, beam wander, and distortions.

A very compact AO system was tested in ESA's Optical Ground Station (OGS) in Tenerife, Spain, and a further improved version will be implemented in the Transportable-Adaptive Optics Ground Station (T-AOGS), which is being developed by Tesat under contract with the German Aerospace Center (DLR). The adaptive optics system shown in Figure 2-10 does not include a required compensation of angle-of-arrival fluctuations of the incoming beam (which has to be performed by a fast tip/tilt mirror tracking system before the AO) and assumes that an image of the telescope entrance pupil is located on the surface of a deformable mirror (DM). The circularly polarized laser beam from a satellite passes a quarter wave plate (QWP1) that converts it into linear polarized light, so that all light passes a polarization beam splitter (PBS1). PBS1 is followed by QWP2, which rotates the polarization by 90 degrees upon reflection on the DM. The beam is subsequently reflected by PBS1 and routed towards a pupil reimaging a focal system composed of two aspheric lenses (L1 and L2).

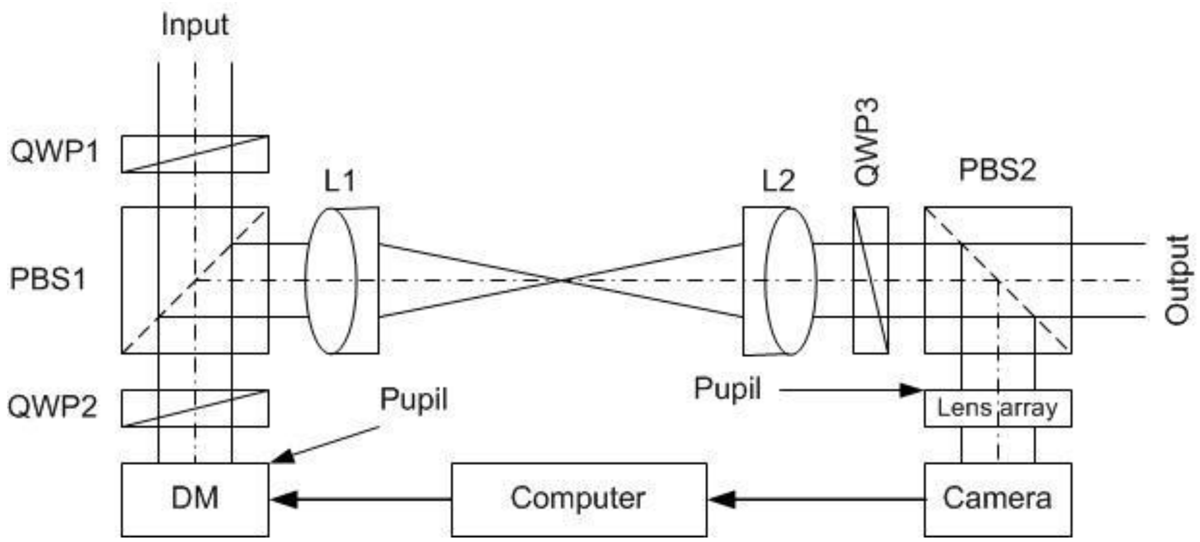


Figure 2-10. Adaptive optics system concept.

The focal ratio between the two lenses is used to adapt the pupil size to the requirements of a Shack-Hartmann sensor, formed by a Lens(let) array and a Camera. QWP3 in front of PBS2 allows adjustment of the optimum intensity distribution between the Shack-Hartmann sensor and the output beam that is used for data detection.

Adaptive optics are required in high data-rate optical communication systems where the received light needs to be coupled into a single-mode fiber preamplifier, a DPSK waveguide, or mixed with a local oscillator laser for heterodyne or homodyne detection.

2.8.2 Adaptive Optics for Deep-Space Links

AO enhancement of deep space optical communications using ground telescope diameters on the order of 10 m is still in a state of development, and is not yet sufficiently mature for widespread implementation. While great strides have been made in AO for astronomy over the last couple of decades, AO requirements for deep-space optical communications are sufficiently different from those for astronomy that more work needs to be done. Astronomers attempt to improve resolution at the cost of received signal, while laser communication engineers need to improve the overall Strehl ratio of the optical system to optimize the amount of signal collected and delivered to the photo-detector.

