Mars Laser Communication Demonstration Project

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MLCD
Mars Laser Communication Demonstration

Outline

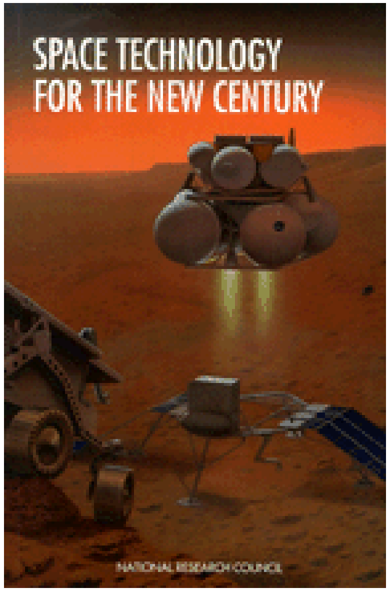
- Introduction
- System Considerations
- Flight Terminal
- Ground Network
  - Receive
  - Transmit
- Summary

Background

- NASA recognizes a future need for high data rate communications to outer planet distances from .1 to 40 AU to support sub-surface exploration, in-situ measurements, and the eventual expansion of human space flight Laser communications has the potential to meet this long term need
- NASA's Office of Space Science (OSS) commissioned a study to investigate the feasibility of conducting a laser communications mission to Mars
- In May 2003, the Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL), the Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL) completed a joint study of laser communications from Mars
- In May 2003, OSS directed a Mars laser communications demonstration mission be established, with GSFC as the lead for project management, JPL as the lead for ground terminal development and operations and MIT/LL as the lead for the Mars Terminal development and systems engineering
- The MLCD project was formed and established as a baseline instrument on the Mars Telecommunications Orbiter (MTO) project, scheduled to launch in October 2009

Why Optical Communications?

NRC & Space Science Enterprise



"Wideband, high data-rate communications over planetary distances could enable live transmissions of high-resolution images from robotic rovers, orbiters, and astronauts on missions to other planets."

"Because optical communications' potential must be demonstrated and quantified under operational conditions, the Optical Communications Initiative will demonstrate critical space and ground technologies in this decade and perform a flight demonstration of high-data-rate communication from Mars in the 2010 timeframe."

Why Optical Communications?

Potential Benefits of Optical Communications

- Increasing the frequency (shorter wavelength) has potential for
  - Smaller components (mass & volume)
  - Higher gains for given aperture size (less power required)
  - Space-based receivers in the future
- High data rates enabling missions of the future which produce high data volumes
  - Synthetic Aperture Radar
  - Hyperspectral Imagers
  - Streaming video (HDTV)

Customers for this Demo

- Optical communications systems designers
- Deep space communications systems designers
- Future users
  - Mission designers
  - Mission managers
    - Flight systems
    - Mission operations
  - NASA Management
  - Scientists
- What are the questions that are heard from the potential customers?
  - Most often
    - Can you point that narrow beam?
    - What do you do when it is cloudy?
  - Also heard
    - What about space laser lifetime? (More generically, all components)
    - How does it compare to current RF technology?
    - What will it really cost?

MLCD Mission Statement

The Mars Laser Communication Demonstration (MLCD) will demonstrate optical communications between Mars and Earth and thereby gain the knowledge and experience base that will enable NASA to design, procure, and operate cost-effective future deep space optical communications systems

Key Objectives - 1

- Develop and validate an end-to-end systems engineering approach to deep space optical communication
  - Develop and maintain link budgets
  - Conduct trades between aperture, detector efficiency, coding, modulation, etc.
- Understand channel
  - Turbulence
  - Solar radiance
  - Weather (clouds, humidity, etc)
    - There will be weather outages at any given terminal so how do we handle them
- Understand operability
  - Ability to predict expected performance for link in advance of actual link establishment
  - Acquisition of signal both on Earth and in space
  - Set-up, tear-down
  - End-to-end data transmission (buffering, retransmission, protocols, etc.)
  - Handovers & weather handling

Key Objectives - 2

- Development of a space qualified flight terminal that can
  - Demonstrate component and system technologies
    - Lasers, modulators, amplifiers, optics, etc
  - Point, acquire and track
  - Serve as pathfinder for future flight terminals
- Develop Earth terminals to close the link and investigate
  - Detectors
  - Pointing, acquisition and tracking
  - Sunshades
  - Sufficient collection capability
  - Location
  - Pathfinder for future earth terminals
- Collect sufficient information to build (have industry build) operational optical communications systems in the future

MLCD Level-1 Requirements

Full Success Criteria

1. Demonstrate downlink communications from Mars at 10 Mbps with a goal of 30 Mbps at 1E-6 BER, with an absolute minimum of 1 Mbps (i.e. everywhere in the orbit)
2. Demonstrate uplink communications to Mars at 10 bps @ 1E-6 BER
3. Measure and characterize the system performance over the following conditions during cruise and over 1/2 Mars year on orbit
   a) S/C operational scenarios (cruise and in orbit)
   b) Day/Night
   c) Weather and atmospheric conditions
   d) Ranges and SEP angles
   e) Zenith angles
4. Demonstrate that the Mars terminal can operate to within 2 degrees SPE angle and the ground terminal to within 3 degrees SEP angle
5. Demonstrate handover to a second terminal

