Latest Status of the CCSDS Optical Communications Working Group

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Abstract – International civil 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 architectures and standards for space communications. Within CCSDS, there is a working group dedicated on developing recommendations and standards for optical communications. These standards include recommendations for the physical layer, coding and synchronization layer, and best practices for measuring and monitoring atmospheric conditions and operating optical links. The working group has developed standards for both Near Earth and deep space robotic and hum exploration missions. The standards generally address both free space links between spacecraft and free space links between spacecraft and ground. This paper will provide an overview and update on the set of standards the CCSDS Optical Communications Working Group has developed.

I. The Interagency Operations Advisory Group (IOAG)

At NASA, the Space Communications and Navigation (SCaN) Program Office within the Space Operations Mission Directorate (SOMD) is responsible for planning, developing, and operating NASA's communications and navigation networks. To develop new technologies, SCaN routinely collaborates with other U.S. Government agencies and with NASA's Space Technology Mission Directorate (STMD). A recent example of this collaboration with STMD is the Laser Communications Relay Demonstration, a Near Earth optical communications demonstration that launched in December 2021. SCaN also collaborates in developing technology with NASA's Science Mission Directorate (SMD) and NASA's Exploration Systems Development Mission Directorate (ESDMD). Furthermore, SCaN receives most of its requirements for the communications and navigation networks from SMD and ESDMD. To help meet NASA's communications and navigation requirements, SCaN endeavors to partner with other civil space agencies around the world and to make as much use of commercial telecommunication services as possible. In fact SCaN, has a goal to move away from NASA owned and operated satellites and to move towards simply buying commercial services when possible.

In recent years, SCaN has supported the development and demonstration of free space optical communications for space to Earth communications. 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.

SCaN is NASA's official representative to the Interagency Operations Advisory Group (IOAG) [1]. The IOAG is an organization made up of international civil 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 considers the future requirements and trends in spacecraft communications needs, develops architectures for communication and tracking networks, and assigns priorities for the development of interoperability standards.

The IOAG performs a lot of its work via internal study groups. IOAG study groups have made recommendations for both radio frequency (RF) and optical communications [2],[3]. In recent years, the IOAG has been developing communications and navigation architectures to support both lunar and Mars exploration. The IOAG recently developed an optical communications architecture for the lunar environment (Figure 1). In that architecture, the Consultative Committee for Space Data Systems (CCSDS) High Photon Efficiency (HPE) standard is the baseline. For example, it has been proposed that the Lunar Orbital Platform – Gateway or a Lunar Communications Relay Satellite 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)

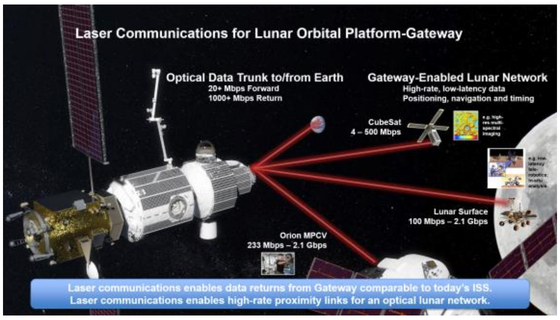

Figure 1: Lunar Optical Communications Architecture adopted by the IOAG

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 assumed that an optically preamplified receiver will be used in space instead of a cryo-cooled photon counting receiver.

Like in the lunar architecture, typical IOAG recommendations specify that civil space agencies should follow specific standards, including those from the International Organization for Standards (ISO), International Telecommunications Union (ITU), commercial industry, and the aforementioned CCSDS.

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

CCSDS is a multi-national forum comprised of the world's major space agencies, observer agencies, commercial companies, and academic institutions. The stated goal of the CCSDS is to enhance governmental and commercial interoperability, while also reducing risk, development time, and project costs. Consensus must be reached by the member agencies before a CCSDS standard can be published.

The CCSDS has established a number of Working Groups that are focused on specific topics. The products from the Working Groups are color-coded according to the following guide:

- Blue Books are completed recommended standards that become ISO standards.
- Magenta Books describe recommended practices.
- Green Books are informational reports.
- Red Books are working copies of the recommended standards before they are promoted to the Blue Book or Magenta Book level.
- White Books are the initial conceptual working draft documents in a topic area.
- Orange Books document experimental work.
- Yellow Books are administrative books.
- Silver Books are historical books. They are retired documents that are kept available to support existing or legacy implementations.
- Pink Books/Pink Sheets are draft revisions to Blue or Magenta Books that are circulated for agency review.

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.

III. The CCSDS Optical Communications Working Group

The CCSDS Optical Communications Working Group was formed in January 2014 and it is developing:

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

- 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 have to account for the severe impact of the Earth's atmosphere on space-to-ground links. 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.

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.

In addition to the typical standards that have to be developed for communications, 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. 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.

Thus, the 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.

These atmospheric challenges to operational optical communications systems are illustrated in Figure 1, 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.

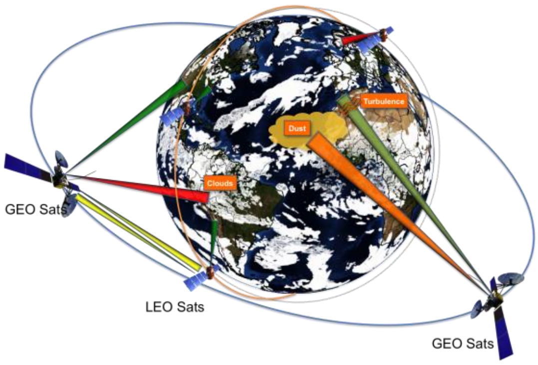

Figure 1: Conceptual Illustration of Atmospheric Effects experienced by space-to-ground optical communications

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.