Astronomical telescopes generally use a guide star (an artificial star generated by a laser emanated from Earth) as a reference source to probe the atmosphere. The guide-star-generated signals are detected by a wavefront sensor, and are processed to implement the reverse effects in a wavefront-modifying element, such as a deformable mirror. The astronomical limitation to the effectiveness of this technique is determined by the brightness of the guide star (relative to the background) and the number of actuated elements that are needed to correct the wavefront. Both of these factors are much worse during daylight operations of laser communications, when the sky background is many orders of magnitude higher, and atmospheric seeing is generally significantly worse. For laser communications, instead of a guide star, generally a portion of the downlink laser communications signal is impinged on a wavefront sensor to infer the magnitude of turbulence-induced wavefront distortions. However, the deep-space downlink laser communications signal is in the photon-starved regime, and one can hardly afford to split a portion of the signal for AO purposes. While the above issues are not, by any means, insurmountable, there has not been sufficient development in these areas for deep-space optical communications AO techniques to be useful with current technology.

In another example, the atmospheric blurring can actually be helpful in nighttime conditions, by distributing photons over a larger surface area. Effective AO under nighttime conditions would tend to concentrate all data photons on a single detector, which actually reduces the effective number of photons detected because of detector blocking losses.

While the OLSG agrees that there may be some role for the use of adaptive optics for deep-space laser communications during nighttime operations, the OLSG believes that the technology is not sufficiently mature for round-the-clock operations at this time, and is not as helpful for communications as it is for imagery.

3 Standardization Guidance

The OLSG has assembled a team of the top experts in spacecraft optical communications from the participating agencies, studied the possible application of optical communications to future missions, and has concluded that cross support for optical communications would be advantageous. The study group has identified some of the unique challenges concerning the use of optical communications for spacecraft (e.g., dealing with atmospheric effects) and has begun to investigate techniques that might be applied in various cross-support scenarios to validate feasibility. The next step is to begin the development of interagency standards that detail the necessary technical and procedural provisions that must be put in place among the agencies for cross support in optical communications to be realized.

It is recognized that the CCSDS is the forum that the IOAG has relied upon to establish the necessary technical and procedural standards that provide for RF cross support. The OLSG recommends that the CCSDS be tasked to expand the role of its current Optical Coding and Modulation Special Interest Group to become an Optical Communication Working Group that will develop the set of standards needed for optical communication cross support.

In its deliberations over the past two years the OLSG has identified spacecraft-to-ground technical interface areas that should be standardized to enable cross support in optical communications. In addition, largely due to the unique atmospheric effects on optical communication signals, the OLSG recommends that a number of areas of operational coordination among operators of optical communication ground terminals also be standardized. Due to the requirement for interoperable cross support, the CCSDS should develop a minimum set of standards for wavelengths, PAT, coding, modulation, and protocols to be deployed by the agencies in their flight and ground systems. The following paragraphs capture the generic findings of the OLSG in the technical and operational procedure areas, and present them in the form of guidance for the development of optical communication cross-support standards. The priority of each recommendation is indicated in parentheses, with Priority 1 being the most critical.

3.1 Technical Guidance

3.1.1 Wavelengths

Operation in the same wavelength is fundamental to cross support among the agencies. In determining the wavelengths for standard cross-support use, technical equipment heritage and operational complexity induced by eye safety should be considered. Eye safety of equipment maintenance and operations staff, as well as astronauts and aircraft crews who may be illuminated by optical communication beams should be considered. The OLSG recommends the use of only two wavelength ranges: one around 1064 nm (1030 nm to 1065 nm) and the optical C-band (1530 nm to 1565nm) centered around 1550 nm.