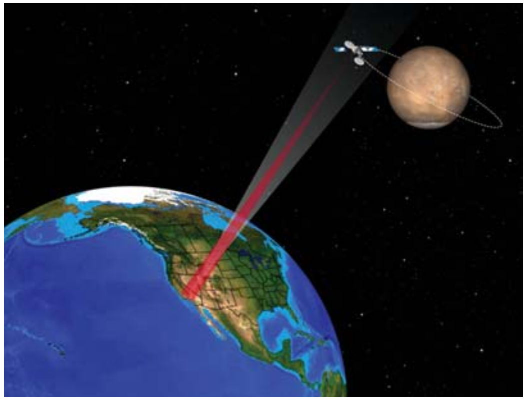
Minimum Success Criteria

1. Demonstrate downlink communications from Mars at 1 Mbps at 1E-6 BER
2. Measure and characterize the system performance over the following conditions during cruise and two weeks on orbit
   a) Day/Night
   b) Weather and atmospheric conditions
   c) Ranges and SEP angles
   d) Zenith angles
3. Demonstrate that the ground terminal can operate to within 12 degrees SEP angle
4. Demonstrate through analysis a handover strategy

MLCD Summary

Mars Laser Communication Demonstration

MLCD



MLCD Important Features

- Demonstrate deep-space Optical Communications from Mars.
- Flight Terminal will be a payload on the Mars Telecom Orbiter spacecraft.
- Launch Date: October 2009
- Demonstration Lifetime Period: 2 years, Extended life time TBD yrs