To date 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
5) Orange Book on Optical High Data Rate Communications – 1550nm

6) Magenta Book on Atmospheric Characterization and Forecasting for Optical Link Operations

As of today, the Orange Book on Optical High Data Rate Communications – 1550nm and the Magenta Book on Atmospheric Characterization and Forecasting for Optical Link Operations are awaiting final CCSDS management approval and editing for official publication and release to the general public.

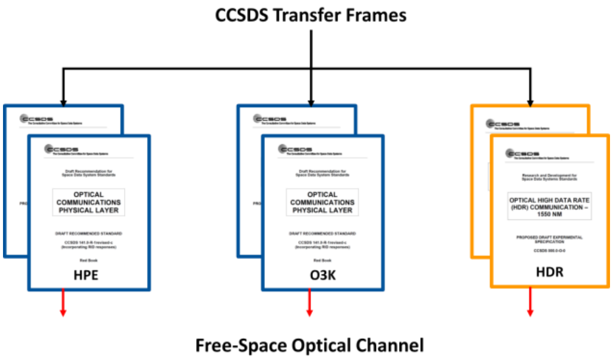

Figure 2: CCSDS Optical Signaling via the Blue and Orange Books

The following CCSDS books are officially in development:

1) Release 2 of the Blue Book on Optical Communications Physical Layer
2) Release 2 of the Blue Book on Optical Communications Coding and Synchronization
3) Orange Book on Reed-Solomon Product Code for Optical Communications
4) Green Book on Optical Communications

The working group is also working on adding ranging to the HPE recommendations and investigating the need and implementation approaches to support variable data rates.

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.

Release 2 of the two Blue Books will standardize the use of Optical On/Off Keying (O3K) modulation and the appropriate coding and synchronization techniques. The first release of those books only included the High Photon Efficiency (HPE) recommendations; HPE is most suitable for power-limited long distance deep space links [6]. For example, HPE will be used in NASA's Deep Space Optical Communications (DSOC) demonstration to be launched in 2022.

O3K is being added to help address LEO direct-to-Earth (DTE) optical communication links where the reduction of complexity, costs, size, weight, and power takes priority over performance maximization. The working group members believe that O3K based optical communications, will be relatively easy and cost effective to implement. They will also be able to support a wide range of applications, from the smallest system on a CubeSat, to larger payloads in the 100kg-satellite class and beyond. The data throughput of a system utilizing the O3K recommendations is intended to be limited to the gigabit/second (Gbps) range using a simple direct-modulated laser source in the space terminal and a robust intensity-modulated direct detection signal on the ground.

The O3K based changes to 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 O3K based changes to the synchronization and coding book focus on aspects like error correction techniques, synchronization, and possible interleaving.

V. The Orange Books

The CCSDS Optical Communications Working Group has developed two CCSDS Orange Books for High Data Rate optical communications. Orange indicates that the two books document experimental work that has not been officially adopted by the entire working group. One book has been officially published and is available to the public while the second book is being readied for public release and should be available in early 2022.

The Orange Book on Optical High Data Rate Communications – 1064 nm has been officially published and is available via the official CCSDS website. This Orange Book was developed by the European Space Agency (ESA) and the German Aerospace Agency (DLR). It focuses on high data rate space to space optical communications at 1064 nm, and it is based on their experience with the European Data Relay System (EDRS) [6].

The Orange Book on Optical High Data Rate Communications – 1550 nm was developed by the French Aerospace Agency (CNES), the Japanese Exploration Agency (JAXA), the Japanese National Institute for Information and Communications Technology (NICT), and NASA. Its focus is on high performance, high data rate, optical communications at 1550 nm. This book has been released by the working group and is currently awaiting official CCSDS editorial processing; the book should be publicly available in early 2022.

In 2021, the working group also reviewed and recommended for publication an Orange Book titled "Reed-Solomon Product Code for Optical Communications". This book was developed by JAXA and is based on their work for their optical terminal flown on the International Space Station. It aims to address coding and synchronization using a Reed-Solomon-Product Code for a variety of short distance (typically 1,000km to 5,000km) optical communications link applications, such as LEO spacecraft to Earth communication, LEO to LEO optical link and so on. This Experimental Specification supports operation of such links at user rates of 100 Mbps to 10 Gbps.

VI. The Green and Magenta 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.

In 2021, the working group completed its work for a Magenta Book on Atmospheric Characterization and Forecasting for Optical Link Operations. This book captures best practices and discusses some approaches to 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).

In 2022, the working group will be working on writing a general Green Book on Optical Communications. This will be an information book to guide people in using the other CCSDS optical communications material, especially the two Blue Books.

VII. Conclusion

Today there is more and more interest in free space optical communications. Space agencies and commercial companies around the world are conducting optical communications demonstrations or even flying operational systems providing mission critical communications. NASA flew a laser communications demonstration to the Moon almost a decade ago and is preparing to launch a deep space demonstration in 2022; NASA also recently launched the Laser Communications Relay Demonstration to Earth orbit and is preparing an optical terminal for the International Space Station and the Orion spacecraft designed to take astronauts back to the Moon. ESA is providing mission critical communications daily via its operational European Data Relay System. JAXA is preparing to launch an operational optical GEO relay satellite in the very near future. This technology will enable new science and exploration missions throughout the solar system.

Collaboration in optical communications via international standards will lower mission cost and risk and likely enable missions which otherwise are unaffordable by one nation on their own. This is especially true with deep space optical communications due to the need for very large and capable optical ground stations on Earth. 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. They identify the key technical parameters that need to be standardized with enough flexibility to ensure robust and innovative implementations.

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