Deep-Space Orbital Telecommunications

Sam Taylor, Tristan Liu, Caelan Maitland, Forrest Jordan, Hunter Rohlman, N. Sebastian Damm, Doug Brough, Conner Lewis, Buck Guthrie, Jennifer Gurtler
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Project Definition

- Project Definition
- Baseline Design
- Feasibility Analysis
- Next Steps
Mission Statement

Project DOTCOM aims to provide a scalable model of a representative network providing **high-speed, reliable communications** between **Earth-Moon and Mars-Moon systems**. A **Model-Based Systems Engineering simulation** and a **hardware network representation** will be used to demonstrate the network concept and provide an illustration of its processes. The software and hardware deliverables with provide insight that will inform the construction of a network architecture for current and future deep-space missions.
Functional Requirements

**FR 1** Communication architecture must be capable of transmitting and receiving data *simultaneously* and *non-simultaneously (store-and-forward)* between the Earth-Moon and Mars-Moon systems.

**FR 2** Satellite constellations around the Moon and Mars must be able to provide *communication* and *vehicle control capabilities* on their *surfaces* and in their *orbits*.

**FR 3** Communication network must ensure safety of and be collaborative with *existing* and *future communications infrastructure*. 
1 Project Definition
1.1 Mission Statement
1.2 Functional Requirements
1.3 CONOPS
1.4 FBD
1 Project Definition
1.1 Mission Statement
1.2 Functional Requirements
1.3 CONOPS
1.4 FBD
Baseline Design
Critical Project Elements

1) **Satellite Constellation Architecture**: Construction of ideal constellation architecture around each planetary body to satisfy coverage requirements.

2) **Extraterrestrial Relay Station**: The extraterrestrial support system allowing for direct access to communications between satellite constellations of each planetary communication system.

3) **Spectrum Allocation**: The project will meet certain data-relay rates for communication between the following: constellation satellites and ground stations, Earth and the Moon, and Mars and the Moon.

4) **Network Protocol**: Structured data transmission methodology that allows for high speed reliable communications from node to node.

5) **Network Representations**: Hardware + software models that demonstrate the network’s features.
Purpose: Distributes communication hardware in orbit so as to allocate connectivity throughout a planet’s surface and orbit. Seeks to make efficient use of resources while also being effective, reliable, and compatible with all hardware, software, and electrical components of the project.

Functional Requirements:

- **FR 1** Communication architecture must be capable of transmitting and receiving data *simultaneously* and *non-simultaneously (store-and-forward)* between the Earth-Moon and Mars-Moon systems.
- **FR 2** Satellite constellations around Moon and Mars must be able to provide communication and vehicle control capabilities on their surfaces and in their orbits.
Baseline Design Overview:
1) Satellite constellation architecture
Extraterrestrial Relay

Purpose: Key design decision in overall network architecture. Seeks to seamlessly integrate network protocols into network architecture while attempting to minimize cost and maximize efficiency of the system over its lifespan.

Functional Requirements:

- **FR 1** Communication architecture must be capable of transmitting and receiving data *simultaneously* and non-simultaneously *(store-and-forward)* between the Earth, Moon, and Mars.

- **FR 3** Communication network must ensure safety of and be collaborative with existing and future communications infrastructure.
Baseline Design Overview
1) Satellite constellation architecture
2) Extraterrestrial Relay Station
2 Baseline Design
2.1 Critical Project Elements
2.2 Satellite Constellation Architecture
2.3 Extraterrestrial Relay
2.4 Spectrum Allocation
2.5 Network Protocol
2.6 Network Representations
2.7 MBSE

Purpose: Use RF communications for constellation data relay and laser communication for interplanetary data relay to provide total planetary coverage and to reach the objective data-transfer rates.

Functional Requirements:

- **FR 1:** Communication architecture must be capable of transmitting and receiving data simultaneously and non-simultaneously (store-and-forward) between the Earth, Moon, and Mars.