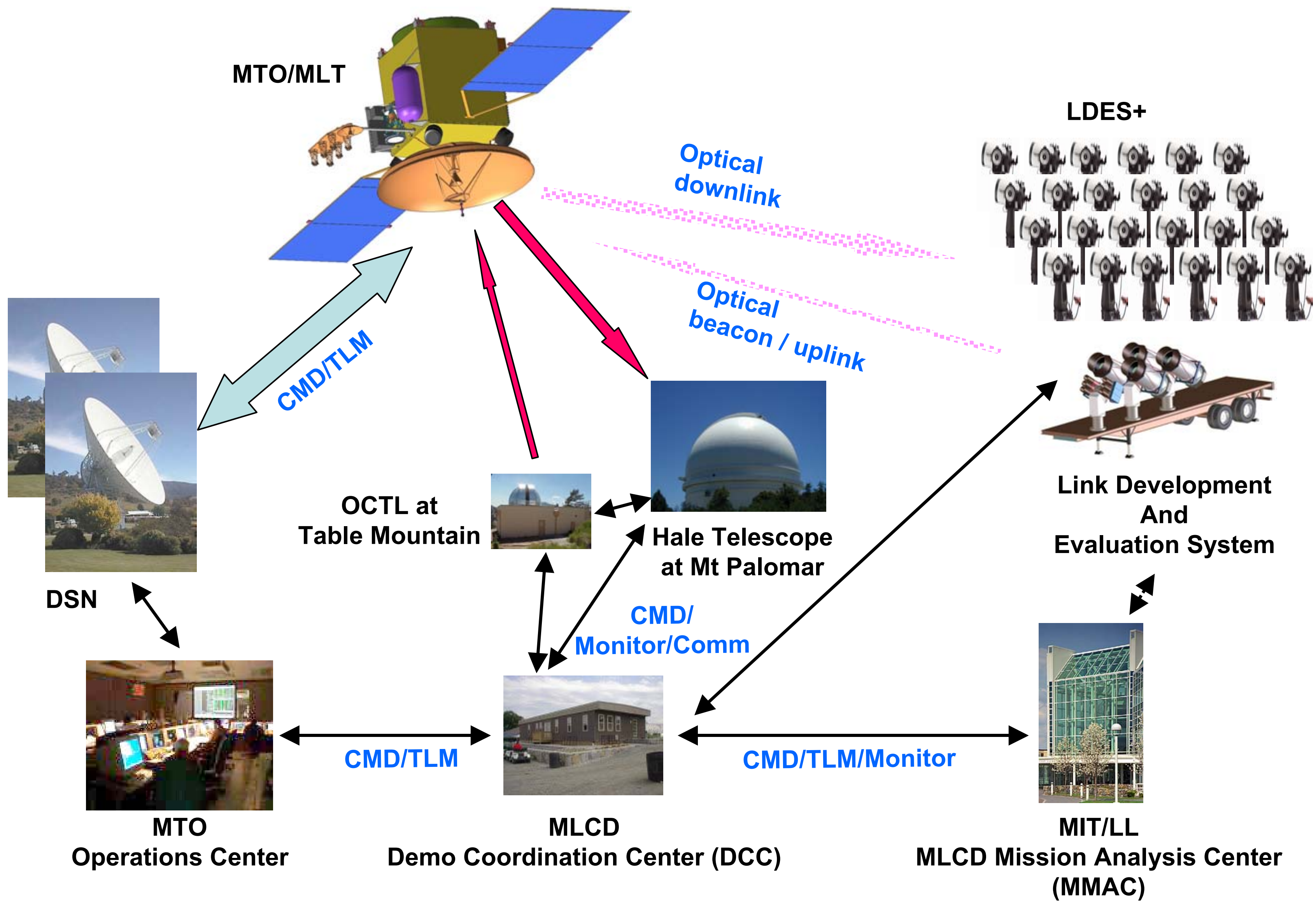
Demonstration Requirements

- Down-Link rate of at least 10 Mbps with a goal of 30 Mbps at 1.0E-6 BER from Mars, with an absolute minimum of 1 Mbps at all points in the orbit.
- Forward-Link of at least 10 bps at 1.0E-6 BER to Mars.
- Measure and characterize the system performance over a variety of conditions during cruise and over at least 1/2 Mars year on orbit. Verify and validate link performance models.
- Characterize system performance near the Sun such that the maximum outage due to solar exclusion is less than 30 days. This requires the ground terminal to work to within 3 degrees of the Sun.
- Demonstrate weather mitigation techniques and handover strategies.

Programmatics

- GSFC has project lead responsibility
  - Project manager, systems engineering, delivery of flight terminal and co-investigator from GSFC
- MIT/LL will implement flight terminal, lead systems engineering activities and provide co-investigator
- JPL will implement operational ground terminals and mission operations, lead the investigation and data analysis with PI, provide deputy project manager

MLCD System Block Diagram



Mars Laser Communication Demonstration

MLCD

Operations: Clear Day In California

Operations: Clouds--Switch to Arizona

Where Are We Now?

Mars Laser Communication Demonstration

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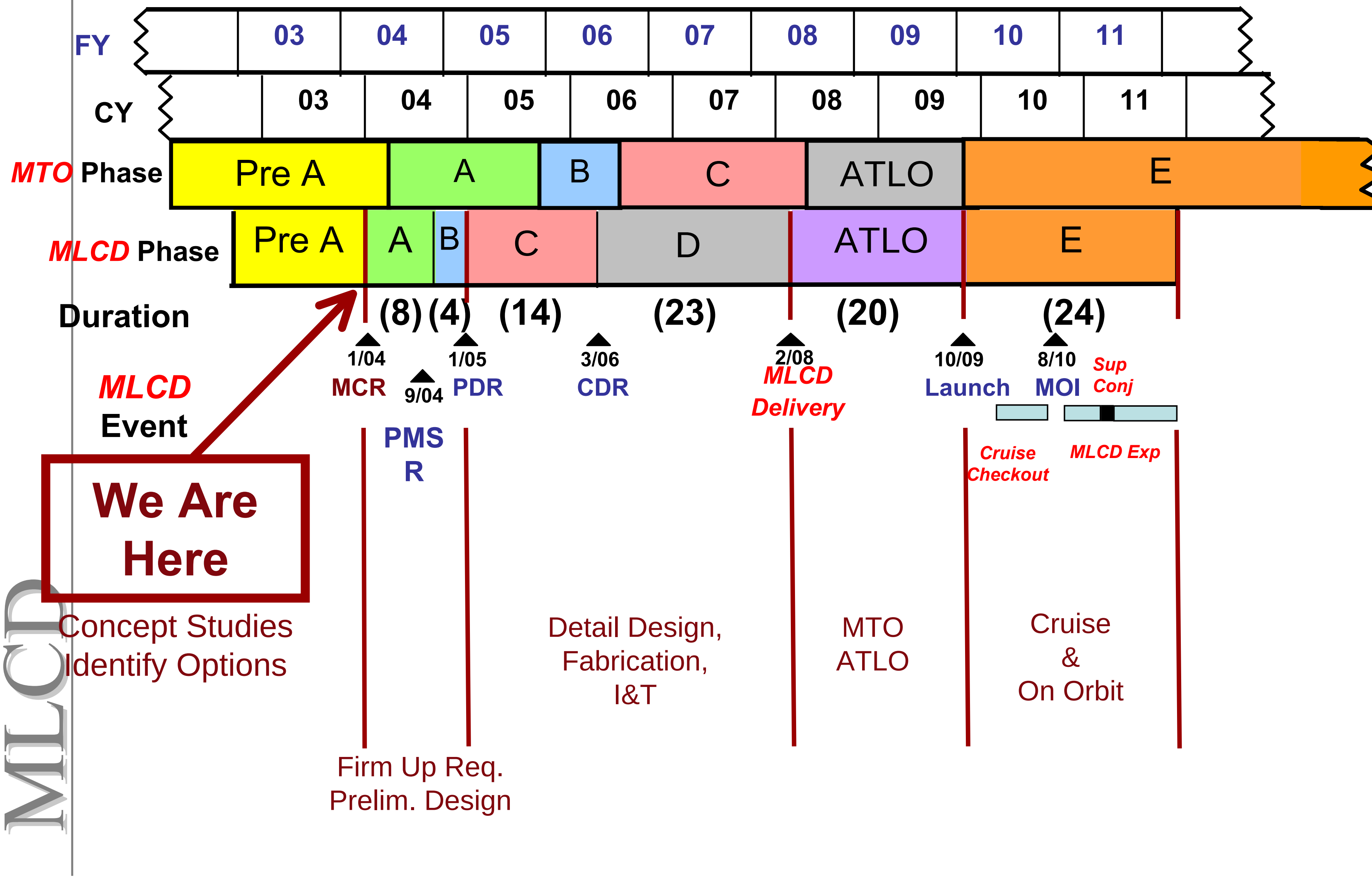
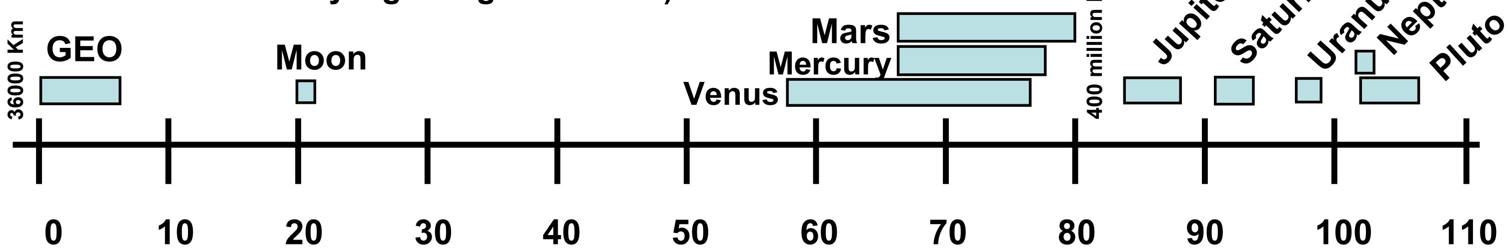


