An Update on the CCSDS Optical Communications Working Group

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Abstract – International space agencies around the world are working together in the Interagency Operation Advisory Group (IOAG) and the Consultative Committee for Space Data Systems (CCSDS) to develop interoperability standards for optical communications. The standards support optical communication systems for both Near Earth and Deep Space robotic and human-rated spacecraft. The standards generally address both free space links between spacecraft and free space links between spacecraft and ground. This paper will overview the history and structure of the CCSDS Optical Communications Working Group and provide an update on the set of optical communications standards being developed. The paper will address the ongoing work on High Photon Efficiency communications, High Data Rate communications, and Optical On/Off Keying communications. It will also cover the working being done within CCSDS on documenting atmospheric measurement techniques and link operations concepts.

I. International Interoperability of Radio Frequency Communications

Civil space agencies can increase communications coverage and availability by sharing space based and ground based communications and navigation infrastructure around the world. The key to allowing this "cross support" (see Figure 1) is communications standards; by developing interoperability standards, one space agency's spacecraft could be served by another space agency's ground antennas.

The overall development of international space communication standards for cross support is coordinated by the Interagency Operations Advisory Group (IOAG) [1]. The IOAG is an organization made up of international space agencies that provides a forum for identifying common needs and coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications. The IOAG meets face to face at least annually and has several telecons throughout the year. Over the years, it has established effective liaisons with key enabling groups for interoperability, including the Consultative Committee for Space Data Systems (CCSDS), the Space Frequency Coordination Group (SFCG), the International Committee on Global Navigation Satellite Systems (ICG), and the International Space Exploration Coordination Group (ISECG). The IOAG considers the future requirements and trends in spacecraft communications needs and assigns priorities for the development of cross support standards. The standard development is then accomplished by the CCSDS, a multi-national forum comprised of the world's major space agencies and observer agencies. The stated goal of the CCSDS is to enhance governmental and commercial interoperability and cross support, while also reducing risk, development time, and project costs. Consensus must be reached by the member agencies before a CCSDS standard can be published.

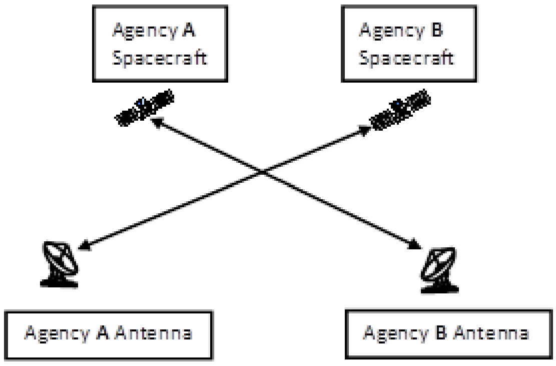

Figure 1: Cross Support

Since its founding CCSDS has developed standards recommendations, which have become International Standards Organization (ISO) standards, for space link communications and for associated ground data systems. These standards enable interoperability and cross support among the international space agencies.

As the standards have been developed, the international civil space agencies have gradually updated their ground space communication antennas and ground data systems to implement the cross support standards. As more and more systems have adapted the CCSDS standards, the agencies have begun to enjoy the benefits of cross support. Options for spacecraft communications have increased and the cost of supporting a single agency's spacecraft has been reduced, as agencies use the communications assets of other entities to fulfill their spacecraft's communication needs.

In recent years, there have been significant advancements in the development of laser-based communication systems for space applications. These optical communication systems hold the promise of better than an order of magnitude higher data rates over radio frequency (RF) space communications, while using less power, having lower mass, and occupying less space than comparable RF communication systems. These new communication systems will need corresponding standards to allow and promote international cross support [2].

II. The Consultative Committee for Space Data Systems (CCSDS)

The CCSDS member and observer agencies contribute technical experts to develop space data standards. The CCSDS has established a number of Working Groups that are focused on specific topics. Each CCSDS Working Group has a leader, chosen from a member agency, and a group of experts contributed by member agencies interested in the products being produced by that Working Group. The products are documents that recommend standard communication protocols, procedures, and concepts that will enable cross support in the particular area of interest of the Working Group. Often there will be multiple subtopics to be addressed by the Working Group so it may organize subgroups to deal with those specific subtopics. Subtopics subgroups usually produce a document that captures the final results of their studies and deliberations.

