International Interoperability Standards Development for Space Optical Communication

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Abstract – NASA and other international space agencies are currently developing optical communication systems for spacecraft applications. These applications include both links between spacecraft and links between spacecraft and ground. Six of the agencies formed the Optical Link Study Group (OLSG), under the Interagency Operations Advisory Group (IOAG), to determine if there is a business case for cross support of each other's spacecraft optical communication links. The OLSG recently completed its work and reported that there is a strong business case for cross support of spacecraft optical links. It further concluded that in order to enable cross support the links must be standardized.

This paper will overview the findings and rationale developed by the OLSG in arriving at their conclusion. It will also overview the history and structure of the international standards body, the Consultative Committee for Space Data Systems (CCSDS), that will develop the standards.

The paper will also describe the set of standards that will be developed and outline some of the issues that must be addressed in the next few years as the standards are developed.

I. Evolution in the International Interoperability of RF Communications

At the beginning of the Space Age each international space agency began developing their own space communication capabilities to communicate with their spacecraft. Most of them did use the same radio band, known as S-band, for spacecraft communication, but that was the only commonality among some of the space agency's networks. The result was that in order to provide global coverage for their spacecraft, each agency had to build ground stations around the Earth. They could not share each other's ground stations since they did not have a common set of communication protocols; they only had a common frequency band.

In 1982, the world's major space agencies formed an organization to address the issue of providing commonality in space data systems that would allow one member's spacecraft to be served by other members' ground antennas. The organization was named the Consultative System for Space Data Systems (CCSDS). The CCSDS is a huge success and today it is a multi-national forum for the development of communications and data systems standards for spaceflight comprised of the world's major space agencies and observer agencies. Presently, there are 11 member agencies, 29 observer agencies, and 151 commercial associates. The member and observer agencies represent 27 nations plus several European organizations. 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 has to be reached by the member agencies before a CCSDS standard can be published.

Since its founding CCSDS has developed standards recommendations, which have become ISO standards, for space link communications and for associated ground data systems. These standards enable interoperability and cross support among the international space agencies. There are over 130 active CCSDS publications to date.

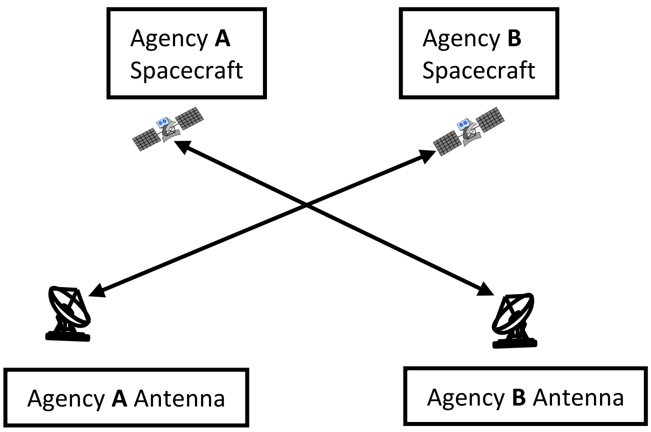

Figure 1: Cross Support

As the standards have been developed over the past 30 years, the international 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. It has increased options for spacecraft communications and reduced the cost of supporting a single agency's spacecraft by using communications assets of other agencies to service their spacecraft's communication needs. As of the writing of this paper, 609 space missions have adopted and used various CCSDS standards.

II. The Development of Space Communication Standards

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, coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications. The IOAG has been meeting face to face at least annually since 2000 and has telecons in between the face to face meeting. Over the years, it has established effective liaisons with key enabling groups for interoperability, including the CCSDS, the Space Frequency Coordination Group (SFCG), the International Committee on Global Navigation Satellite Systems (ICG), and most recently the International Space Exploration Coordination Group (ISECG). The IOAG has increased its membership to 11 member and observer agencies over the years and held its 18th meeting in February 2014. 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.

