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

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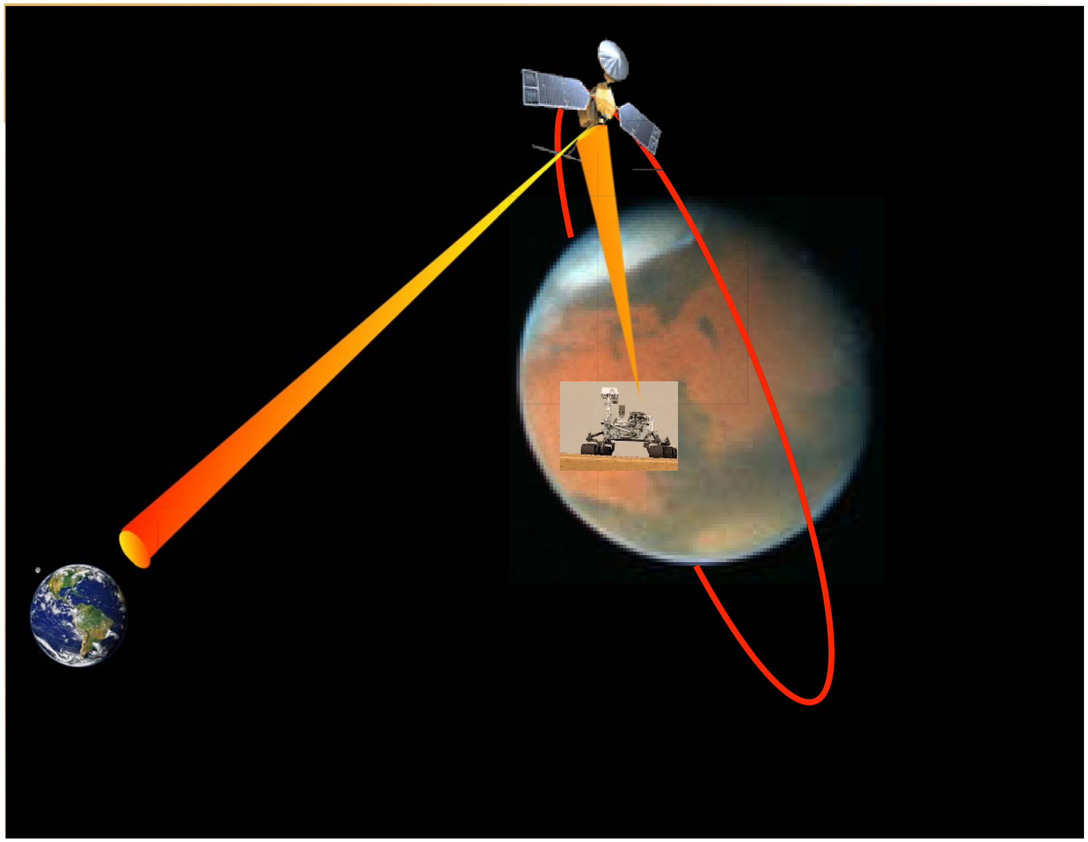
Agenda

- **Introduction**
- Acquisition, tracking, beam pointing
- Link availability
- Days in the life

Deep Space links:

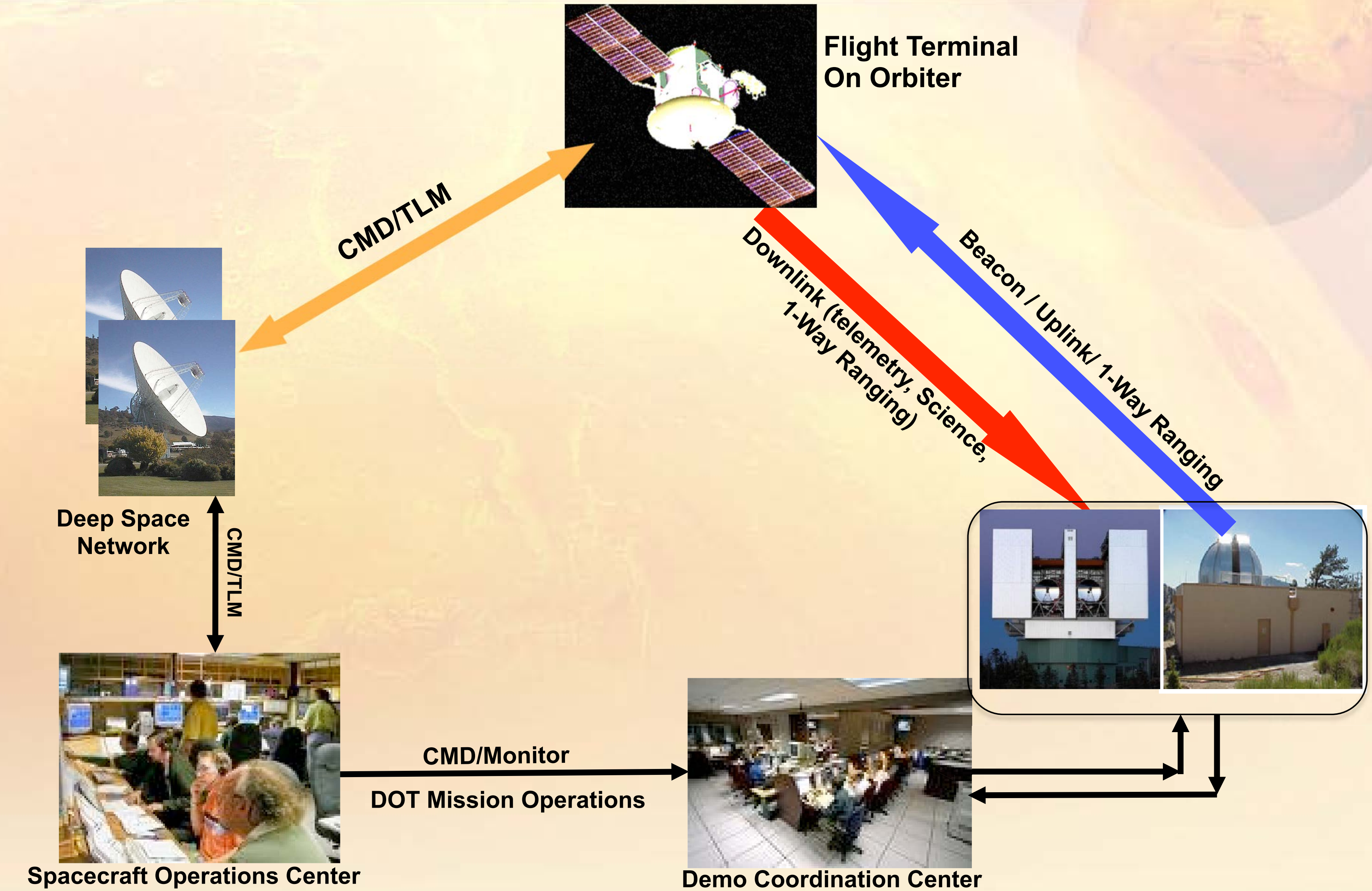
- Trunkline uplink (forward) – Direct detection, or coherent detection
- Trunkline downlink (return) – Direct or Coherent Detection
  - Space-to-space
  - Space-to-Earth
- Planet surface-to-orbiter
- Planet surface-to-Earth
- Surface-to-surface
- Emergency forward (optical)
- Emergency return (optical)



Unique Features of Deep Space Lasercom

Consideration	Near-Earth Links	Deep-Space Links
Transmit beam width (typical)	> 10 µrad	<10 µrad
Round-trip light-time	seconds	minutes to hours
Beacon irradiance at spacecraft	3-10 nW/m^2	1-3 pW/m^2 (very dim)
Point-ahead angles	2-5 beam widths	15-60 beam widths
Receiver optical signal-to-background power (daytime operations)	> +10 dB	< -10 dB (extremely faint)
Laser peak power (required for PPM)	<20 W	> 500 W

Deep Space Optical Link Architecture



Key ConOps Drivers

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

Channel Capacity Variations

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

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Operational Modes; Objectives

Mode	*Objective*

On-orbit Calibration	• Boresight flight terminal line-of-sight to spacecraft reference axis
	  • Characterize acq/trk detector array (e.g. pixel to pixel variation)
	  • Calibrate centering of vibration isolation platform
	  • Calibrate point-ahead mirror and its algorithm

Standby	• Maintain health and safety of flight optical terminal • Keep track of current time and upcoming mode changes
Acquisition	• Acquire the beacon uplink signal and stabilize it on the detector
Uplink	• Track the uplink beacon signal to enough accuracy to keep pointing losses to <TBD (~2dB)
Downlink	• Point the downlink beam to the ground station
Safe	• Recovering via RF or optical comm

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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Ground Network Options