The Working Groups meet in face-to-face meetings twice a year. A lot of work is also conducted between those face-to-face meetings via telecons and emails.

The products from the Working Groups are color-coded according to the following guide:

- Blue Books are completed recommended standards that become ISO standards. They are normative, sufficiently detailed, and pre-tested so they can be used to directly and independently implement interoperable systems.
- Magenta Books describe recommended practices. They are normative, but at a level that is not directly implementable for interoperability. These are reference architectures, application program interfaces, operational practices, etc.
- Green Books are informational reports. These are not normative. These may be foundational for Blue and Magenta Books, describing their applicability, overall architecture, concept of operations, etc.
- Red Books are working copies of the recommended standards before they are promoted to the Blue Book or Magenta Book level. These should be used with caution as they can change before officially released.
- White Books are the initial conceptual working draft documents in a topic area.
- Orange Books document experimental work. They are normative, but generally cover very new technology that does not yet have consensus of enough member agencies to standardize.
- Yellow Books are administrative books. They document CCSDS procedures, proceedings, test reports, etc.

- Silver Books are historical books. They are retired documents that are kept available to support existing or legacy implementations. The implication is that other agencies may not provide cross-support.

- Pink Books/Pink Sheets are draft revisions to Blue or Magenta Books that are circulated for agency review. Pink Books are reissues of the full book while Pink Sheets are change pages only.

Once Blue Books are finalized they are brought to an ISO Standards subgroup where they are promoted to ISO Standards. ISO Technical Committee 20 Subcommittee 13 (TC 20/SC 13) is the ISO administrative subcommittee of CCSDS. By special arrangement with ISO, CCSDS documents are processed as ISO TC 20/SC 13 projects at the Draft International Standard (DIS) stage. Effectively, the CCSDS membership now has a dual role, functioning as the CCSDS standards body and as the ISO TC 20 /SC 13 standards body.

III. The CCSDS Optical Communications Working Group

The CCSDS Optical Communications Working Group was formed in January 2014 and it is chaired by NASA with a deputy from ESA. The working group is developing:

- New standards in wavelength, modulation, coding, interleaving, synchronization, and acquisition, which are best suited for free-space optical communications systems.

- New standards for definition, exchange, and archiving of weather data for predicting and operating optical communication links among optical ground stations and their network operations centers.

Standards specifically for free space optical communications are required that account for the severe impact of the Earth's atmosphere on space-to-ground links. The standards currently cover the wavelength, modulation, coding, interleaving, and synchronization of optical communications signals. The atmospheric impacts on the link are typically more severe than the corresponding impacts on RF links, and thus the standards being developed by the Working Group are different from the existing RF standards. Several space agencies are developing optical communications terminals that can support both space-to-ground and space-to-space links and the objective is to develop maximum synergy, as far as practical, between the various scenarios.

The working group has been considering various applications of free space optical communications to guide standards development. The various applications include Earth relay satellites, Low Earth Orbit (LEO) direct-to-ground, lunar direct-to-Earth, and deep space optical direct-to-Earth communications. Just as there are different RF systems for these very different applications, there will need to be different optical communications systems as well. For example, both flight and ground optical systems to support deep space direct-to-Earth links are expected to be large and relatively expensive; a typical Mars relay might have a 30 cm telescope at Mars and a 10 meter telescope on Earth. Deep space systems will also generally be power limited and thus it will be extremely important to be as photon efficient as possible; efficiency will be more important than an extremely high data rate. LEO direct-to-ground systems, on the other hand, have a lot more power available and thus likely will be driven more by a requirement for higher data rates than photon efficiency.

To date, the working group has been working on three different scenarios for optical communications: High Data Rate, High Photon Efficiency, and Low Complexity. High Data Rate links are expected to be used for Near Earth applications where extremely high performance is desired. High Photon Efficiency links are expected to be used for deep space direct-to-Earth links and are basically "photon starved" links; these links could also be used in Near Earth applications where there is limited mass and power to support communications, such as on a CubeSat. It is expected that the underlying technologies and techniques for modulation, coding, and synchronization will be significantly different between the two signal cases. Finally, the working group has identified a need for a standard that is less complex and less costly to implement than the High Data Rate standard. The first recommendation that meets this desire for a less complex and costly implementation is the Optical On/Off Keying recommendation currently in development. The Working Group hopes this will be used in those application where cost or simplicity is more important that high performance, efficiency, or data rate.