System Considerations

Why is Deep Space Lasercom Different from Near Earth Lasercom?

(For constant efficiency signaling at all rates)

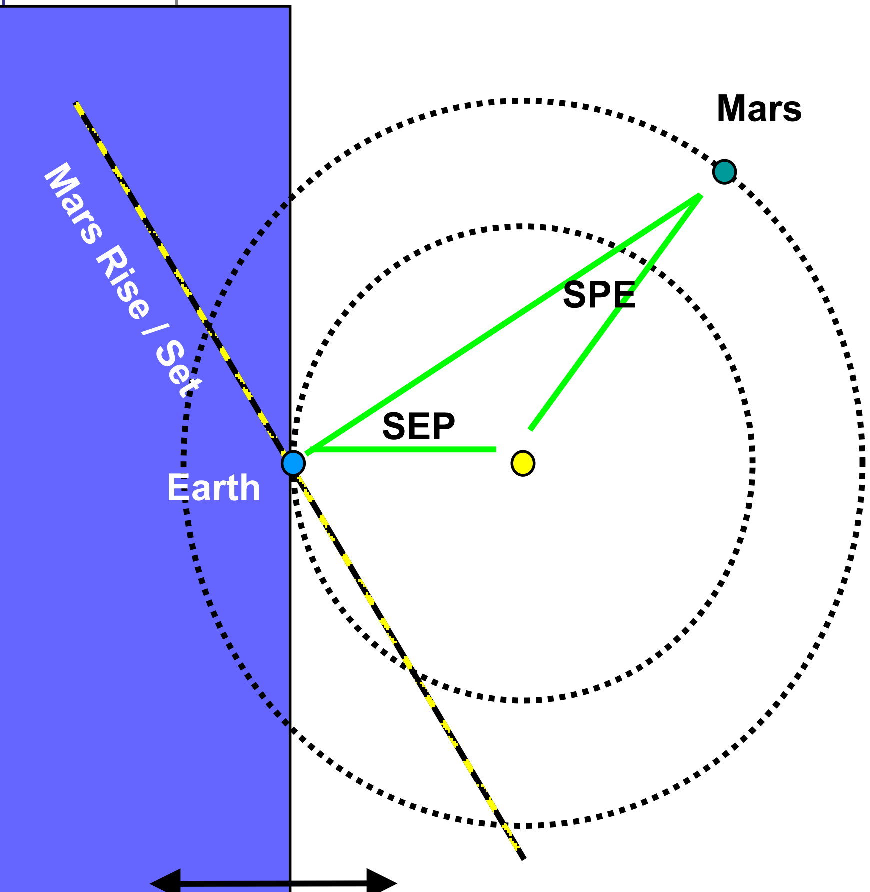


10 Gbps GEO | using present near-earth lasercom technology | 100 bps Mars | 0.25 bps Pluto

Need 50 dB !