Uplink designs for LEO have been demonstrated to be designed eye-safe for both wavelengths. The OLSG, however, recognizes that 1550 nm provides more margin in terms of eye safety. Nevertheless, according to the present analysis and current ICAO regulations, uplink designs for deep space (i.e., above GEO) cannot be designed to be eye-safe independent of the chosen wavelength. It might be possible to develop eye-safe uplink designs for GEO, depending on the hazard calculation applied—a topic proposed for discussion with the ICAO. Non-eye-safe uplinks create operational constraints; however, the associated safety mechanisms are known and practiced at laser ranging stations. The OLSG recommends that it should continue the dialogue with ICAO, with the goal of accommodating optical space communications within the ICAO laser safety standard for all types of aircraft passing through the uplink optical laser beam (Priority 1). The OLSG also recommends that it should continue the dialog with the NASA JSC Space Medicine Office to discuss the implications of the revised eye safety calculations performed by the OLSG for ground-to-spacecraft, LEO spacecraft-to-ground, and satellite-to-satellite cases, and for atmospheric scintillation effects (Priority 1).

Therefore, the CCSDS should assume that two wavelength ranges—1064 nm and 1550 nm—will be used. The CCSDS should study the possibility of dual wavelength ground terminals in the event that a single wavelength is not achievable, assuming that dual wavelength onboard terminals are not recommended (Priority 2). Best practices for a common optical interface should be defined that will allow one agency's back-end equipment to be connected to another agency's optical front-end. The OLSG assumes that a tracking interface will be available and that the cross-supported agency will adapt its back-end equipment to this interface; therefore, there is no need to standardize this tracking interface at this stage. Development of the optical interface standard would be a minimum first step to facilitate primitive cross support in the absence of true interoperability.

3.1.2 Pointing, Acquisition, and Tracking (PAT)

Essential to the initiation and maintenance of optical communication links is a standard method of accomplishing pointing, acquisition, and tracking. The OLSG analysis assumed high power uplink beacons would be used in the acquisition process; therefore, the CCSDS should assume that PAT is accomplished by uplink beacons and standardize the acquisition sequence. These beacons should be defined to be either un-modulated or modulated and should be consistent with any modulations used for data uplink (see section 3.1.4). Standards should be developed for both cases. The CCSDS should standardize the uplink beacons and associated acquisition sequence (Priority 1).

In parallel to the beacon standardization, the space agencies should conduct a rigorous detailed study independent of the CCSDS to determine if there are ways of accomplishing beaconless PAT, as this would also facilitate a solution to the eye safety issues (Priority 2). Technological advances in stability may make beaconless PAT possible in the future for near-Earth missions.

3.1.3 Modulation and Coding on Return Link

The OLSG examined return optical communications links where the primary benefit is the transmission of large amounts of science data at high data rates. The study group assumed that there is always a prime RF link for spacecraft tracking, telemetry, and command (TTC) operations. The RF link can be concurrent to the optical link or not. The CCSDS should plan for eventual use of optical links as the primary link from the spacecraft, with an RF backup.

The OLSG has identified two basic domains for operation of cross-supported optical communication systems: those where the signal arriving at Earth has a low photon density due to the large distances involved (e.g., deep space scenario); and those where the received photon density can be high (e.g., near-Earth scenario). Depending on the miniaturization of the design, LEO missions can also operate under low photon density conditions.

The OLSG determined that Pulse Position Modulation (PPM) is the superior modulation type for low photon density link domains such as deep space optical communications. For high photon density link domains, such as near-Earth communications, schemes like on-off keying (OOK), which falls under the category of IMDD; Binary Phase Shift Keying (BPSK); or Differential Phase Shift Keying (DPSK) should be considered. Coherent detection methods like BPSK and DPSK may be more power-efficient methods compared to OOK, allowing for higher data throughput. Therefore, the CCSDS should develop two sets of standards for modulation and coding for return links to deal with the low and high photon density domains (Priority 1).

Standards should be developed for error correction codes and associated interleaving schemes that support each of the two domains. In many cases, standard RF correction codes can be applied and therefore, the CCSDS should strive for maximum re-usage of existing coding standards; however, error correction codes for PPM have not yet been standardized. It should be recognized, however, that the data rates on these optical links will be up to ten times that of RF links operating in the same scenarios, and therefore, the modulation and coding process must be performed at a faster rate.