- **FR 2:** Satellite constellations around the Moon and Mars must be able to provide communication and vehicle control capabilities on their surfaces and in their orbits.
Baseline Design Overview:
1) Satellite constellation architecture
2) Extraterrestrial Relay Station
3) Spectrum Allocation
   a) RF = red
   b) Laser = blue
Network Protocol

Purpose: An approach to network architecture designed to handle intermittent connectivity in the network. Works to optimize transmission windows under high variability, be compatible with protocols existing within the network, and provide high speed telecommunications and data transmission throughout the network.

Functional Requirements:

- **FR 1** Communication architecture must be capable of transmitting and receiving data simultaneously and non-simultaneously (store-and-forward) between the Earth, Moon, and Mars.

- **FR 3** Communication network must ensure safety of and be collaborative with existing and future communications infrastructure.
Network Protocol

2. Baseline Design
2.1 Critical Project Elements
2.2 Satellite Constellation Architecture
2.3 Extraterrestrial Relay
2.4 Spectrum Allocation
2.5 Network Protocol
2.6 Network Representations
2.7 MBSE

DTN Operating Assumptions
1. Long round trip data times
2. Intermittent connectivity
3. High bit error rates

Store and forward operating strategy

DTN Protocol Stack
- Universal compatibility with other protocols (TCP, LTC, etc.)
Baseline Design Overview:
1) Satellite constellation architecture
2) Extraterrestrial Relay Station
3) Spectrum Allocation
   a) RF = red
   b) Laser = blue
4) Network Protocol
2 Baseline Design
2.1 Critical Project Elements
2.2 Satellite Constellation Architecture
2.3 Extraterrestrial Relay
2.4 Spectrum Allocation
2.5 Network Protocol
2.6 Network Representations
2.7 MBSE

Network Representations

**Purpose:** Demonstrate the key features of the DOTCOM network and how its components will operate in order to meet our functional requirements.

1) A Model-Based Systems Engineering (MBSE) approach will be taken to create a software model of the detailed processes involved with data transmission between nodes of the network.

2) A hardware representation will be used to illustrate the functional capabilities that underlie the DOTCOM network concept. (protocol & comm systems).
Model-Based Systems Engineering (MBSE)

Purpose: MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases using System Markup Language (SysML). These system models are useful for showing relationships among system functions, requirements, developers, and users. MBSE will be used to do simulations based modifying our network design architecture, allowing us to optimize the communications network for the specific targets required by General Atomics, as well as verify all functional requirements.

Functional Requirements:

- **FR 1**: Communication architecture must be capable of transmitting and receiving data simultaneously and non-simultaneously (store-and-forward) between the Earth, Moon, and Mars.
- **FR 2**: Satellite constellations around the Moon and Mars must be able to provide communication and vehicle control capabilities on their surfaces and in their orbits.
- **FR 3**: Communication network must ensure safety of and be collaborative with existing and future communications infrastructure.
Baseline Design

1. **Network Protocol**
   - Will implement Delay Tolerant Networking protocol.
   - Provide environmental transmission optimization and compatibility with existing and future networks.

2. **Spectrum Allocation**
   - RF for short distance and laser communication for long distance data-transfer.

3. **Extraterrestrial Relay Station**
   - Ground based relay station for increased accessibility, decreased cost, and easier communications.

4. **Satellite Constellation Architecture**
   - Establish a medium-altitude constellation that provides complete coverage while minimizing the number of satellites required to do so.