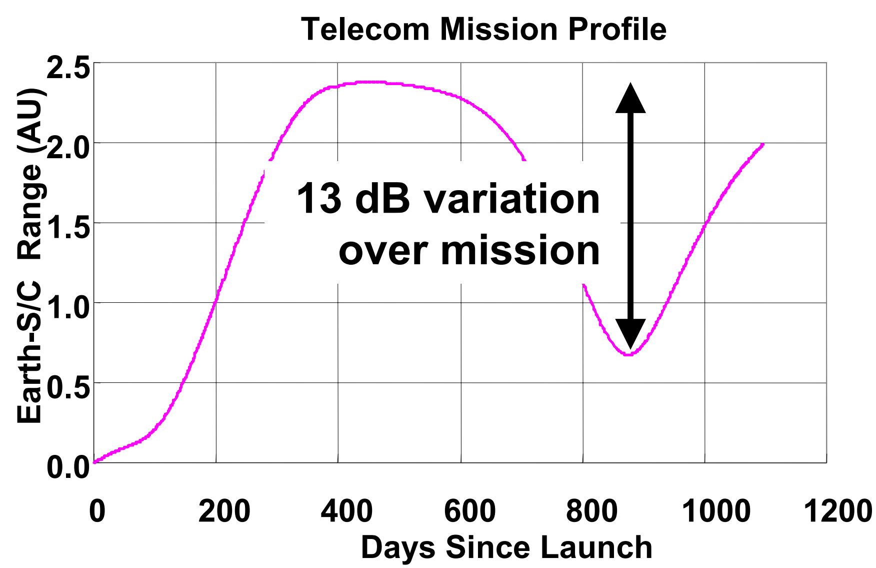
10^6 Gbps GEO | required class of lasercom technology | 10 Mbps Mars | 25 Kbps Pluto

MTO Distances and Angles



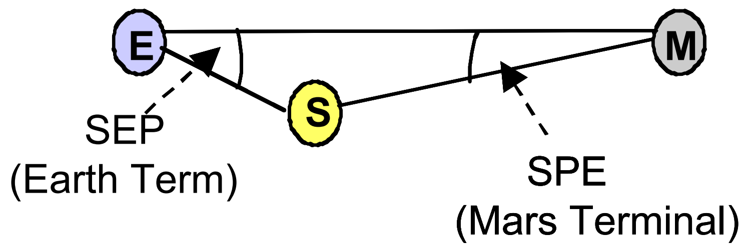
Day-night operation adds about 10 dB of variation in efficiency (ground-based)

- Mars is seen in daylight most of the mission
- Mars is simultaneously at its farthest distance and at its smallest SEP angle
- 1 Mbps at maximum distance in daylight is the design driver



Operating Close to the Sun

Solar Conjunction

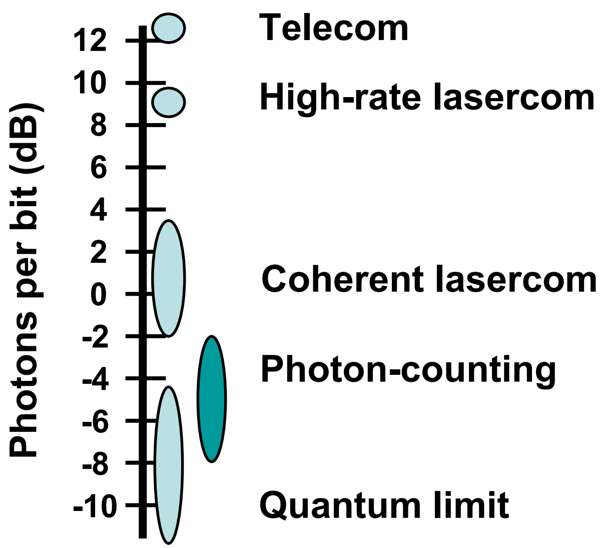


¥SEP angle small → Affects Earth Terminal
¥SPE angle small → Affects Mars Terminal
¥At Mars: SEP slightly > SPE

SPE Angle (Degrees)	SEP Angle (Degrees)	Outage (Days)
2	2.8	23
4	5.7	49
6	8.6	75
8	11.4	100
10	14.3	126
15	21.9	190
20	28	255

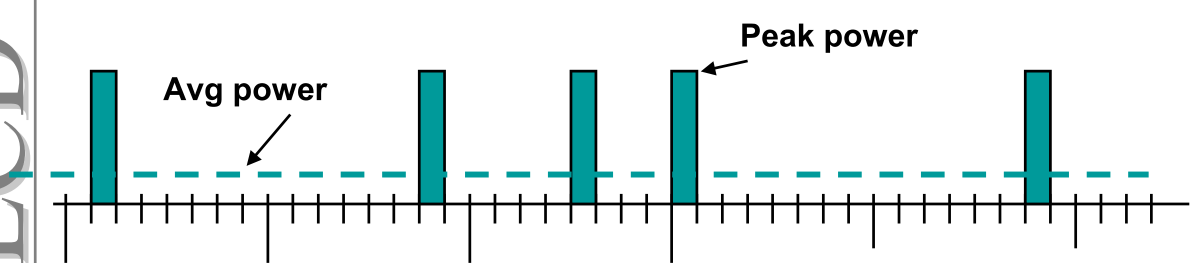
Efficient Signaling and Coding

Lasercom Efficiencies



- Very near quantum limit
- Does not require extreme spectral or spatial purity
- Well-matched to pulsed modulation (high peaks pwrs)
- Note: -7 dB photons per bit = 5 BITS PER PHOTON!