In addition to the typical standards that have to be developed for any communications system, such as modulation and coding, space optical communications also require a standard for the definition, exchange, and archiving of weather and atmospheric data. That is because optical space communications through Earth's atmosphere are adversely affected by the presence of cloud cover and optical turbulence, and to a lesser extent, by aerosols in the atmosphere. These atmospheric challenges to operational optical communications systems are illustrated in Figure 2, which shows geostationary (GEO) and low Earth orbiting (LEO) satellites interacting with and working around atmospheric degradations. GEO and LEO satellites are shown orbiting the Earth. Optical links are shown by the cones: dark green represents a Cloud Free Line of Sight (CFLOS) and thus full data rate link, light green represents a link degraded by turbulence, orange represents a link attenuated by aerosols, red represents a link blocked by clouds, and yellow indicates an uplink from a LEO to a GEO.

Each of these atmospheric effects may require one or more different mitigation strategies, which may, in turn, be dependent on the operational design of a particular system.

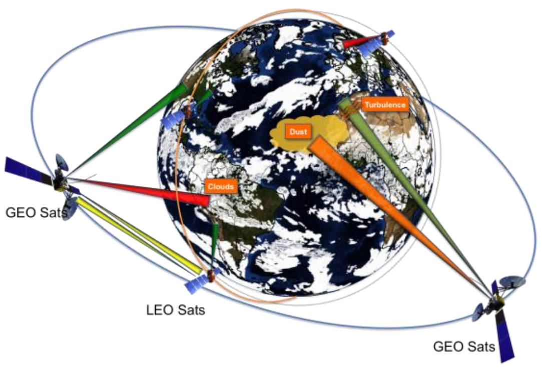

Figure 2: Conceptual Illustration of Atmospheric Effects experience by space-to-ground optical communications

Because space-to-ground optical communications are affected by the presence of cloud cover and other atmospheric effects it is important to specify, accurately measure, analyze, characterize, and ultimately predict critical atmospheric parameters for the purposes of: selection of Earth Terminal Sites (ETS), development of concepts of operation—including real-time knowledge of atmospheric parameters needed to make link handover decisions, evaluation of the long-term atmospheric characteristics of ETS, and development of link budgets.

Thus the CCSDS Optical Communication Working Group is developing standards for the development of local instruments that can characterize the atmospheric channel, as well as techniques on how to use the data to optimize and inform link handover decisions.

While optical ground stations to support Near Earth missions are much less expensive to develop and build, sharing those resources will also help to make optical communications more reliable and affordable. Optical communications through the Earth atmosphere is nearly impossible in the presence of most types of clouds. Therefore, the optical communication system solution for a particular mission has to utilize optical ground stations that are geographically diverse, such that there is a high probability of a cloud-free line of site (CFLOS) to a ground station from a spacecraft at any given point in time (e.g., at the same longitude or at a sufficient number of stations at different longitudes to allow the stored onboard data to be transmitted within the allocated time). Sharing ground stations around the world helps to increase the probability of getting the data to the ground within the time period required.

The working group has developed the following CCSDS books:

1) Blue Book on Optical Communications Physical Layer
2) Blue Book on Optical Communications Coding and Synchronization
3) Green Book on Atmospheric Characterization for Optical Communication Systems
4) Orange Book on Optical High Data Rate Communications – 1064nm

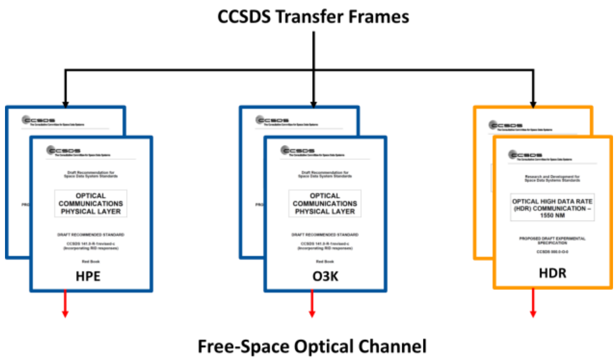

Figure 3: CCSDS Optical Signaling via the Blue and Orange Books

The following CCSDS books are in development:

1) Orange Book on Optical High Data Rate Communications – 1550nm
2) Green Book on Optical Communications
3) Magenta Book on Atmospheric Characterization and Forecasting for Optical Link Operations

IV. The Blue Books

The Blue Book on Optical Communications Physical Layer defines the physical layer parameters and techniques required for interoperability of optical communications. The Blue Book on Optical Communications Coding and Synchronization defines the coding, synchronization, interleaving parameters and techniques required for interoperability of optical communications. The first published version of both books covers the High Photon Efficiency (HPE) scenario; the working group is currently working on a revision to both books. The revision will cover Optical On/Off Keying. As previously mentioned, the working group believes Optical On/Off Keying based optical communications will be relatively easy and cost effective to implement; there has also been a lot of interest in an Optical On/Off Keying standard expressed by various industry observers in the working group.

A. High Photon Efficiency

High Photon Efficiency optical communications are needed for applications in which power efficiency is the dominant consideration in link design. Figure 4 shows a representative Deep Space optical communications architecture requiring high photon efficiency. Desired features of the HPE specification include a near-capacity channel coding scheme, modularity between Open Systems Interconnection (OSI) layers, flexible parameters that enable HPE operation at a variety of signal and background fluxes, robustness to atmospheric fading, and support for a wide range of data rates.

CCSDS has published the HPE standard for optical communications. On the downlink, the standard specifies a pulse-position modulation (PPM) scheme intended to be received with a direct-detection receiver. The standard includes a serially-concatenated convolutionally-coded PPM (SCPPM) channel code [3], along with an appropriate interface to the data link layer above it. A channel interleaver is used to combat atmospheric fading, and guard slots are used for compatibility with existing laser technology and to aid in synchronization. The system supports data rates between 16 kbps and 2.1 Gbps.

The SCPPM code operates within about 1 db of capacity, as shown in Figure 5. The allowable PPM orders, code rates, slot widths, and symbol repeat factors are shown in Table 1.

On the uplink, the standard includes a beacon intended to be tracked by the spacecraft as part of its pointing system. Optionally, a low-rate data rate signal is supported, using a 2-PPM signal encoded with a low-density parity-check code and an optional channel interleaver.

At the physical layer, downlink transmission occurs between 1530 and 1577 nm, and uplink transmission at 1064, 1070, or 1030 nm. Appropriate center frequency tolerance, laser line width, in-band and spillover emissions, polarization, extinction ratio, timing jitter, pulse shape, and pulse repetition rates are described in the standard.

