Notional Concept of Operations (ConOps) for Deep Space Optical Communications

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• Introduction
  • Acquisition, tracking, beam pointing
  • Link availability
  • Days in the life
Deep Space links:

- Trunkline uplink (forward) – Direct detection, or coherent detection
- Trunkline downlink (return) – Direct or Coherent Detection
  - Space-to-space
  - Space-to-Earth
- Planet surface-to-orbiter
- Planet surface-to-Earth
- Surface-to-surface
- Emergency forward (optical)
- Emergency return (optical)
<table>
<thead>
<tr>
<th>Consideration</th>
<th>Near-Earth Links</th>
<th>Deep-Space Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit beam width (typical)</td>
<td>&gt; 10 $\mu$rad</td>
<td>&lt;10 $\mu$rad</td>
</tr>
<tr>
<td>Round-trip light-time</td>
<td>seconds</td>
<td>minutes to hours</td>
</tr>
<tr>
<td>Beacon irradiance at spacecraft</td>
<td>3-10 nW/m$^2$</td>
<td>1-3 pW/m$^2$ (very dim)</td>
</tr>
<tr>
<td>Point-ahead angles</td>
<td>2-5 beam widths</td>
<td>15-60 beam widths</td>
</tr>
<tr>
<td>Receiver optical signal-to-background power (daytime operations)</td>
<td>&gt; +10 dB</td>
<td>&lt; -10 dB (extremely faint)</td>
</tr>
<tr>
<td>Laser peak power (required for PPM)</td>
<td>&lt;20 W</td>
<td>&gt; 500 W</td>
</tr>
</tbody>
</table>
Deep Space Optical Link Architecture

Flight Terminal On Orbiter

CMD/TLM

Deep Space Network

Downlink (telemetry, science, 1-Way Ranging)

Beacon / Uplink / 1-Way Ranging

CMD/Monitor

DOT Mission Operations

Spacecraft Operations Center

Demo Coordination Center
Flight terminal considerations
- Beacon signal level required at the spacecraft
- Platform jitter characteristics
- RF link availability (at least a low capability in foreseeable future)

Earth terminal considerations
- Site geography and number of ground stations
- Atmospheric conditions when links are through atmosphere
- Uplink laser safety (to aviation and earth-orbiting spacecraft)
- Data hose
  - At 0.267 Gb/s downlink data-rate (from Mars)
    - ~8 Tbits (~1 Tbyte) delivered in a 9-hour continuous link
      - Data storage requirements at the spacecraft dependent on number of ground stations
      - Data storage requirements at the ground site
      - Data dissemination via high-speed (fiber or other) links at the ground site

Mission considerations
- Asymmetric data link
- Allocated data transfer time
- Allocated latency in transferring data
  - May drive onboard data storage requirements
With ground-based terminal, channel capacity is highly time dependent

- **Long-term predictability**
  - Spacecraft-Earth distance
  - Line-of-sight constraints
  - Sun-angles
  - **Mitigation**: Storage at the spacecraft, or multiple ground stations

- **Medium-term predictability**
  - Atmospheric attenuation
    - Ground state: available, partial to complete outage
  - Atmospheric turbulence/scintillation
  - **Mitigation**: Buffering and data-retransmission upon request

- **Short-term predictability**
  - Fast moving clouds
  - Highly turbulent atmosphere
  - **Mitigation**: Long interleaver codes and fly-wheeling through fades. Also optical DTN (delay-tolerant and disruption-tolerant networking protocols)

With space-based terminal, dealing only with long-term predictability issues

- No atmospheric (weather and turbulence) issues
- Also, best for uplink beacon
• Introduction
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<table>
<thead>
<tr>
<th>Mode</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-orbit Calibration</td>
<td>• Boresight flight terminal line-of-sight to spacecraft reference axis</td>
</tr>
<tr>
<td></td>
<td>• Characterize acq/trk detector array (e.g. pixel to pixel variation)</td>
</tr>
<tr>
<td></td>
<td>• Calibrate centering of vibration isolation platform</td>
</tr>
<tr>
<td></td>
<td>• Calibrate point-ahead mirror and its algorithm</td>
</tr>
<tr>
<td>Standby</td>
<td>• Maintain health and safety of flight optical terminal</td>
</tr>
<tr>
<td></td>
<td>• Keep track of current time and upcoming mode changes</td>
</tr>
<tr>
<td>Acquisition</td>
<td>• Acquire the beacon uplink signal and stabilize it on the detector</td>
</tr>
<tr>
<td>Uplink</td>
<td>• Track the uplink beacon signal to enough accuracy to keep pointing</td>
</tr>
<tr>
<td></td>
<td>losses to &lt;TBD (~2dB)</td>
</tr>
<tr>
<td>Downlink</td>
<td>• Point the downlink beam to the ground station</td>
</tr>
<tr>
<td>Safe</td>
<td>• Recovering via RF or optical comm</td>
</tr>
</tbody>
</table>
PAT Operational Modes; Description

- **On-orbit calibration mode**
  - High rate telemetry
  - Sensor and actuator placement in specific configurations
  - No uplink beacon, and no ground interaction

- **Standby mode**
  - Minimal data and power state.
  - Flight terminal is not actively transmitting or receiving

- **Acquisition mode**
  - Initialized with an estimated location/attitude with the associated knowledge error (i.e. covariance)
  - PAT assembly actively tries to locate Earth.
    - PAT will generate a search pattern based on the state estimate.
  - PAT commands the actuator to do the search.
  - Mode ends with either 1) acquisition of target on detector or 2) time out on search pattern
  - Variable length of time depending on the initial conditions. Can be bounded.