The CCSDS should develop standards for combinations of modulation and coding for channel-dependent effects (e.g., those caused by elevation angle and atmospheric conditions). Ground performance measurements should be used to support adaptive modulation and coding. VCM standards should be prepared (Priority 3) and ACM standards should be prepared (Priority 4). The CCSDS should strive for re-use of existing RF domain VCM/ACM standards.

3.1.4 Modulation and Coding on Forward Link

The data forward link could be modulated on the same wavelength as the PAT signal, or on a separate dedicated wavelength. If the PAT signal and data forward link are combined on the same wavelength, they must be compatible.

Although the forward link may operate at lower data rates than the return link, it still can operate at rates that are a factor of ten higher than comparable RF links. These links should be targeted for large file upload requirements such as software uploads, but may also carry command data, or ground performance data for interpretation by the onboard optical terminal for pointing or return link data adaptation. It should be assumed that there is a backup RF link available for critical commanding if required. Again, the OLSG has identified two different domains—high photon density and low photon density—where use of different types of modulations is advisable due to the different levels of photon density. There may be benefits to using the same forward and return link modulation and coding schemes; however, this is left as a mission-specific implementation choice.

Therefore, the CCSDS should develop two sets of standards for modulation and coding for forward links to deal with the low and high photon density domains (Priority 2).

3.1.5 Protocols

The OLSG assumes that because there are more frequent fluctuations in the optical link as compared to comparable RF links, bit errors and subsequent uncorrectable frame errors may require retransmissions to be automated. The OLSG assumes that the recommended protocols in IOAG Service Catalog 1 can be used, and in more advanced scenarios, the recommended protocols in IOAG Service Catalog 2 shall be applied.

The CCSDS should conduct a study to confirm that IOAG Service Catalog 1 and IOAG Service Catalog 2 can be used, and recommend an association of the optical physical modulation and coding layers with the existing higher protocol layers (Priority 1). If the existing protocols are considered insufficient, then CCSDS should develop optical communication-specific protocols.

3.2 Optical Communications Cross Support Methodology Guidance

Since local atmospheric conditions at ground stations significantly impact optical communications, optical communication links may have to be quickly transferred to alternate ground stations to maintain a cloud-free line-of-sight, and thus a high degree of availability. This requirement necessitates a higher degree of coordination among the ground stations and their associated Network Operations Centers (NOCs), compared to what has been developed by the CCSDS for comparable RF cross support. This coordination should also include the sharing of atmospheric data collected at optical communication ground stations. In addition, to prevent the loss of data when optical links are disrupted, retransmission schemes that are capable of operation over high data rate links should be developed.

3.2.1 Operations Consideration

The CCSDS should consider standardizing two operational aspects of optical communication to aid in the execution of cross support:

- Coordination of weather information to reduce link interruptions
- Development of standards for data retransmissions when disruptions do occur

3.2.1.1 Current Weather and Predictive Weather Requirements

The coordination of optical communication links for weather disruptions requires that optical communication forecasts and meteorological data from ground sites be exchanged among the various NOCs involved in cross-support operations (see section 2.2). Therefore, the CCSDS should develop data exchange standards for optical communication forecasts and meteorological data from ground sites (Priority 1). CCSDS should reuse existing standards (e.g., Binary Universal Form for the Representation of meteorological data [BUFR], GRIdded Binary [GRIB] format, Network Common Data Form [NETCDF]) from the meteorological community when possible.

3.2.1.2 Retransmission Schemes

When optical links are disrupted and handover to another ground station is required, it is necessary to keep track of the data that has and has not been successfully transferred to prevent the loss of data. The OLSG recommends that the CCSDS should develop standard practices for each scenario (e.g., LEO, GEO, Lunar, L1/L2, deep space) that will enable automatic retransmission (Priority 2). This automatic retransmission should not only protect against data loss during handovers, but should also prevent the loss of data during any link fading or short-term dropouts experienced during normal communication with a ground station.