5. **System Prototype Design/Testing**
   - Demonstrate DTN capability through use of a scaled, physical system, as well as conceptual network architecture using MBSE simulation.
Project Deliverables

1) Complete MBSE simulation of the entire system architecture encompassing all aspects of the design and implementations.
2) Physical hardware simulation to test a scaled model of the network protocol using differentiated nodes representing key parts of the network architecture (laser communications, RF communications, and varied transmission windows).
Evidence of Baseline Feasibility
Medium-Altitude Constellation Feasibility

- Cost effective, requiring minimal vehicles
- Accommodating of communications hardware, with modest power and pointing accuracy requirements
- More resilient to vehicle failure than a high-altitude constellation
3 Evidence of Baseline Design Feasibility
3.1 Mid-Altitude Satellite Constellation
3.2 Ground-Based Relay Station
3.3 RF Communications
3.4 Laser Communications
3.5 DTN
3.6 MBSE
3.7 Hardware Design

Medium-Altitude Constellation Feasibility

- 6 satellites
- Walker-Delta constellation
- Medium altitude
  - 10,750 km over Mars
  - 5,510 km over Moon
Ground-Based Relay Station Feasibility

- Advantages:
  - Low Costs
    - Development
    - Maintenance
  - Good Accessibility
    - Maintenance
    - Upgrades
    - Scaling

- Disadvantages:
  - Location Restrictions
  - More Infrastructure
RF Communications for Surface to Constellation Data Relay Feasibility

- Fewer satellites in constellation and less ground stations
- Easier to achieve total planetary coverage (pointing accuracy for RF is less strict than laser)
  - Larger footprint with RF = better coverage
- Less atmospheric interference and more reliable, can use X band (<12GHz), not affected by atmosphere (could be an issue on Mars)
3 Evidence of Baseline Design Feasibility

3.1 Mid-Altitude Satellite Constellations
3.2 Ground-Based Relay Station
3.3 RF Communications
3.4 Laser Communications
3.5 DTN
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Laser Communication for Interplanetary Data Relay Feasibility

- High data rates = large data packages to be sent in shorter amount of time (especially important for long distance relay)
- Can achieve the required data rates between planetary bodies DR 1.6 & 1.7
- Wavelengths are 10,000 times shorter, allowing for a narrower beam and significantly more bandwidth
- Optical band unlicensed and highly unregulated compared to electromagnetic spectrum (RF)

RF vs Laser Comparison Analysis

- Laser: Low mass s/c disturbance isolation assembly, flight qualified photon counting detector array, high efficiency flight laser amplifier, high efficiency photon counting detector array for ground-based receiver
- RF: needs more power, has larger antenna diameter, and weighs more than a laser system. Coverage of celestial bodies is much easier with RF

<table>
<thead>
<tr>
<th>Link</th>
<th>Optical</th>
<th>RF</th>
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</thead>
<tbody>
<tr>
<td>GEO-LEO</td>
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<td></td>
</tr>
<tr>
<td>Antenna Diameter</td>
<td>10.2 cm (1.0)</td>
<td>2.2 m (21.6)</td>
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<tr>
<td>Mass</td>
<td>65.3 kg (1.0)</td>
<td>152.8 kg (2.3)</td>
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<tr>
<td>Power</td>
<td>93.8 W (1.0)</td>
<td>213.9 W (2.3)</td>
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<tr>
<td>Power</td>
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<tr>
<td>LEO-LEO</td>
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<tr>
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<td>55.6 kg (2.4)</td>
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<tr>
<td>Power</td>
<td>33.1 W (1.0)</td>
<td>77.8 W (2.3)</td>
</tr>
</tbody>
</table>

RF vs Laser Comparison Analysis

- Beam spread by optical carrier is narrower and allows for increased intensity of signal at receiver for given transmitted power
- Smaller wavelengths = smaller antenna with same gain compared to RF b/c antenna gain scales inversely proportional to the square of operating wavelength

$\lambda = \text{carrier wavelengths, } D_R = \text{aperture diameter}$

3 Evidence of Baseline Design Feasibility
3.1 Mid-Altitude Satellite Constellations
3.2 Ground-Based Relay Station
3.3 RF Communications
3.4 Laser Communications
3.5 DTN
3.6 MBSE
3.7 Hardware Design

DTN Feasibility

1) Flight ready tech with open source software and NASA development tool
2) DTN provides:
   a) Decreased latency over networks with variable connections
   b) More data throughput
   c) Faster corrections for missing or corrupted bundles
   d) Compatible with TCP, UDP, LTP, SCPS
   e) User set congestion control options
   f) Built in security and encryption options