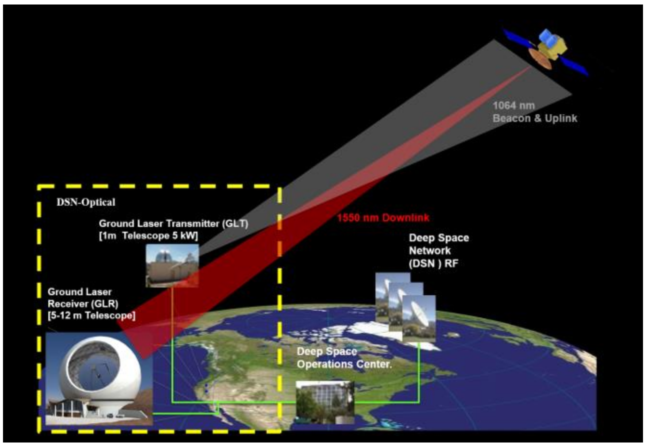

Figure 4: Representative HPE optical communications architecture

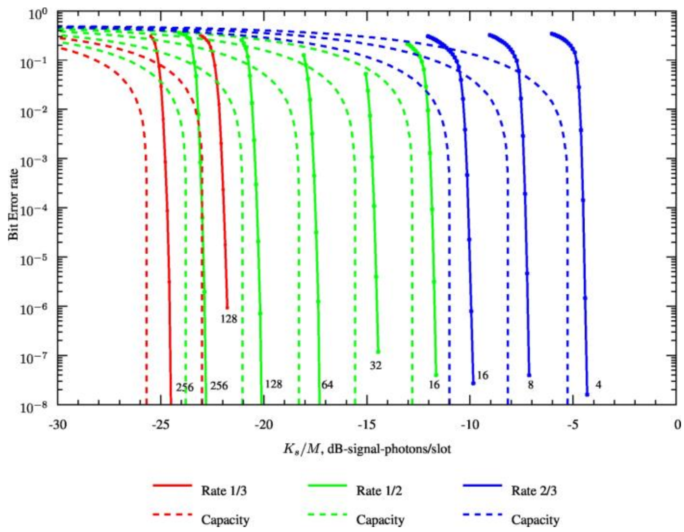

Figure 5: SCPPM performance, for Kb=0.01

PPM order	4, 8, 16, 32, 64, 128, 256
Code rate	1/3, 1/2, 2/3
Slot width (ns)	1/8, 1/4, 1/2, 1, 2, 4, 8, 512
Repeat factor	1, 2, 4, 8, 16, 32

Table 1: Allowable parameters values in HPE downlink specification

Recently, the working group members agreed to recommend to the IOAG that HPE be used as the baseline for a lunar optical communications architecture (Figure 6). For example, it is has been proposed that the Lunar Orbital Platform – Gateway carry an optical communications terminal to provide optical communications using HPE:

- To and from Earth
- To and from the lunar surface
- To and from satellites in lunar orbit
- To and from the Orion Multi-Purpose Crew Vehicle (MPCV)

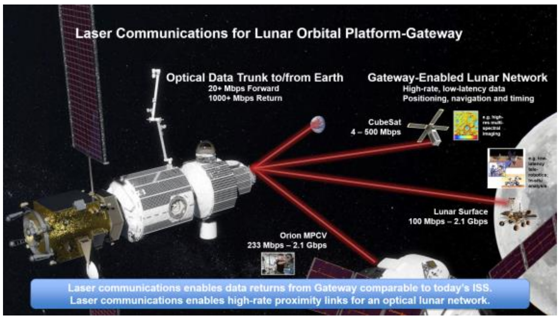

Figure 6: Lunar Optical Communications Architecture adopted by the IOAG

The architecture specifies that HPE be used for direct to Earth and intersatellite links, and that HPE telemetry signaling be used for both the forward and return link. Furthermore, the recommended architecture specifies that 1550 nm channels be used for all of the links. It is assume that an optically preamplified receiver will be used in space instead of a cryo-cooled photon counting receiver.

B. Optical On/Off Keying

The working group members are currently revising the published Blue Books on optical communications so that it will also contain a standard for Optical On / Off Keying (O3K). O3K is being pursued as an example of a low complexity optical communications system. The low complexity scenario addresses LEO direct-to-Earth (DTE) optical communication links where the reduction of complexity, costs, size, weight, and power takes priority over performance maximization (Figure 7).

In this scenario, reduced complexity is achieved by making the best use of specific LEO-DTE scenario boundary conditions such as short ranges below 2000 km at low elevations, which lead to a moderate range-loss in the link budget. This scenario allows for a strongly asymmetric link layout employing a very compact space terminal in combination with larger antennas at the Optical Ground Station (OGS). The data throughput of the low complexity systems is intended to be limited to the gigabit/second (Gbps) range using a simple direct-modulated laser source and optical amplifiers in the space terminal and a robust intensity-modulated direct detection signal on the ground. Use of larger OGS aperture diameters eliminates the need to perform complex atmospheric corrections on the ground segment.

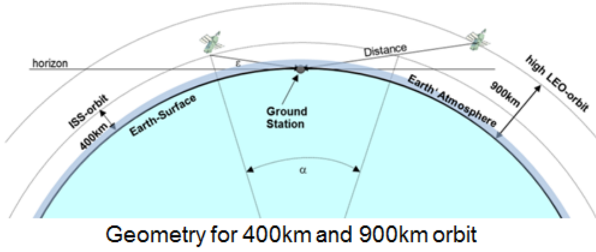

Figure 7: LEO Direct-to-Earth Optical Communications Links

The O3K standard will be able to support a wide range of applications, from the smallest system on a CubeSat, to larger payloads in the 100kg-satellite class. The physical layer book will describe technical parameters like the wavelength and signal definition in the downlink from the space terminal to ground, as well as for an optional beacon system from ground to space. In addition, the maximum data throughput will be represented in the maximum channel symbol rate. The synchronization and coding book content will focus on aspects like error correction techniques, synchronization, and possible interleaving.