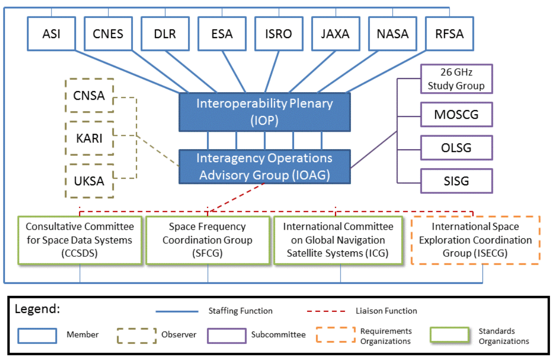

Figure 2. Interagency Operations Advisory Group

The CCSDS member and observer agencies contribute technical experts to develop space data standards. Since there are a number of technical disciplines involved in end to end (between spacecraft and their control centers) space communications, the CCSDS has established a number of Working Groups (WG), each of which focuses on specific topics. The CCSDS WGs have a leader, chosen from a member agency, and a group of experts contributed by member agencies interested in the particular topic being addressed by the WG. The products of the WGs are documents that recommend standard communication protocols, procedures, and concepts that will enable cross support in the particular area of interest of the WG. Often there will be multiple subtopics to be addressed by the WG so the WG may organize subgroups to deal with specific subtopics. These subtopics groups usually have a document product that captures the final results of their studies and deliberations.

The WGs meet in face-to-face meetings twice a year. Typically one of the meetings is hosted by NASA and held in the United States while the other meeting is hosted by a member or observer agency elsewhere in the world, but typically in Europe. The WGs also conduct a lot of work between those face-to-face meetings via telecons and emails.

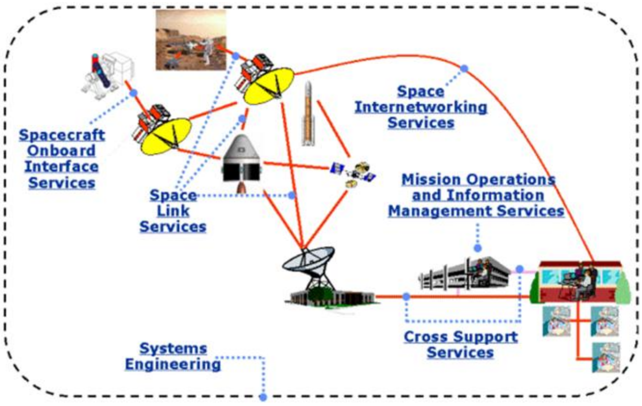

Figure 3. CCSDS End-to-End Scope

CCSDS documents are color coded according to the following guide:

- Blue Books are completed recommended standards that become International Standards Organization (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. 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.

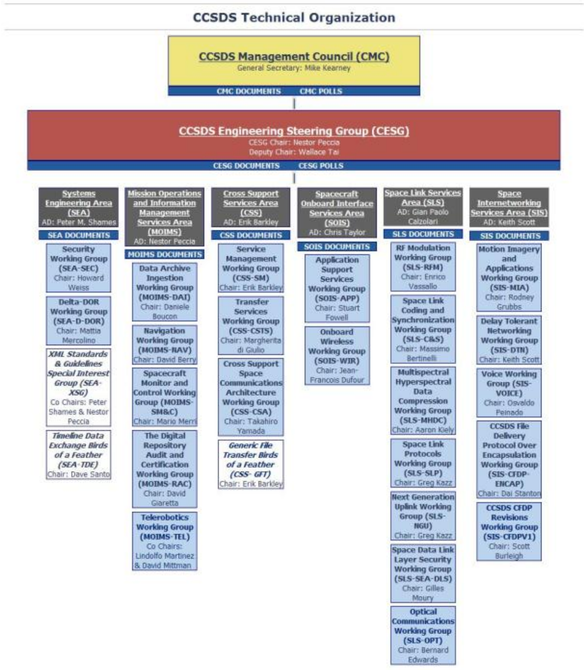

Figure 4. CCSDS Working Groups

III. A New Era in Space Communications

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 RF space communications while using less power, having lower mass, and occupying less space than comparable RF communication systems. A few international space agencies have already begun to demonstrate the technology in space and build experimental ground stations.