- Downside: requires ‘smart’ intermediary nodes with data storage capability
DTN vs TCP/IP Latency

Network Node
- Sending Computer (Terrestrial Internet)
- Earth Ground Station (Optical)
- Moon Ground Station (RF)
- Mars Relay Satellite (RF)
- Mars Ground Vehicle

Time --->
- 3 ms
- 25 min
- 100 ms

Latency
3 Evidence of Baseline Design Feasibility
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Network Diagram, i.e. CONOPS

1. Signal originates from a ground station on Earth

2. Signal is transmitted to a Lunar ground station

3. Signal is relayed into the constellation

4. Signal is distributed through the network to its destination

Legend:
- Red: Interplanetary link
- Blue: Constellation link
- Green: Terminal link

Signal can also be relayed to a Martian ground station for distribution.
3 Evidence of Baseline Design Feasibility

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   f) Built in security and encryption options

- Downside: requires ‘smart’ intermediary nodes with data storage capability
NASA DevKit DTN Simulation

Bping is set to run from node 2->4 automatically. An Xterm will pop up after 15 seconds, and the bping will start. Configured for a network manager on node n2.
Reverting to full screen capture at every frame.
To disable this check run with --no-un-check
(though that is not advised, since it will probably produce faulty results).

Initializing...
Buffer size adjusted to 4096 from 4096 frames.
Opened PCM device default
Recording on device default is set to:
1 channels at 22850Hz
Capturing!
X Error: BadAccess (attempt to access private resource denied)
access private resource denied
X Error: BadAccess (attempt to access private resource denied)
access private resource denied
access private resource denied

closed

file bpsend [pos:4] curiosity.png
As team DOTCOM’s project is heavily future-tense technology with full implementation not expected until 2040, a lack of hard document-based engineering exists for this area of study, allowing MBSE to shine

- Moves record authority from documents to continuously updating digital SysML modeling, a perfect fit for today’s highly-asynchronous online work environment where all involved parties must have up-to-date information
- MBSE allows design changes to be more readily explained and disseminated through the project workforce before a project is actually built
- Allows for any mistakes or defects in design to be caught earlier in development, a must-have for a project on a timeline and theoretical budget such as ours

The combined strengths of MBSE make for a more cohesive project environment for all shareholders while reflecting the interconnected nature of engineering a space-based communications network
Focus on System Models

Within MBSE, project focus is on **System Models** generated from the **Overall Network Architecture** through representative diagrams.

Subsystems of the System Architecture Model include the **Domain Models**.
Development of Domain Models

Domain Models are the Critical Project Elements

Subteams will develop their domain models to be implemented into MBSE
MBSE Software

Best Option: **Eclipse - Papyrus**: free to use, flexible UI, demonstrable system architecture

Others: need license

- IBM Rhapsody
- Cameo
- Capella
- Enterprise Architect
3 Evidence of Baseline Design Feasibility
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Hardware Design Feasibility

- The design gives a hands-on demonstration of the DTN through the RF/laser communication
- Demonstrate the performance of DTN with RF and laser communication as pertaining to the overall network concept
- Raspberry Pi computers exchanging communications via both signal transmission methods and operating using DTN procedures
Next Steps

Project Definition → Baseline Design → Feasibility Analysis → Next Steps
Studies Left

- What other DTN features can we illustrate in our hardware representation?
  - Network congestion, bandwidth, transmit/receive timestamps.
- Detailed cost analysis on all system elements.
- Analyze and compare various network designs to optimize the system:
  - # of nodes & locations, constellation orbits, connection windows, data routing, implementation (timeline).
### DTN Trade Study

<table>
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<th>Criteria</th>
<th>Weight</th>
<th>Evaluation</th>
<th>Score</th>
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</thead>
<tbody>
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<td>IP</td>
<td>DTN</td>
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<td>Robustness</td>
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<td>Latency</td>
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<td>Complexity</td>
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<td><strong>Total Score</strong></td>
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<td>41.5</td>
<td>71</td>
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</table>