Example: 8-ary Pulse Position Modulation



Pulse in one of 8 = 2^3 slots (3 bits)

Very powerful Error-Correction Coding and Decoding implicitly deduces when a pulse is missed or when noise fills in incorrect pulses

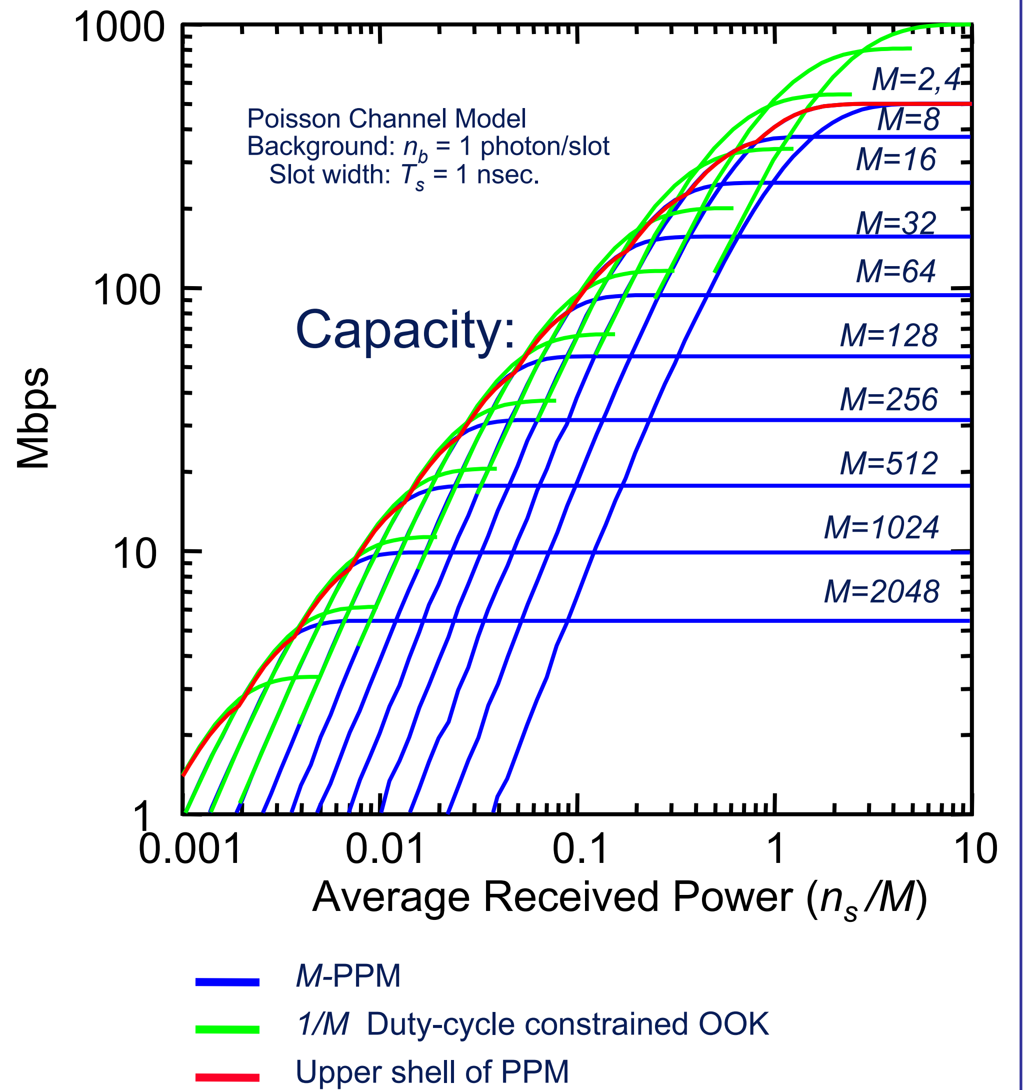
Code Design Methodology

Code parameter optimization:

- Identify avg. receiver power n_s/M, background rate n_b, from link table.
- Choose optimal PPM size M^* from upper shell of capacity curves for appropriate model.
- Identify achievable data rate R_d.
- Identify code rate:
  $R_c = R_d\, M^*\, T_s / \log_2 M^*$
- Design code for rate R_c, M^*-PPM.