For example, NASA recently launched the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft in September 2013. On board the spacecraft was a technology demonstration of optical communications; the entire demonstration, including flight and ground systems, was referred to as the Lunar Laser Communication Demonstration (LLCD) [2]. LLCD was NASA's first step towards the robust use of free space high rate optical communications. The demonstration consisted of an optical communications terminal in a lunar orbit, a primary optical ground station located at White Sands, New Mexico (the Lunar Lasercom Ground Terminal) and two additional backup optical ground stations: The Optical Communications Telescope Laboratory at Table Mountain, California, and the European Space Agency's Optical Ground Station at Tenerife, Spain. LLCD proved the feasibility of optical communications from beyond Earth orbit by routinely transmitting at rates up to 622 Mbps from the Moon. LLCD also proved the feasibility of optical international cross support through its use of the ESA ground station in Tenerife.

Figure 5. The Lunar Laser Communication Demonstration's (LLCD) Transportable Lunar Lasercom Ground Terminal

NASA plans to follow LLCD with the Laser Communications Relay Demonstration (LCRD) [3]. LCRD leverages the knowledge and experience gained from LLCD, and it will consist of two optical communications terminals to be launched to GEO in 2018 as a hosted payload on a commercial communications satellite. It will also have two ground stations in the United States that will support bi-directional communications at 1.25 Gbps. In addition, NASA is currently studying the concept of putting an optical communications terminal on the International Space Station to communicate with LCRD to enhance the demonstration. LCRD is seen as a pathfinder for NASA's Next Generation Tracking and Data Relay Satellite.

The European Space Agency is preparing to launch the first satellite in the European Data Relay Satellite System (EDRS) [4]. EDRS will provide optical inter-satellite links at 1.8 Gbps. It is a joint effort with the German Aerospace Center Deutsches Zentrum für Luft- und Raumfahrt (DLR). The Lasercom Terminal (LCT) will be flown on the Earth relay satellites and on Low Earth Orbit (LEO) spacecraft; the terminals are built by Tesat-Spacecom of Backnang, Germany. EDRS will build upon the success of Alphasat [5], a technology demonstration satellite currently in orbit, and of previous LEO to LEO optical communication demonstrations using Tesat-Spacecom supplied terminals.

Figure 6. ESA's Optical Ground Station (OGS) at the La Teide Observatory, Tenerife, Canary Islands, Spain

The German Aerospace Center (DLR)'s Institute of Communications and Navigation (IKN), located in Oberphfaffenhofen, Germany, also has a heritage of more than 25 years in working on optical inter-satellite and satellite-to-ground links. Research being pursued at IKN includes atmospheric work for LEO and aircraft downlinks. They are also developing OSIRIS, an optical communications terminal for small LEO satellites [6]. IKN has developed fixed and transportable ground stations for multiple scenarios.

Figure 7. DLR's Institute of Communications and Navigation's (IKN) Transportable Ground Terminal

Japan's National Institute of Information and Communications Technology (NICT) and the Japanese Aerospace Exploration Agency (JAXA) have a long history with optical communications demonstrations. Their next demonstration will be of a small optical terminal called SOTA (Small Optical TrAnsponder) [7]; SOTA is expected to be launch in 2014 and will communicate primarily to optical ground stations in Japan. However, SOTA will also be supported by optical ground stations in France, operated by the French Aerospace Agency Centre National D'Etudes Spatiales (CNES), and

Germany (DLR) as part of a demonstration of international collaboration. It is a small terminal with a limited data rate capability of 1 or 10 Mbps.