DTN Latency and Throughput - NASA

End-to-end (IP): Must wait for complete path

DTN: Incremental progress without end-to-end path

TCP/UDP Latency

TCP/UDP Throughput

DTN Latency

DTN Throughput

Time
DTN VS IP intermediary nodes
FR 1 Communication architecture must be capable of transmitting and receiving data \textit{simultaneously} and \textit{non-simultaneously (store-and-forward)} between the Earth, Moon, and Mars

\textbf{DR 1.1} The mission shall provide real time (light-time delay with additional delay less than 1 second) relay of data from the Lunar and Martian environments to Earth-based communications networks.

\textbf{DR 1.2} The mission shall provide global surface telecommunications coverage (>99%) of the Lunar and Martian surface.

\textbf{DR 1.3} The mission shall provide simultaneous telecommunications availability (>99%) of the Lunar and Martian surface.

\textbf{DR 1.4} The mission shall provide simultaneous telecommunications availability (>99%) of the Lunar and Martian orbit.

\textbf{DR 1.5} The mission shall provide the ability to relay data between mission segments (Earth/Lunar/Martian communication networks).

\textbf{DR 1.6} The mission shall allow for high speed data transmission between the Moon and Mars, with threshold and objective rates to be 50 Mbps and 500 Mbps, respectively.

\textbf{DR 1.7} The mission shall allow for high speed data transmission between the Moon and Earth, with threshold and objective rates being 500 Mbps and 5 Gbps, respectively.
FR 2 Satellite constellations around the Moon and Mars must be able to provide communication and vehicle control capabilities on their surfaces and in their orbits.

DR 2.1 The mission shall provide the ability to command Lunar and Martian surface vehicles.

DR 2.2 The mission shall provide the ability to command Lunar and Martian orbiting vehicles.

DR 2.3 The mission shall provide simultaneous communication support to 5 or more locations on the Lunar Surface and 10 or more locations on the Martian Surface.

DR 2.4 The mission shall provide non-simultaneous store and forward (within six hours of transmission) communication support of 10 or more locations on the Lunar Surface and 20 or more locations on the Martian Surface.

DR 2.5 The mission shall provide simultaneous communication support of 10 or more space vehicles in Lunar Orbit and 15 or more space vehicles in Martian Orbit.

DR 2.6 The mission shall provide non-simultaneous store and forward (within six hours of transmission) communication support of 20 or more space vehicles in Lunar Orbit and 30 or greater space vehicles in Martian Orbit.
**FR 3** Communication network must ensure safety of and be collaborative with *existing* and *future communications infrastructure*.

**DR 3.1** The mission shall utilize existing NASA communications infrastructure wherever possible.

**DR 3.2** The mission shall not interfere with the operational capabilities of the Lunar Gateway.

**DR 3.3** The mission shall be capable of supporting Lunar Gateway communications signals.

**DR 3.4** The mission shall be capable of interfacing with government and/or commercial communications infrastructure.

**DR 3.5** The mission shall comply with FTC/ITU regulations.
## Laser vs RF Trade Study

### 5.2.2 Trade Study Evaluation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Evaluation RF Coms</th>
<th>Evaluation Laser Coms</th>
<th>Score RF Coms</th>
<th>Score Laser Coms</th>
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<tr>
<td>Range and Coverage</td>
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<td>10</td>
<td>4</td>
<td>40</td>
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<td>Bandwidth and Frequency</td>
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<td>Total Score</td>
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<td>94</td>
<td>75</td>
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Table 20: Communications Method Trade Study Surface To Constellation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Evaluation RF Coms</th>
<th>Evaluation Laser Coms</th>
<th>Score RF Coms</th>
<th>Score Laser Coms</th>
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<td>Power Requirements</td>
<td>1</td>
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<td>8</td>
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<td>Range and Coverage</td>
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<td>63</td>
<td>82</td>
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Table 21: Communications Method Trade Study Interplanetary
## Link Difficulty Summary NASA Deep Space Optical Communications