3.2.2 Operations Procedures

The CCSDS should consider the standardization of operations procedures to aid in cross support of optical communication links. Because optical communication links can be disrupted, fast action is required when it is necessary to reassign and hand over the link to an alternate ground station. Some possible focus areas for procedure standardization are outlined below. The CCSDS should review the service management standard and identify areas that must be modified to accommodate optical communications and develop the necessary amendments (Priority 2).

3.2.2.1 Station Reservation

Scheduling of ground station contacts for optical communications is similar to that for RF ground stations, with additional considerations for backup alternative sites that would be called upon in the event that a primary site experiences a disrupted link. These procedures would rely on the standards developed for collection and distribution of weather and cloud data.

3.2.2.2 Handovers

Handover of an optical link to another ground station should be executed using standard procedures for sending the new pointing command to the spacecraft, establishing a time for the new contact (such as a time before approaching clouds can disrupt the link), and passing control to the new station.

3.3 *Planning and Engineering Best Practice Guidance*

The CCSDS should develop best practices for the systems engineering of optical communication links for missions for the topic areas described in sections 3.3.1 through 3.3.4 (all are Priority 2, unless otherwise indicated).

3.3.1 Meteorological Information and Predictive Weather

Agencies should share databases containing the meteorological data collected from their ground sites. This data will be useful in trade studies using tools such as the Laser Communications Network Optimization Tool (LNOT) and the Lasercom Simulator (LSIM) for initial site selection and mission communication designs. Also, best practices should be developed for predictive weather to allow optical communication forecasts.

3.3.2 Mission and Eye Safety Link Budgets

A standard approach should be developed by the CCSDS for the calculation of optical link budgets during the mission planning and engineering phases. This standard link budget calculation approach should be developed for both uplinks and downlinks.

This standard methodology for link budget calculation should be used when conducting eye safety assessments. In addition, the specific guidance from the ICAO regarding eye safety for aircraft should be cited, including a standard calculation method.

The OLSG recommends that space agencies coordinate with their respective civil aviation authorities to support optical space communications within ICAO (Priority 1).

3.3.3 Compatibility Testing

The CCSDS should develop a standardized approach for testing compatibility of flight terminals with ground terminals for uplink, downlink, and the beacon by identifying test cases (not the test procedures).

3.3.4 Terminology/System Decomposition

The OLSG has learned during its two years of dialogue that common understanding of terminology is essential to work on optical communications cross support. Therefore, it is recommended by OLSG that the CCSDS develop a set of common terms relative to the optical communication topic, as well as a conceptual depiction of the functional makeup of optical communication flight and ground terminals.

4 Recommendations

Actions recommended by the OLSG for all space agencies and the OLSG, itself, are listed in the tables in sections 4.1 and 4.2, respectively. The table in section 4.3 lists the recommended standardization guidance for the CCSDS.

4.1 *Actions for all Agencies*

Recommended Actions for All Space Agencies	Priority
The OLSG recommends that space agencies coordinate with their respective civil aviation authorities to support optical space communications within ICAO.	1
The space agencies should conduct a rigorous detailed study independent of the CCSDS to determine if there are ways of accomplishing beaconless PAT, as this would also facilitate a solution to the eye safety issues.	2

4.2 *Actions for the OLSG*

Recommended Actions for the OLSG	Priority
The OLSG should continue the dialogue with ICAO, with the goal of accommodating optical space communications within the ICAO laser safety standard for all types of aircraft passing through the uplink optical laser beam.	1
The OLSG should continue the dialog with the NASA JSC Space Medicine Office to discuss the implications of the revised eye safety calculations performed by the OLSG for ground-to-spacecraft, LEO spacecraft-to-ground, and satellite-to-satellite cases, and for atmospheric scintillation effects.	1