With all of the demonstrations being performed and with the building of experimental ground stations, the IOAG commissioned a study in 2010 on the business case for establishing cross support standards for optical communications. The study group was named the Optical Link Study Group (OLSG) and it was co-chaired by NASA and ESA.

The OLSG had six member agencies and assessed the business case by defining mission scenarios, developing a credible operational concept for each scenario, and examining the corresponding space communication system designs, estimated costs, and their expected performance. Some of the scenarios that the OLSG looked at were Earth relay satellites, Low Earth Orbit (LEO) direct-to-ground, lunar direct-to-Earth, and deep space optical direct to Earth communications.

Earth relay satellites are satellites placed in Earth orbit to relay signals from other spacecraft, airplanes, balloons, etc. to centralized ground stations. Examples are NASA's Tracking and Data Relay Satellite System and the soon to be deployed European Data Relay System. Earth relay satellites are expensive to develop, build, and operate. Sharing of an Earth relay satellite will reduce the cost of providing worldwide coverage for optical inter-satellite communication links. Sharing of Earth relay satellites should also provide higher availability by making more resources available to a specific spacecraft.

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 help to increase the probability of getting the data to the ground within the time period required.

Optical ground stations to support deep space direct-to-Earth links are expected to be large, relatively expensive ground stations. This is especially true for stations supporting very high data rates from Mars and beyond. The effective aperture size will be on the order of 5 to 10 meters to support high rate optical signals from Mars and even larger for signals from farther out in the solar system. Just as in the Near Earth application case, the sharing of deep space optical ground stations will save cost and increase availability. This will help to make future deep space optical communications a reality as the sharing of infrastructure will lower the cost for any single space agency.

In all of the scenarios examined, the OLSG found that "cross support will allow sharing of the cost and usage of the global optical terminal infrastructure needed to serve future missions, and will boost missions' scientific return." [8] Thus it found there is a business case for cross support of optical communications for space links. The OLSG completed its Final Report in 2012, with an official addendum with more details added in 2013, stating that a business case had been found for optical communication cross support. Having a worldwide standard for optical communications would enable cross support by other space agencies, thereby increasing the number of communication paths available to a given mission. So, in addition to finding a business case for optical communications cross support, the OLSG recommended actions to be taken to advance the development of interoperable international standards for cross support.

Some of the other important findings produced by the OLSG are [9]:

1) OLSG recommended that both 1064 and 1550 nm wavelengths be considered for interoperability in optical communication systems.
2) OLSG did an extensive study of flight-to-ground CCSDS standards and determined that new standards need to be developed for optical communications below the Data Link Protocol sublayer. Existing CCSDS standards originally developed for RF systems for the Data Link Protocol sublayer and above can be reused for optical communications.
3) OLSG identified a new area for standardization required due to the potential of weather disruptions of optical communication links: weather data sharing and link handover.
4) OLSG interacted with the International Civil Aviation Organization (ICAO) and with the Human Spaceflight Office at NASA's Johnson Space Center in Houston, Texas, to better understand any

concerns relative to eye safety of optical communication links and found that some rules should be reviewed in detail and refined.

The report went on to recommend that a CCSDS Working Group be established and that cross support standards should be developed in a time frame that would support the migration of space missions to optical communications.

The IOAG has decided that the OLSG will continue in a limited format for now. Specifically, the OLSG will focus on aviation safety concerns and continue to interact with ICAO, which establishes the standards that most local civil authorities use as guidance. The primary concern of the aviation community is the high power uplink beacons that may be required from ground terminals to aid optical communication link acquisition by optical communication terminals aboard spacecraft. The current ICAO standard for laser emissions that could affect flight crews is defined in terms of a Maximum Permissible Exposure (MPE) threshold. Due to the narrow beam width of the beacon laser and the short length of time air crews would be in the beam, it is believed that beacon lasers could be operated safely. However, until that is agreed upon by all stakeholders, optical ground sites should be selected in areas that minimize the threat of aircraft entering the uplink beacon or communication beams and include systems for aircraft detection with interruption of the transmission when an aircraft is projected to fly into the beam.