Design methodology allows for added constraints:

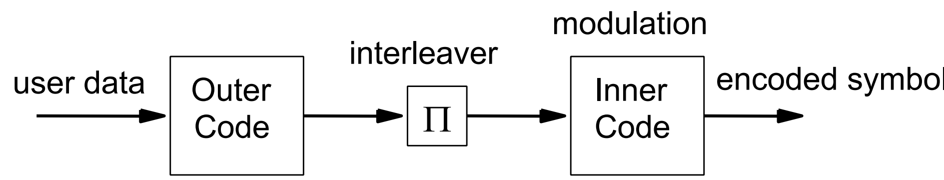
- Upper bound on uncoded symbol error rate (truncate each curve)
- Upper bound on maximum M (omit some curves)
- Lower bound on deadtime between symbols (extend curve with slope 1)



Abbreviated History of Optical Coding

Many proposed codes for the deep space optical cannel can be placed in the following framework:

Encoder:



	Outer code	Inner code
RSPPM	**Reed-Solomon**, of length $(n,k) = (M^a\text{-}1,k)$ $a=1$, [McEliece, JPL, 1981] $a>1$, [Hamkins,Moision, JPL, 2003]	 M-PPM M-PPM
SCPPM	**Convolutional code** Non-iterative, [Massey, 1981] M-ary conv., non-interative, [Mecherle, USC, 1986] Iterative decoding, [Moision, Hamkins, JPL, 2002]	 M-PPM M-PPM accumulate+M-PPM
Turbo-PPM LDPC-PPM	**Turbo codes, LDPC codes** PCCC, 2-PPM, [Kiasaleh, JPL/UTD, 1998] PCCC, M-PPM [Hamkins, JPL, 1999] LDPC, M-PPM [Moision, Hamkins, JPL]	 2-PPM M-PPM M-PPM

Uplink Beacon for Pointing & Stabilization

- An Uplink Beacon from Earth will provide 3 functions for the Mars terminal:
    1) Pointing reference (Requires 1-Hz track bandwidth)
    2) Reference source for jitter rejection within terminal (Requires 200-Hz track BW)
    3) Uplink communications (Rates of 1 to 10's of Bits/second)

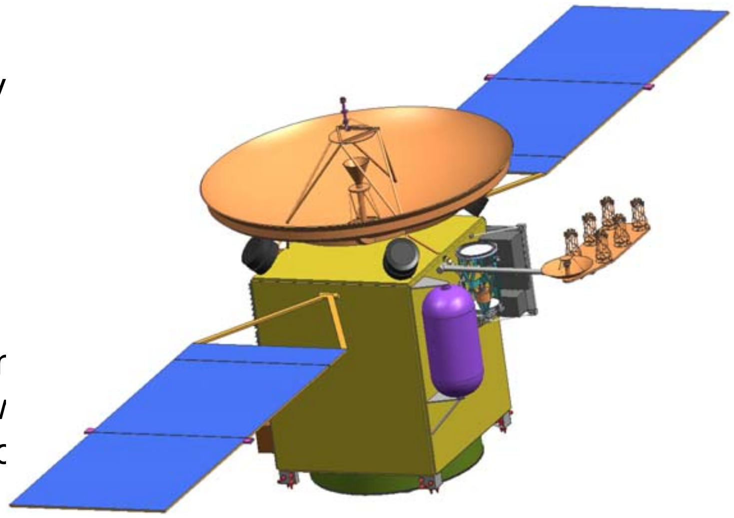
- Pointing / tracking at Mars is a design driver for the Mars terminal:
    - ➢ Uplink beacon makes Mars terminal simplest
    - ➢ Scalable to much longer distances, with inertial stabilization

- Challenges in pointing the Beacon:
    - ➢ Must understand relationship of optical centroid to fixed reference point on Mars
        - Requires fixed, or predictable, source function (albedo/illumination)
    - ➢ Must be able to accurately offset aimpoint from trackpoint (100's of microradians)
    - ➢ Must be able to track Mars in the presence of daytime sky background
    - ➢ Must contend with the effects of atmoshpheric turbulence

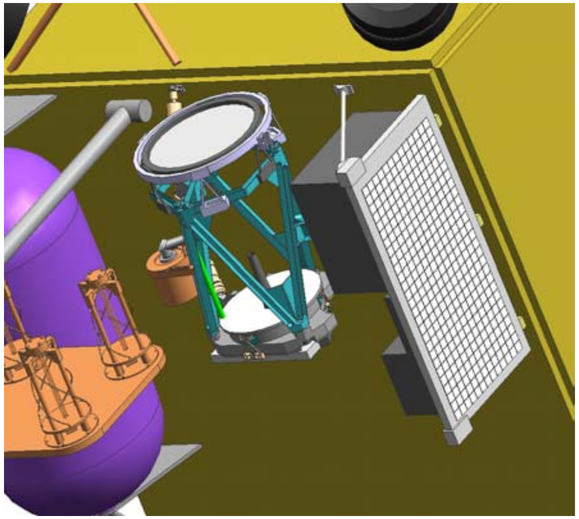
Mars Lasercom Terminal (MLT)