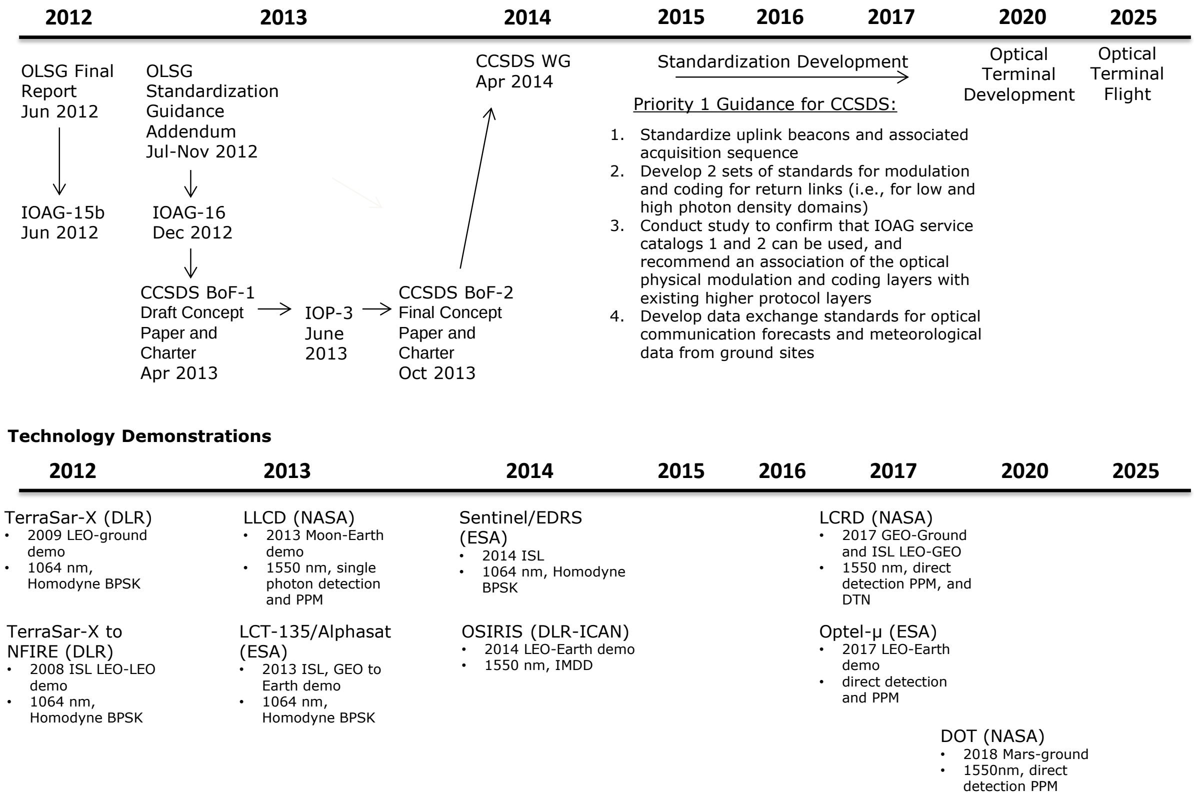
4.3 Standardization Guidance for the CCSDS

Recommended Standardization Guidance for the Consultative Committee for Space Data Systems (CCSDS)	Priority
The CCSDS should study the possibility of dual wavelength ground terminals in the event that a single wavelength is not achievable, assuming that dual wavelength onboard terminals are not recommended. Best practices for a common optical interface should be defined that would allow one agency's back-end equipment to be connected to another agency's optical front-end.	2
The CCSDS should standardize the uplink beacons and associated acquisition sequence.	1
The CCSDS should develop two sets of standards for modulation and coding for return links to deal with the low and high photon density domains.	1
The CCSDS should develop standards for combinations of modulation and coding for channel-dependent effects (e.g., those caused by elevation angle and standard atmospheric conditions). The CCSDS should develop Variable Coding and Modulation (VCM) standards.	3
The CCSDS should develop standards for combinations of modulation and coding for channel-dependent effects (e.g., those caused by elevation angle and actual atmospheric conditions). The CCSDS should develop Adaptive Coding and Modulation (ACM) standards.	4
The CCSDS should develop two sets of standards for modulation and coding for forward links to deal with the low and high photon density domains.	2
The CCSDS should conduct a study to confirm that IOAG Service Catalog 1 and IOAG Service Catalog 2 can be used, and recommend an association of the optical physical modulation and coding layers with the existing higher protocol layers. If the existing protocols are considered insufficient, then CCSDS should develop optical communication-specific protocols.	1
The CCSDS should develop data exchange standards for optical communication forecasts and meteorological data from ground sites. The CCSDS should reuse existing standards (e.g., BUFR, GRIB, NETCDF) from the meteorological community when possible.	1
The CCSDS should develop standard practices for each scenario (e.g., LEO, GEO, Lunar, L1/L2, deep space) that will enable automatic retransmission.	2
The CCSDS should review the service management standard and identify areas that must be modified to accommodate optical communications and develop the necessary amendments.	2