IV. Optical Communications Standardization within the CCSDS

With the OLSG Final Report in mind and as requested by the IOAG, the CCSDS officially formed an Optical Communications Working Group to develop world-wide standards for space optical communications. The WG is co-chaired by NASA and ESA and it had its kick-off meeting in January 2014. The working group plans to develop:

- New standards in wavelength, modulation, coding, interleaving, synchronization and acquisition which are likely different from existing RF standards.

- 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 space optical communications are required for the modulation, coding, interleaving, synchronization, and acquisition of signals and will have to take into account 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. 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 currently expects to develop standards for two different scenarios: high photon flux links and low photon flux links. High photon flux links are expected to be used for Near Earth applications where extremely high data rates are desired. Low photon flux 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. Likewise, high photon flux links could be used in deep space, such as from the surface of Mars to Mars orbit. It is expected that the underlying technologies and techniques for modulation, coding, and synchronization will be significantly different between the two signal cases.

In addition to the typical standards that have to be developed for any communications system, such as modulation and coding, space optical communications also requires a standard for the definition, exchange and archiving of weather and atmospheric data. That is because optical space communications through Earth's 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 at least one ground station from the spacecraft at any given point in time. The exchange of weather and atmospheric data among optical ground stations and network operations center is critical to maximizing the data return from a mission while efficiently utilizing the various optical ground stations involved [10]. The new working group will define the physical parameters that should be collected and shared between ground stations via, if possible, existing CCSDS cross support services.

The WG currently plans to develop the following CCSDS books:

1) Blue Book for Optical Communications Physical Layer
2) Blue Book for Optical Communications Coding and Synchronization
3) Green Book for Optical Communications Concepts and Terminologies
4) Green Book for Real-Time Weather and Atmospheric Characterization Data
5) Green Book for Optical Communications Physical Layer and Coding and Synchronization Sublayer
6) Blue or Magenta Book(s) for Real-Time Weather and Atmospheric Characterization Data

The WG has started working on the first four books with the goal of publishing the books in a couple of years; work on the last two books will start sometime in the future as resources permit. The first four books are described below.

The Blue Book for Optical Communications Physical Layer shall define the physical layer parameters and techniques required for interoperability of optical communications. It will address low and high photon flux signal scenarios for space-to-Earth and space-to-space links and will standardize one or more techniques for them. This book will focus on modulations for low and high signal photon flux scenarios and with pointing, acquisition, and tracking. The German Aerospace Agency, DLR, has volunteered to be the CCSDS Book Editor for this book.

The Blue Book for Optical Communications Coding and Synchronization shall define the coding, synchronization, interleaving parameters and techniques required for interoperability of optical communications. It will address low and high photon flux signal scenarios for Space-to-Earth and space-to-space links link and standardize one or more techniques for them. NASA has volunteered to be the CCSDS Book Editor for this book.

The Green Book for Optical Communications Concepts and Terminologies will define common terminology and atmospheric models to be used in link and pointing budget calculations, and define a basic concept of operations, including how to conduct handovers from one location to the next. The book will focus on terminology definitions, atmospheric models, and how to perform link and pointing budget calculations. ESA has volunteered to be the CCSDS Book Editor for this book.

The Green Book for Real-Time Weather and Atmospheric Characterization Data will define the physical quantities to be measured at existing and potential optical ground station sites in support of space-to-Earth links CFLOS (Cloud Free Line of Sight) and link budget caculations. The book will include material showing how to produce and use long term weather and atmospheric statistics and how to take real-time measurements. The book will also touch on performing predictive weather in support of optical communications handovers. NICT has volunteered to be the CCSDS Book Editor for this book.

V. Conclusion

Optical Communications is an important communications technology for future space missions. It has the potential to 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 is eventually limited by bandwidth allocation restrictions, power requirements, flight terminal antenna size, and weight limitations. The cost and complexity of expanding the existing space communications networks to enable these higher data rates using RF solutions alone with large aperture antennas is a significant undertaking. 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 is 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. In both space-to-space and space-to-Earth links, optical communications can potentially provide high data rates with smaller systems on user spacecraft and on the ground.