### Link difficulty summary of recent and planned NASA optical communications

<table>
<thead>
<tr>
<th></th>
<th>Data rate (Mb/s)</th>
<th>Distance (AU)</th>
<th>Link difficulty (Mb/s-AU²)</th>
<th>Link difficulty (dB-Mb/s-AU²)</th>
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<tr>
<td><strong>LLCD</strong></td>
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<tr>
<td>Downlink</td>
<td>622.0</td>
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<tr>
<td>Uplink</td>
<td>20.0</td>
<td>2.70E-03</td>
<td>1.46E-04</td>
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<td><strong>LCRD</strong></td>
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<td><strong>DSOC</strong></td>
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<td>Downlink</td>
<td>267.0</td>
<td>2.00E-01</td>
<td>1.07E+01</td>
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<td>Uplink</td>
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<td>8.08E+01</td>
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Source: NASA Fact Sheet: Deep Space Optical Communications (DSOC)
[https://www.nasa.gov/sites/default/files/atoms/files/fs_dsoc_factsheet_150910.pdf](https://www.nasa.gov/sites/default/files/atoms/files/fs_dsoc_factsheet_150910.pdf)
<table>
<thead>
<tr>
<th>Mission</th>
<th>Laser</th>
<th>Wavelength</th>
<th>Other parameters</th>
<th>Application</th>
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<tr>
<td>Semi-conductor Inter-satellite Link Experiment (SILEX) [52]</td>
<td>AlGaAs laser diode</td>
<td>830 nm</td>
<td>60 mW, 25 cm telescope size, 50 Mbps, 5 µrad divergence, direct detection</td>
<td>Inter-satellite communication</td>
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<tr>
<td>Ground/Optical Lasercomm Demonstration (GOLD) [27]</td>
<td>Argon-ion laser/GaAs laser</td>
<td>Uplink: 514.5 nm Downlink: 830 nm</td>
<td>1.5 W, 0.6 m and 1.5 m transmitter and receiver telescope size, respectively, 1.024 Mbps, 25 µrad divergence</td>
<td>Ground-to-satellite link</td>
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<tr>
<td>RF Optical System for Aurora (ROSA) [53]</td>
<td>Diode pumped Nd:YVO4 laser</td>
<td>1064 nm</td>
<td>6 W, 0.135 m and 10 m transmitter and receiver telescopes size, respectively, 320 Kbps</td>
<td>Deep space missions</td>
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<tr>
<td>Deep Space Optical Link Communications Experiment (DOOCE) [54]</td>
<td>Master oscillator power amplifier (MOPA)</td>
<td>1058 nm</td>
<td>1 W, 10-20 Mbps</td>
<td>Inter-satellite/space mission</td>
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<tr>
<td>Mars Orbiter Laser Altimeter (MOLA) [55]</td>
<td>Diode pumped Q switched Cr:SLM:YAG</td>
<td>1064 nm</td>
<td>3.4 W, 420 µrad divergence, 10 Hz pulse rate, 638 bps, 850 µrad receiver field-of-view (FOV)</td>
<td>Altimetry</td>
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<tr>
<td>General Atomics Aeronautical Systems, Inc., (GA-ASI) &amp; TESAT [56]</td>
<td>Nd:YAG</td>
<td>1064 nm</td>
<td>2.6 GHz</td>
<td>Remotely piloted aircraft (RPA) to LEO</td>
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<td>Allair UAV-to-ground Lasercomm Demonstration [57]</td>
<td>Laser diode</td>
<td>1550 nm</td>
<td>200 mW, 2.5 Gbps, 19.5 µrad angular error, 10 cm and 1 m in uplink and downlink telescope size, respectively</td>
<td>UAV-to-ground link</td>
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<tr>
<td>Mars Polar Lander [58]</td>
<td>AlGaAs laser diode</td>
<td>880 nm</td>
