International Interoperability Standards Development for Space Optical Communications

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Optical Communications
International Standardization

- IOAG and CCSDS
- CCSDS Optical Communications Working Group
- Standardizing Atmospheric Characterization
- Overview of the NASA / CNES / JAXA / NICT High Data Rate Recommendation
- Overview of the High Photon Efficiency Recommendation
- Low Complexity Effort within the CCSDS Optical Communications Working Group
Background
Sharing optical communication ground stations or relay satellites among the international space agencies would allow the agencies to share the cost of the communications infrastructure.

- For example, due to cloud blockage, it is critical to have multiple ground stations in use during space to ground optical operations to provide high availability.

Therefore NASA is pursuing international cross-support by working within the Interagency Operations Advisory Group (IOAG) and the Consultative Committee for Space Data Systems (CCSDS).

The goal is to develop international cross support of optical communications by various agencies as we have in traditional Radio Frequency (RF) communications today.
Traditional International RF Cross Support

Agency A
Spacecraft

Agency B
Spacecraft

Agency A Antenna

Agency B Antenna
A Real Example: The Lunar Laser Communication Demonstration (LLCD)

Lunar Lasercom Ground Terminal (LLGT) at NASA’s White Sands Complex (WSC)

Lunar Lasercom Space Terminal (LLST)

LADEE Mission Ops Center at ARC

LADEE Science Ops Center at GSFC

RF Ground Station

LLCD Monitor at GSFC

Echo (LLOT) – “OCTL” at Table Mtn. CA

OGS at Tenerife, Spain

Lunar Lasercom Ops Center (LLOC) & Mission Analysis Center at MIT/LL
Inter-Agency Operations Advisory Group (IOAG) and Consultative Committee for Space Data Systems (CCSDS)
Interagency Operations Advisory Group (IOAG)

Legend:
- **Member**
- **Observer**
- **Subcommittee**
- **Staffing Function**
- **Liaison Function**
- **Requirements Organizations**
- **Standards Organizations**
Central Role of the IOAG

- Technology Drivers
- Operations Drivers
- International Standards
- Cross-Support Service Catalogs
- Inter-Operability Plenary
- Requirements for International Space Mission Interoperability
- Spectrum Allocation
- Shared Mission Support Infrastructure
- International Space Mission Community
The Consultative Committee for Space Data Systems (CCSDS)

- CCSDS – An Agency-Led International Committee
  - Currently 11 Member agencies
  - Currently 29 Observer Agencies
  - Agencies represent 27 nations (plus European orgs)
  - Currently 151 Commercial Associates
  - ~160-180 attendees at Spring/Fall meetings

- Also functions as an ISO Subcommittee
  - TC20/SC13 - Space Data & Info Transfer Systems
  - Represents 20 nations
CCSDS Overview
End-to-End Architecture

Six Technical Areas, Twenty-Seven Teams

- Working Group (producing standards)
- Birds-Of-a-Feather stage (pre-approval)
- Special Interest Group (integration forum)

Typical Mission Profile

One Organization’s Assets

End Users

Applications/Archives

Another Organization’s Assets

Mission Ops & Info Mgt Services
- Data Archive Ingestion
- Navigation
- Spacecraft Monitor & Control
- Digital Repository Audit/Certification
- Telerobotics

Space Internetworking Services
- Motion Imagery & Apps
- Delay Tolerant Networking
- Voice
- CFDP over Encap
- CFDP Revisions

Cross Support Services
- CS Service Management
- CS Transfer Services
- Cross Supt Service Arch.
- Generic Gnd-to-Gnd File Transfer

Space Link Services
- RF & Modulation
- Space Link Coding & Sync.
- Multi/Hyper Data Compress.
- Space Link Protocols
- Next Generation Uplink
- Space Data Link Security
- Optical Coding and Mod

Spacecraft Onboard Interface Services
- Onboard Wireless WG
- Application Supt Services (incl. Plug-n-Play)

Security
- Security
- Delta-DOR
- Timeline Data Exchange
- XML Standards and Guidelines

Systems Engineering

End Users

Applications/Archives

Typical Mission Profile

Mission Control Center

End Users

Applications/Archives

End Users
The CCSDS Optical Communications Working Group (OCWG)

- This is the first official CCSDS Working Group to consider the end-to-end needs of optical communications
  ⇒ In other words, this Working Group is dedicated to optical communications

- Chairman: Bernard Edwards, NASA
- Deputy-Chairman: Klaus-Juergen Schulz, ESA

- The Working Group has been investigating the following scenarios or “needs” for optical communications:
  - High Data Rate
  - High Photon Efficiency
  - Low Complexity

- It is also working on recommendations for characterizing the atmosphere and discussed possible concept of operations with regards to space-to-ground links
Current Projects of the CCSDS Optical Communications Working Group

Blue Book for Optical Communications Physical Layer

Blue Book for Optical Communications Coding & Synchronization

Green Book for Atmospheric Characterization for Optical Communication Systems

Magenta Book for Atmospheric Characterization and Forecasting for Optical Link Operations