The working group members have reached consensus on the physical layer recommendation for O3K and are working on Revision 1 of the Blue Book on Optical Communications Physical Layer to include the new recommendations. The plan is to release Revision 1 in 2020. Some specifications include the use of Non-Return-to-Zero (NRZ) with various channel rates between 1 Mbps and 10 Gbps. There is also an option for the ground stations to transmit a beacon to aide pointing, acquisition, and tracking. Supported options include a beacon at ~1589 nm, ~1064 nm, and ~1530 nm. However, the working group members are still studying and analyzing various proposals for the coding and synchronization layer.

V. The Atmospheric Characterization Books

The published CCSDS Green Book on Atmospheric Characterization for Optical Communication Systems provides a comprehensive description of the critical atmospheric parameters, and describes suggested types of instruments that can be used to measure these parameters. The book includes material showing how to produce and use long-term weather and atmospheric statistics and how to take real-time measurements. The book describes various types of whole sky imagers some of which operate in the visible wavelengths and others in the longwave infrared. In addition, the book describes a ceilometer for the use of atmospheric attenuation measurements, as well as a Differential Imaging Motion Monitor (DIMM) for atmospheric seeing/turbulence measurements.

The working group is currently working on a Magenta Book on Atmospheric Characterization and Forecasting for Optical Link Operations. This book will discuss best practices and touch on performing predictive weather in support of optical communications handovers. The scope of this book includes the use of atmospheric prediction techniques on time frames from minutes (LEO scenarios) to hours (Deep Space scenarios).

VI. The Experimental Books on Optical High Data Rate Communications

The CCSDS Optical Communications Working Group has published one CCSDS Orange Book for High Data Rate optical communications and is working on a second one to be published very soon.

High Data Rate optical communications links are expected to be used for Near Earth applications where extremely high performance is desired. When the working group was originally formed, there was a desire to include the High Data Rate scenario in the Blue Book on Optical Communications Physical Layer and in the Blue Book on Optical Communications Synchronization. However, it was impossible to reach consensus on a single recommendation for High Data Rate optical communications; after protracted discussions, it was decided to produce two CCSDS Orange Books. However, the hope it that in the near future, the members of the working group can reach a consensus and publish a single Blue Book(s) recommendation for High Data Rate.

The Orange Book on Optical High Data Rate Communications – 1064 nm has been officially published. This Orange Book was developed by ESA and the German Aerospace Agency (DLR). It focuses on high data rate optical communications at 1064 nm, and it is based on their experience with the European Data Relay System (EDRS).

The Orange Book on Optical High Data Rate Communications – 1550 nm is being developed by the French Aerospace Agency (CNES), the Japanese Exploration Agency (JAXA), NICT, and NASA. It will focus on future high performance, high data rate, optical communications at 1550 nm. This book should be published and made available to the general public in the near future.

A. ESA/DLR Orange Book

The purpose of the ESA and DLR Orange Book for Optical High Data Rate Communication – 1064 nm is to provide recommendations for optical communication solutions that are based on the European Data Relay System (EDRS). EDRS is a European constellation of GEO satellites that relay communications between satellites, airplanes, and ground stations. The key technical features of the optical system are the use of the 1064 nm wavelength, BPSK modulation, and a user data rate of 1.8 Gbps.

The Orange Book contains the technical specification for implementing the Physical Layer and the Coding and Synchronization sublayer of optical communications systems supporting the High Data Rate scenario. Among the characteristics that must be implemented to ensure terminal compatibility and successful link acquisition and data transfer are:

- *Optical signal*: band plan, laser center frequency, tuning range, tuning rate, line width, intensity/frequency/phase noise, polarization, extinction ratio, and modulation scheme; and
- *Coding and synchronization*: frame structure, channel coding/interleaving/ scrambling, frame synchronization, multiplexing.

The described optical communications mechanisms will be useful in particular for LEO-GEO and GEO-GEO Inter-Satellite Link (ISL) operational scenarios. However, they can also be used for space-ground and airborne-space links, if additional measures are taken, e.g., adaptive optics, interleaving, erasure coding.