Recommended Standardization Guidance for the Consultative Committee for Space Data Systems (CCSDS)	Priority
The CCSDS should develop best practices for the systems engineering of optical communication links for missions, including practices for meteorological information and predictive weather, mission and eye safety link budgets, compatibility testing, and terminology/system decomposition.	2

The above CCSDS actions should be executed in accordance with the schedule below.

Optical Communication Standardization and Development



Appendix A. List of Acronyms

ACM	Adaptive Coding and Modulation
ANSI	American National Standards Institute
AO	Adaptive Optics
ARQ	Automatic-Repeat Request
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
BKG	Bundesamt fuer Kartographie und Geodaesie
BPSK	Binary Phase Shift Keying
BUFR	Binary Universal Form for the Representation of meteorological data
CCSDS	Consultative Committee for Space Data Systems
CFDP	CCSDS File Delivery Protocol
CNES	Centre National D'Études Spatiales
COP-1	Communication Operation Procedure-1
COP-P	Communication Operation Procedure for Proximity links
CSA	Canadian Space Agency
CW	Continuous Wave
DIMM	Differential Imaging Motion Monitor
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DM	Deformable Mirror
DoD	Department of Defense
DOT	Deep Space Optical Terminal
DPSK	Differential Phase Shift Keying
DTN	Disruption Tolerant Networking
EDRS	European Data Relay System
EEIS	End-to-end Information System
ESA	European Space Agency
ESO	European Southern Observatory
ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre

EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FEC	Forward Error Correction
GEO	Geostationary Earth Orbit
GPS	Global Positioning System
GRIB	GRIdded Binary
GSFC	Goddard Space Flight Center
HQ	Headquarters
ICAO	International Civil Aviation Organization
IEC	International Electrotechnical Commission
IKN	Institut für Kommunikation und Navigation
IMDD	Intensity Modulation Direct Detection
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IOAG	Interagency Operations Advisory Group
IOP	Interagency Operations Panel
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KARI	Korea Aerospace Research Institute
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCH	Laser Clearing House
LCRD	Laser Communications Relay Demonstration
LCT	Laser Communication Terminal
LEO	Low Earth Orbit
LLCD	Lunar Laser Communications Demonstration
LLST	Lunar Lasercomm Space Terminal
LNOT	Laser Communications Network Optimization Tool

LSIM	Lasercom Simulator
MOC	Mission Operations Center
MPE	Maximum Permissible Exposure
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NETCDF	Network Common Data Form
NFIRE	Near Field Infrared Experiment
NOHD	Nominal Ocular Hazard Distance
NWP	Numerical Weather Prediction
OCTL	Optical Communication Telescope Laboratory
OGS	Optical Ground Station
OLSG	Optical Link Study Group
OOK	On-Off Keying
OSHA	Occupational Safety and Health Administration,
PAT	Pointing, Acquisition, and Tracking
PBS1	Polarization Beam Splitter
PPM	Pulse Position Modulation
PSK	Phase Shift Keying
QWP	Quarter Wave Plate
RF	Radio Frequency
SC-PPM	Serially Concatenated Pulse Position Modulation
SNR	Signal to Noise Ratio
T-AOGS	Transportable-Adaptive Optics Ground Station
TESLA	Terminal For Small Satellite LEO Application
TLV	Threshold Limit Values
TMF	Table Mountain Facility
TOGS	Transportable Optical Ground Station
TTC	Tracking, Telemetry and Command
USSTRATCOM	United States Strategic Command

VCM	Variable Coding and Modulation
WRF	Weather Research and Forecasting