Orange Book: Optical High Data Rate Communications 1550 nm

Orange Book: Optical High Data Rate Communications 1064 nm

CNES/JAXA/NASA
In Development

ESA/DLR
In Development

In Development

COMPLETED

Will cover High Photon Efficiency (e.g., PPM for deep space) and Low-Complexity Systems Scenarios
Standardizing Atmospheric Characterization
Atmospheric Characterization and Prediction

Clouds are primary source of attenuation

Characterization and prediction of the atmospheric channel is critical to inform space link handovers and to maximize system availability
Goals for the Atmospheric Standardization Program

✦ Provide narrative on atmospherics and why it’s critical to accurately characterize
✦ Develop content regarding how long-term statistics of atmospherics are used to choose an optimal network of geographically diverse ground sites.
✦ Provide content on the required instruments and parameters to support long-term site characterization and real-time decision making

LIDAR derived large atmospheric fades due to low water based clouds

Develop several standardization books within CCSDS to capture these objectives
NASA/CNES/JAXA/NICT
High Data Rate Recommendation

Overview
Architectural Considerations

✦ Space Relay
  ✦ Edge-to-Edge FEC
    ✷ Desire for ~capacity-achieving codes as well as codes with simple implementation
  ✦ Optical link from user to relay; optical or RF link from relay to ground
  ✦ Wide range of supported user rates (~10 Mbps to 10+ Gbps)
  ✦ Example missions: JDRS, LCRD

✦ Direct-to-Earth
  ✦ High-rate (~> 100 Gbps) link for large volume, short duration data transfer
  ✦ Example missions: large data volume LEO DTE
High Data Throughput Signaling Proposal Overview

CCSDS Transfer Frames

Frame Sync Marker Attachment → Slicer → FEC: DVB-S2, RS, or G.975 1.3 → Convolutional Channel Interleaver

Q-Repeat → Physical Layer Framing → Randomizer → Modulation: Burst-Mode DPSK@1550nm

To amplifier or telescope
Optical relay serves as a transparent link-layer bridge between User Platform and Ground Relay.
High Photon Efficiency Recommendation
Overview
High Photon Efficiency Application Area

Attributes:
• Long-distance
• Photon-starved channel
• Direct-detection
HPE Signaling

- Signal Features
  - Near-capacity channel coding
  - Modular – asynchronous with upper layers
  - Robust to atmospheric fading (interleaver)
  - Robust to non-random data input
  - Compatible with existing/emerging technology

- Flexible parameters:
  - PPM order, $M \in \{4, 8, 16, 32, 64, 128, 256\}$
  - Code rate, $r \in \{1/3, 1/2, 2/3\}$
  - Slot width, $T_s \in \{\frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1, 2, 4, 8, 512\}$ ns
  - Repeat factor, $q_d \in \{1, 2, 4, 8, 16, 32\}$

- Data rates between 16 kbps and 2.1 Gbps

- Photon efficient: generally with 1 dB of capacity
Encoder Algorithm Overview

Encoder functional block diagram:

- Purpose of encoder: convert information bits to coded PPM symbols
- This is a **serially-concatenated convolutional code with accumulate PPM** (SCPPM)
- Components:
  - CRC32: checksum on information bits
  - Convolutional code: constraint-length 3, rate 1/3, 1/2, or 2/3 code
  - Bit interleaver: reorders each block of 15120 bits according to $\pi(i) = 11i + 210i^2 \mod 15120$
  - Accumulator: XOR’s input with previous output, i.e., polynomial $1/(1+D)$
  - Bit-to-symbol mapping: assign each $\log_2 M$ codebits to a PPM symbol, $M = 4, 8, 16, 32, 64, 128, 256$
CCSDS Layers

This is how the two Blue Books fit into the layers:

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<th>CCSDS protocols</th>
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<tr>
<td>Network and upper layers</td>
<td>Network and upper layers</td>
<td>TM or AOS space data link protocol</td>
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<td>Data link layer</td>
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<td>Physical layer</td>
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- Forward error correction codes
- Synchronization techniques
- Interleaving techniques
- Wavelength(s) / Frequency(ies)
- Pointing, acquisition and tracking
- Modulations
Deep Space Optical Comm Architecture

1064 nm Beacon & Uplink

1550 nm Downlink

Ground Laser Transmitter (GLT)
[1m Telescope 5 kW]

Ground Laser Receiver (GLR)
[5-12 m Telescope]

Deep Space Operations Center.
Low Complexity Effort within the CCSDS Working Group
The international community has not reached a concise recommendation, policy, vision, etc with regards to the future Low Complexity recommendation.

- Work is led by the German Aerospace Agency (DLR) Institute of Communications and Navigation within their research department.

- NASA has not participated fully in the past. However, we now are engaging U.S. Industry to determine what they would like to see in an international recommendation and to push for those features important to them.
Conclusion
Conclusion

• This is an exciting time for optical communications which has the potential to enable new science and exploration missions throughout the solar system.

• In the not so distant future, international space agencies will rely on optical communications for high bandwidth applications.

• A set of standards for space optical communications needs to be developed to enable interoperability. An international standard will allow optical communications terminals built by one agency to use the infrastructure of another.

• International cross support of optical communications is the evolutionary next step to today’s RF cross support.

• NASA is looking forward to working with the international community and US Industry in developing the appropriate standards.