B. CNES/JAXA/NASA/NICT Orange Book

The CCSDS Orange Book for High Data Rate Optical Communications – 1550 nm, is being developed by CNES, JAXA, NASA, and NICT. This specification aims to address a variety of near-

Earth optical communications link applications, including relay, crosslink, and direct-to-Earth links from ground, airborne, and space users, as depicted in Figure 8, using fiber telecommunications compatible wavelengths in the 1550-nm regime. To support such a wide array of applications, the optical signaling must be very flexible. For relay applications, data transfer from users in low- to medium-Earth orbit to a ground terminal via a relay satellite (or multiple satellites) in geosynchronous orbit is envisioned. Today, such links are designed to operate at hundreds of Mbps to a few Gbps. The Orange Book specification will support these links as well as future relay links at rates of tens to hundreds of Gbps. For direct-to-Earth links, the specification aims to support the higher link rates afforded by short link distances from, say, low Earth orbit to ground. Such links are expected to operate at rates >100 Gbps to support large data transfers with short contact times.

The Orange Book specification being developed leverages design features and lessons learned from ongoing development programs including NASA's Laser Communication Relay Demonstration (LCRD) [7] and JAXA's Japanese Data Relay System (JDRS) [8]. However, the Orange Book specification targets future operational systems and is not necessarily constrained by the design details of those pathfinder systems. High-level features of the Orange Book specification include:

- Generic Framing Procedure at the data link interface that can accept CCSDS and other transfer frames, including variable-rate variable-length frames
- Option to use high-efficiency modern forward error correcting codes, such as DVB-S2 as well as more traditional Reed Solomon codes which are easily implementable at high data rates
- Framing that supports multi-hop edge-to-edge forward error correction
- Variable-rate burst-mode phase-shift keying modulation on a 1550-nm carrier, which can be demodulated with either a non-coherent (e.g., differential phase shift keying [DPSK]) or a coherent receiver (e.g., homodyne binary phase shift keying [BPSK])

Data rate flexibility required for the various link applications is provided by varying the code and modulation rates, as well as using standard fiber telecommunications approaches such as Wavelength Division Multiplexing (WDM). CNES, JAXA, NASA, and NICT hope to release this Orange Book as an official CCSDS Experimental Standard sometime in 2020.

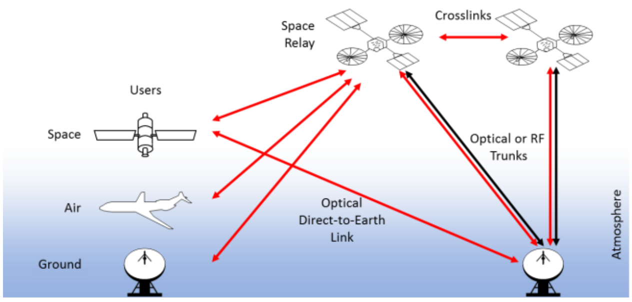

Figure 8: CCSDS Orange Book -- 1550 nm Link Scenarios

VII. Generic Framing Procedure

Recently, the CCSDS Optical Communications Working Group has been investigating the use of Generic Framing Procedure (GFP), a frame encapsulation technique defined by the International Telecommunications Union (ITU) G.7041/Y.1303 standard. GFP has been proposed for inclusion in the CNES, JAXA, NASA, and NICT Orange Book previously mentioned and the team developing that experimental standard briefed its merits to the larger working group.

In the already published Blue Books on optical communications, the optical coding and synchronization layers accept fixed-length frames rate-matched to the optical channel. As shown in Figure 9, this works for CCSDS fixed-length transfer frames such as frames from CCSDS TM or from the CCSDS Advanced Orbiting Systems (AOS) protocol. This approach also works well for fixed-length frames from the CCSDS Universal Space Link Protocol (USLP). However, this does not work for Variable Length USLP or for directly accepting Ethernet frames without encapsulation; directly accepting Ethernet frames has been mentioned by several industry participants in the working group as a cost effective approach to meeting the needs of their customers.