- **Uplink mode**
  - Track uplink beacon source. Stabilize to required performance
  - No point ahead used.

- **Downlink mode**
  - Track uplink beacon source.
  - Apply point ahead calculation using Earth ephemeris mode.
  - Aim downlink beam, using point ahead for disturbance rejection of downlink beam.
  - Mode duration is determined by pass duration (including margin)
  - Preceded always by an acquisition mode. Assumes target is already acquired and is being tracked.
  - Acquisition and tracking for retransmission

- **Safe mode**
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1. Single site with largest possible aperture
   - e.g. 3 telescopes co-located in one site
   - 3X effective aperture diameter; high channel capacity
   - ~20% availability in 24 hours
   - ~60% clear weather, available 8 hours only
   - Lowest infrastructure cost
   - Requires adequate storage at spacecraft

2. Three sites distributed in the same geographic area, but in weather diverse sites
   - ~30% availability in 24 hours (92% x 0.33)
   - Moderate cost of 3 stations

3. Three sites distributed globally, with a cluster of 3 telescopes each
   - >90% availability in 24 hours
   - High cost of 9 telescopes

4. Linearly dispersed ground stations
   - >90% availability in 24 hours, with 5 telescopes
   - Moderate-to-high cost of 5 telescope
   - Highest availability
• Assumed a set of 4 complementing ground transceiver network
  ∗ Goldstone (GS), CA,
  ∗ Tiede (T), Canary Islands,
  ∗ La Silla (LS), Chile,
  ∗ Alice Springs (AS), Australia
• 4-site gap-time is 5%
• Numerous instances of 2- or 3-site coverage
• Link performance degradation at SEP <10°

66% link availability with this arrangement

Contact-time and gap-time distribution for 4-site global network.
Availability increases for 2- and 3-site simultaneous contacts

<table>
<thead>
<tr>
<th>Station</th>
<th>Single Site (Tbits)</th>
<th>4-Site Ground Network (Tbits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS</td>
<td>260-329</td>
<td></td>
</tr>
<tr>
<td>AS</td>
<td>330-441</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>193-227</td>
<td></td>
</tr>
<tr>
<td>LS</td>
<td>554-648</td>
<td>856 - 1374</td>
</tr>
</tbody>
</table>

Single- vs. four-site data-volume after accounting for cloud-free-line-of-sight availability
Handover between ground stations

- Ground station selection based on
  - Local Availability
  - Local Weather
  - Local Visibility
  - Line-of-site
  - When footprint of the downlink beam excludes simultaneous use of two ground stations

Re-acquisition

- Momentary link loss, for whatever reason, requiring repeat of acquisition cycle

Predictive Weather

- Understanding weather conditions at the site well enough to enable the capability of switching to another ground station based on weather predicts.
Hybrid RF/Optical strategy allows:

✧ **Use RF links for:**
  - Communications and navigation requiring high availability (~97%)
    - Maximizing availability

✧ **Use Optical links for:**
  - Downlink for large volumes of data
    - Science data tolerant of time delay
      - maximizing
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**Cruise phase checkout and testing day(s)**
- Payload checkout
- Operations, as much time as granted
- Procedure refinement
- Ground receiver optimization
- Operations experience accumulation

**In-orbit phase checkout and testing day(s)**
- Verify system performance
- Acquire data at different link ranges
- Acquire data at different modulation formats (PPM orders)
- Acquire data at small to large Sun-angles
- Make precision range measurements
- Accumulation of atmospherics data along with uplink and downlink data, for later correlation
- Station handover performance tests
Long term
• Predictive avoidance data requested at least 24 hours prior to link
• Coordination through spacecraft mission operations center

Medium term
• Spacecraft ephemeris data acquired
• Ground terminal readiness decision (atmospheric data …)
• Ground terminal calibration

Short term
• Track celestial target and point uplink laser beam based on trajectory calculations
• Flight terminal is commanded via spacecraft to receive uplink and transmit downlink
• Downlink data analysis (BER, link margin… analysis)
• Attempts to improve both link margin and BER
• Data correlated with atmospherics measurements
• Uplink and downlink performance correlation
• RF/optical link decision (if data availability is critical)

Special days
• Calibrations
• Commissioning of the telescope
Deep space link entails a variety of different scenarios

Key con-op drivers:
- Lasercom requirements
- Mission requirements
- Pointing, acquisition, and tracking (both uplink and downlink)
- Link availability

Operational boundary conditions (weather, availability, visibility, and line-of-site) drive handover options

Mitigation techniques were identified to optimize channel capacity

A hybrid of RF and Optical link strategy maximizes downlink data volume

A hybrid of decision plans ahead of time and during the link is expected to provide the most efficient link.
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