The authors strongly believe that in the not so distant future, international space agencies will rely heavily on optical communication systems. Future Earth relay satellites will supply both RF and optical services to users. To facilitate the development of optical communications in the future, a set of standards for space optical communications needs to be developed to enable inoperability. An international standard will allow optical communications terminals built by one agency to use the infrastructure of another. This is the evolutionary next step to today’s RF cross support.

While single nations and agencies have cost-constrained assets and limited reach, collaborations and consortiums of multiple nations and agencies will allow for more grand missions and explorations for both human and robotic missions. Such opportunities include grand concepts to explore the moon, asteroids, and Mars with both human and robotic explorers. Optical communications is an enabling technology for those future missions. Collaboration in optical communications will lower mission cost and risk and likely enable missions which otherwise are unaffordable by one nation on their own. International optical communication standards that are adopted and implemented by international space agencies are needed as soon as possible. It is definitely an exciting time to be working in this critical technology area.

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References

1. "The Interagency Operations Advisory Group (IOAG) - A decade of leadership in International Space Cooperation" presented at the SpaceOps 2012 by Jean-Marc Soula (CNES). A complete list of authors include Jean-Marc Soula CNES ; Philip Liebrecht NASA; Martin Pilgram DLR ; Jon Walker NASA; James Costrell NASA (Retired) ; Gian-Paolo Calzolari ESA ; Wolfgang Hell ESA
2. B. S. Robinson, D. M. Boroson, D. A. Burianek, D. V. Murphy, "The Lunar Laser Communications Demonstration", International Conference on Space Optical Systems and Applications, May 2011
3. B.L. Edwards, D. J. Israel, K. Wilson, J. Moores, and A. Fletcher, "Overview of the Laser Communications Relay Demonstration Project", SpaceOps 2012 Conference, 2012
4. M. Witting, H. Hauschildt, A. Murrell, J. Lejault, J. Perdigues, J. Lautier, C. Salenc, K. Kably, H. Greus, F. Garat, H. Moeller, S. Mezzasoma, R. Meyer, B. Guetlich, S. Philipp-May, A. Pagels-Kerp, B. Theelen, M. Wiegand, M. Leadstone, G. Eckert, G. Wuetschner, L. Laux, O. Gerard, D. Poncet, R. Mager, K. Schoenherr, F. Heine, S. Seel, K. Panzlaff, H. Zech, H. Kaempfner, A. Schneider, I. Canas, C. Perez, and H. Schuff, "Status of the European Data Relay Satellite System", 2012 International Conference on Space Optical Systems and Applications, 2012
5. G. Muehlnikel, H. Kampfner, F. Heine, H. Zech, D. Troendle, and R. Meyer, "The Alphasat GEO Laser Communication Terminal Flight Acceptance Tests", 2012 International Conference on Space Optical Systems and Applications, 2012
6. D. Giggenbach, "Lasercomm Activities at the German Aerospace Center's Institute of Communications and Navigation", 2012 International Conference on Space Optical Systems and Applications, 2012
7. Y. Takayama, M. Toyoshima, Y. Koyama, H. Takenaka, M. Akioka, K. Shiratama, I. Mase, O. Kawamoto, "Current Development Status of Small Optical TrAnsponder (SOTA) for satellite-ground laser communications", SPIE 2012 Conference
8. Interagency Operations Advisory Group, "Optical Link Study Group Final Report," IOAG.T.OLSG.2012. 5 June 2012
9. J. Rush and K. Schulz, "Results of the Optical Link Study Group", Space Operations 2012 Conference, 2012
10. R. Alliss and B. Felton, "The mitigation of Cloud Impacts on Free Space Optical Communications", SPIE Proceedings, Vol 8380, 83819, 2012