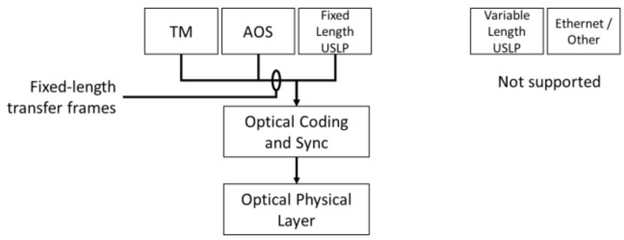

Figure 9: Frame transfer services provided by the currently published CCSDS Optical Communications Recommendations

A GFP frame consists of a core header, a payload header, an optional extension header, a GFP payload, and an optional payload frame check sequence.

Most of the working group members believes strongly that CCSDS signaling recommendations would be more widely applicable if they accepted variable-rate variable-length frames at the input to the coding and synchronization layer. This could easily be accomplished by using Generic Framing Procedure to adapt higher-layer frame formats to the fixed-rate octet transport service. This is why it is being used in the CNES, JAXA, NASA, NICT Orange Book previously mentioned. GFP is now being investigated by more working group members because it is a widely adopted industry standard for terrestrial optical transport systems and it supports many common client interfaces. Figure 10 shows how GFP could be used in the CCSDS recommendations already published.

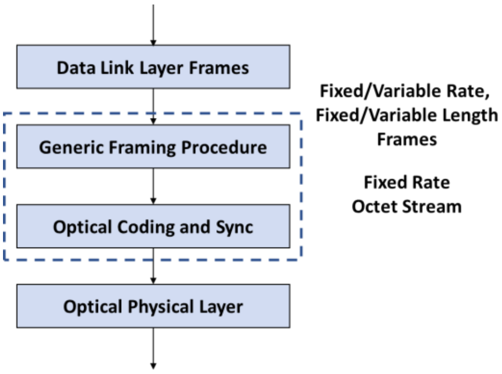

Figure 10: Proposal for Generic Frame Transport

VIII. Conclusion

Free space optical communications is the future of space communications. While there will always be a need for RF communications, optical communications is ready to support mission critical communications today. ESA has proven this with the operational European Data Relay System. JAXA is also working on an operational optical GEO relay satellite to be launched in the near future. This technology will enable new science and exploration missions throughout the solar system. Optical communications can provide increasingly higher data rates over comparable RF systems. While the capacity of current and near-term RF communications technology is still increasing, it will be eventually limited by bandwidth allocation restrictions, power requirements, flight terminal antenna size, and weight limitations. A future space communications network should offer both RF and optical communication services. RF can be reserved for those cases where high availability and thus low latency are absolutely required, since optical communications through the atmosphere for space-to-Earth links will always be impacted by clouds. For space-to-Earth links, optical communications can be reserved for scenarios in which a potential delay in reception is not a problem; in space-to-space links, optical communications can provide both high data rates and high availability.

Today, many space agencies around the world are investing in optical communications infrastructure in space and on the ground. It is obvious that, just as in RF systems, there is a need for cross support between the agencies. Collaboration in optical communications will lower mission cost and risk and likely enable missions which otherwise are unaffordable by one nation on their own. The CCSDS Optical Communications Working Group is developing a set of standards for space optical communications to help enable inoperability. These standards should be considered as the "building codes" of future space, airborne, and ground optical terminals. To ensure the space segments of different vendors are compatible with optical ground stations or ground station networks of different providers, key technical parameters need to be standardized with enough flexibility to ensure robust and innovative implementations.

Acknowledgments

Within NASA, optical communications physical coding, and synchronization standards development is being done at NASA's Goddard Space Flight Center, at the Massachusetts Institute of Technology's Lincoln Laboratory in Lexington, Massachusetts, and at the California Institute of Technology's Jet Propulsion Laboratory in Pasadena, California, under contract with NASA. Atmospheric work is being done by Northrop Grumman Corporation under contract to NASA. NASA's work is funded by the Space Communications and Navigation Program Office within NASA's Human Exploration and Operations Mission Directorate.

The Optical On/Off Keying standardization effort within CCSDS has been led by DLR's Institute of Communications and Navigation (IKN) in Oberpfaffenhofen, Germany.

ESA is accomplishing optical communications work at facilities in Darmstadt, Germany and Noordwijk, in the Netherlands, and at its optical ground station in Tenerife in the Canary Islands.

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