<td>100 mJ energy in 100 ns pulse, 2.5 kHz rate, 128 kbps</td>
<td>Spectroscopy</td>
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<tr>
<td>Cloud-Aerosol Lidar and Infrared PathfinderSatellite Observation (CALIPSO) [59]</td>
<td>AlGaAs laser diode</td>
<td>355 nm/1064 nm</td>
<td>118 mJ energy, 20 Hz rate, 24 µm pulse</td>
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<td>Klue’s Optical Downlink to Odyssey Mariner (KDOM) [60]</td>
<td>AlGaAs laser diode</td>
<td>847 nm/810 nm</td>
<td>50 MHz, 40 cm and 4 m transmitter and receiver telescopes size, respectively, 5 µrad divergence</td>
<td>Satellite-to-ground downlink</td>
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<td>Airborne Laser Optical Instrument (LOI) [61]</td>
<td>Lasereye laser diode</td>
<td>800 nm</td>
<td>300 mW, 50 Mbps</td>
<td>Aircraft and GEO satellite link</td>
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<td>Tropospheric Emission Spectrometer (TES) [62]</td>
<td>Nd:YAG</td>
<td>1064 nm</td>
<td>360 W, 5 cm telescope size, 6.2 Mbps</td>
<td>Interferometry</td>
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<td>Galileo Optical Experiment (GOPEX) [25]</td>
<td>Nd:YAG</td>
<td>532 nm</td>
<td>230 mJ, 32 µm pulse width, 110 µrad divergence, 0.6 m primary and 0.2 m secondary transmitter telescope size, 12.19 x 12.19 mm charge coupled device (CCD) array receiver</td>
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<tr>
<td>Engineering Test Satellite VI (ETSI-VI) [62]</td>
<td>AlGaAs laser diode (downlink) Argon laser (uplink)</td>
<td>Uplink: 530 nm Downlink: 830 nm</td>
<td>13.6 mW, 1.024 Mbps bidirectional link, direct detection, 7.5 cm spacecraft telescope size, 1.5 m Earth station telescope</td>
<td>Bi-directional ground-to-satellite link</td>
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<tr>
<td>Optical Inter-orbit Communications Imaging Test Satellite (OCITS) [63]</td>
<td>Laser Diode</td>
<td>819 nm</td>
<td>200 mW, 2.048 Mbps, direct detection, 25 cm telescope size</td>
<td>Bi-directional inter-orbit link</td>
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<td>Solid State Laser Communications in Space (SSLACOS) [64]</td>
<td>Diode pumped Nd:YAG</td>
<td>1064 nm</td>
<td>1 W, 630 Mbps return channel and 10 Mbps forward channel, 15 cm telescope size, coherent reception</td>
<td>GEO-GEO link</td>
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<td>Short Range Optical Inter-satellite Link (SROIL) [65]</td>
<td>Diode pumped Nd:YAG</td>
<td>1064 nm</td>
<td>40 W, 1.2 Gbps, 4 cm telescope size, BPSK homodyne detection</td>
<td>Inter-satellite link</td>
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<td>Mars Laser Communications Demonstration (MLCD) [66]</td>
<td>Fiber laser</td>
<td>1064 nm and 1076 nm</td>
<td>5 W, 1-30 Mbps, 30 cm transmitter telescope size and 5 m and 1.6 m receiver telescope size, 64 PPM</td>
<td>Deep space missions</td>
</tr>
</tbody>
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| Table II |
| WAVELENGTHS USED IN PRACTICAL FSQ COMMUNICATION SYSTEMS |
NASA Deep Space Network (DSN) Ground Station Locations

Fig. 15. Locations’ of NASA Deep Space Network and ESA ESTRACK sites
NASA Lunar Communication 2020

- Optical comm with 1 Gbps return rate; 100 Mbps forward
- RF: Up to 250 Mbps return data and 100 Mbps forward data using 40 GHz Ka-band
## Constellation Architecture Trade Study

<table>
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<th>Criteria</th>
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Preliminary Constellation Design Groundtracks