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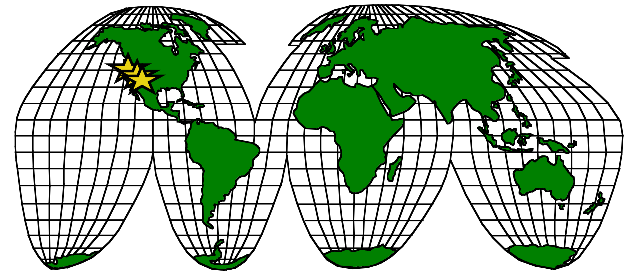
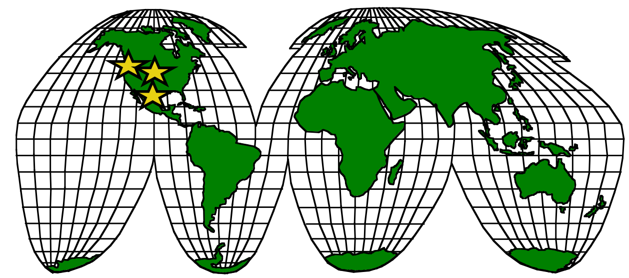
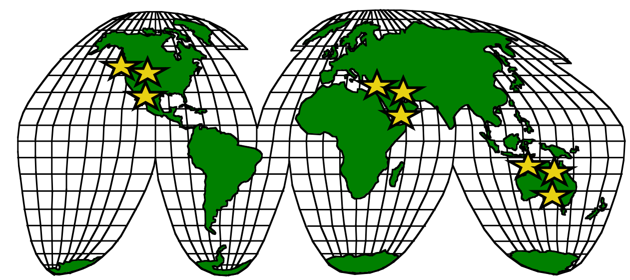
1. **Single site with largest possible aperture**
   - e.g. 3 telescopes co-located in one site
     - 3X effective aperture diameter; high channel capacity
   - ~20% availability in 24 hours
     - ~60% clear weather, available 8 hours only
   - Lowest infrastructure cost
   - Requires adequate storage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



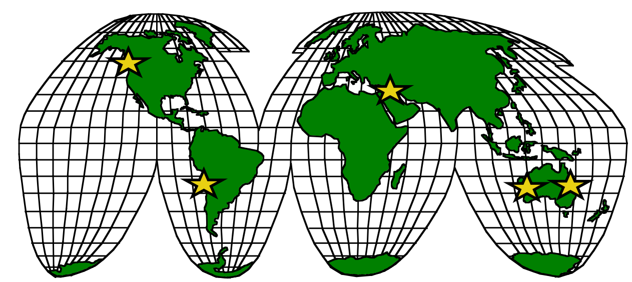
2. **Three sites distributed in the same geographic area, but in weather diverse sites**
   - ~30% availability in 24 hours (92% x 0.33)
   - Moderate cost of 3 stations



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



Mars Downlink Data Volume Example

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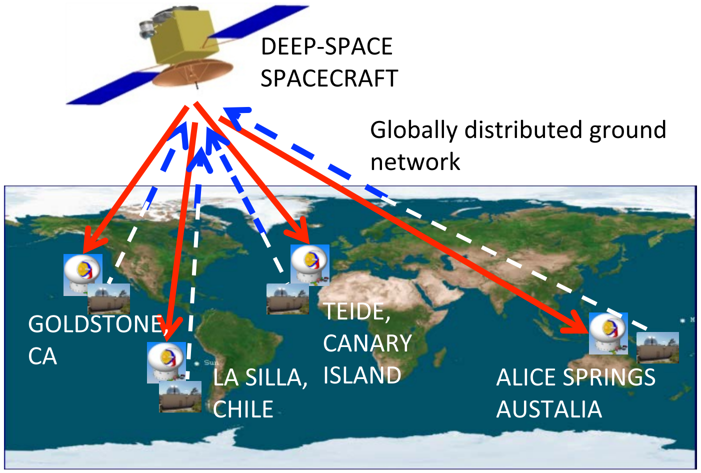
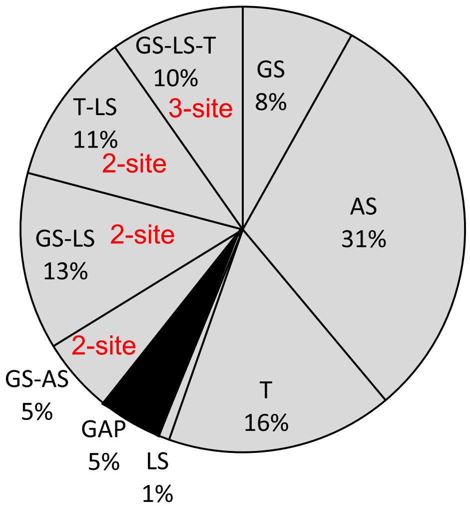
- Assumed a set of 4 complementing ground transceiver network
  - Goldstone (GS), CA,
  - Tiede (T), Canary Islands,
  - La Silla (LS) , Chile,
  - Alice Springs (AS), Australia
- 4-site gap-time is 5%
- Numerous instances of 2- or 3-site coverage
- Link performance degradation at SEP <10°



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

Station	Single Site (Tbits)	4-Site Ground Network (Tbits)
GS	260-329	856 - 1374
AS	330-441	
T	193-227	
LS	554-648	

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

Operational Boundary Conditions

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

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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Operations Strategies

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

Days In The Life (partial list)

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

Summary

- **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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