Flight Terminal Overview

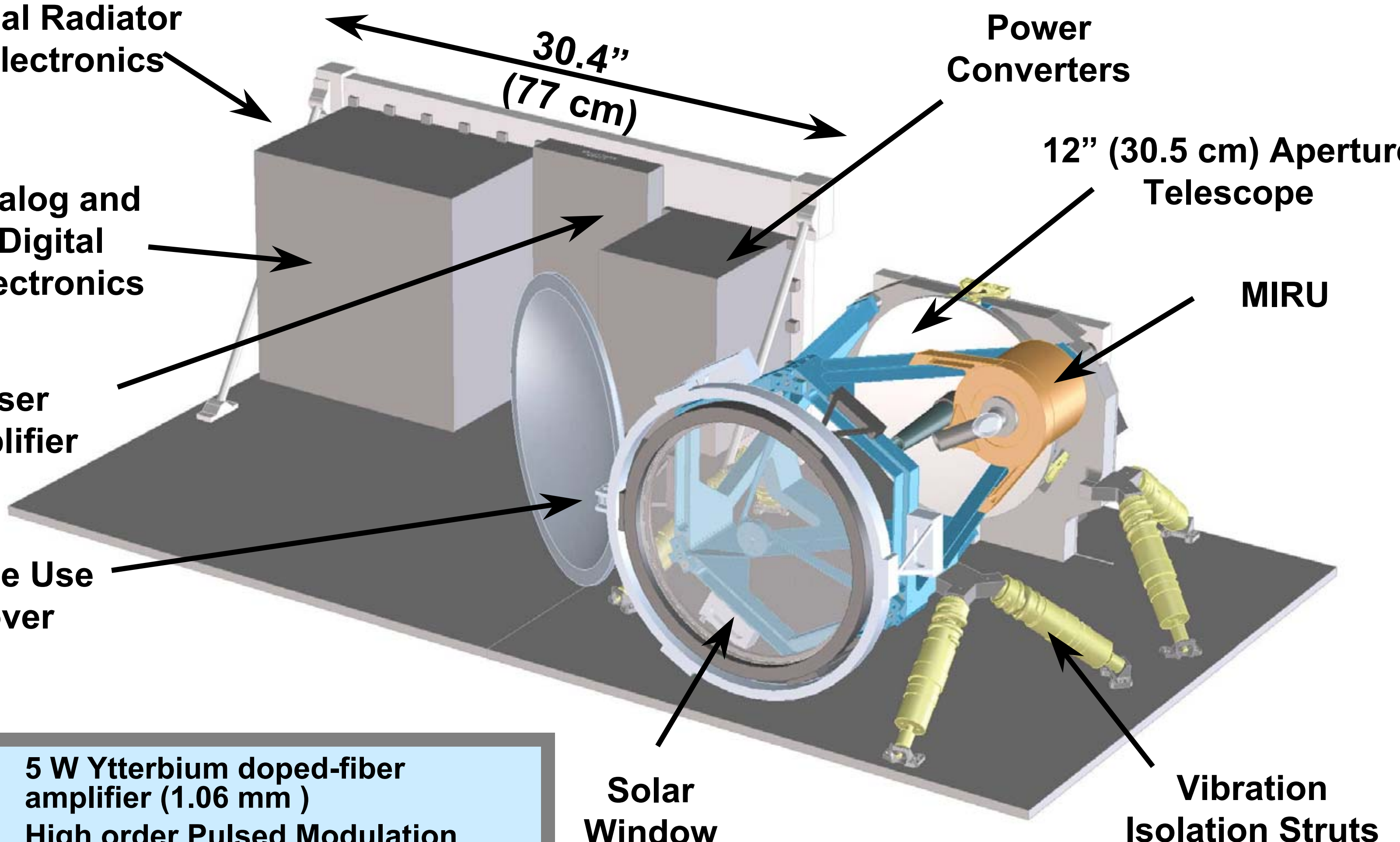
- GSFC has responsibility for flight terminal
  - Developed for GSFC by MIT Lincoln Laboratory
- Baseline design
  - 30 cm diameter terminal (telescope)
  - Coded Pulse Position Modulation
  - Fiber amplifier at 1064 nm wavelength
  - Relies upon uplink beacon from Earth for pointir reference. Uplink beacon signal may contain lov data rate modulation for transmitting non-interac instrument commands
  - Not to exceed 70 kg or 150 W



- Mounted with optical axis co-aligned with HGA electrical boresite.
  - Power provided for simultaneous operation with Ka DTE downlink.
  - Mechanical disturbance due to motion of proximity antenna gimbal may exceed payload jitter rejection capability.
    - Simultaneous operation of Electra data relay and OpComm not required.
- Data source
  - Internal PN sequence generator
  - Science & engineering data



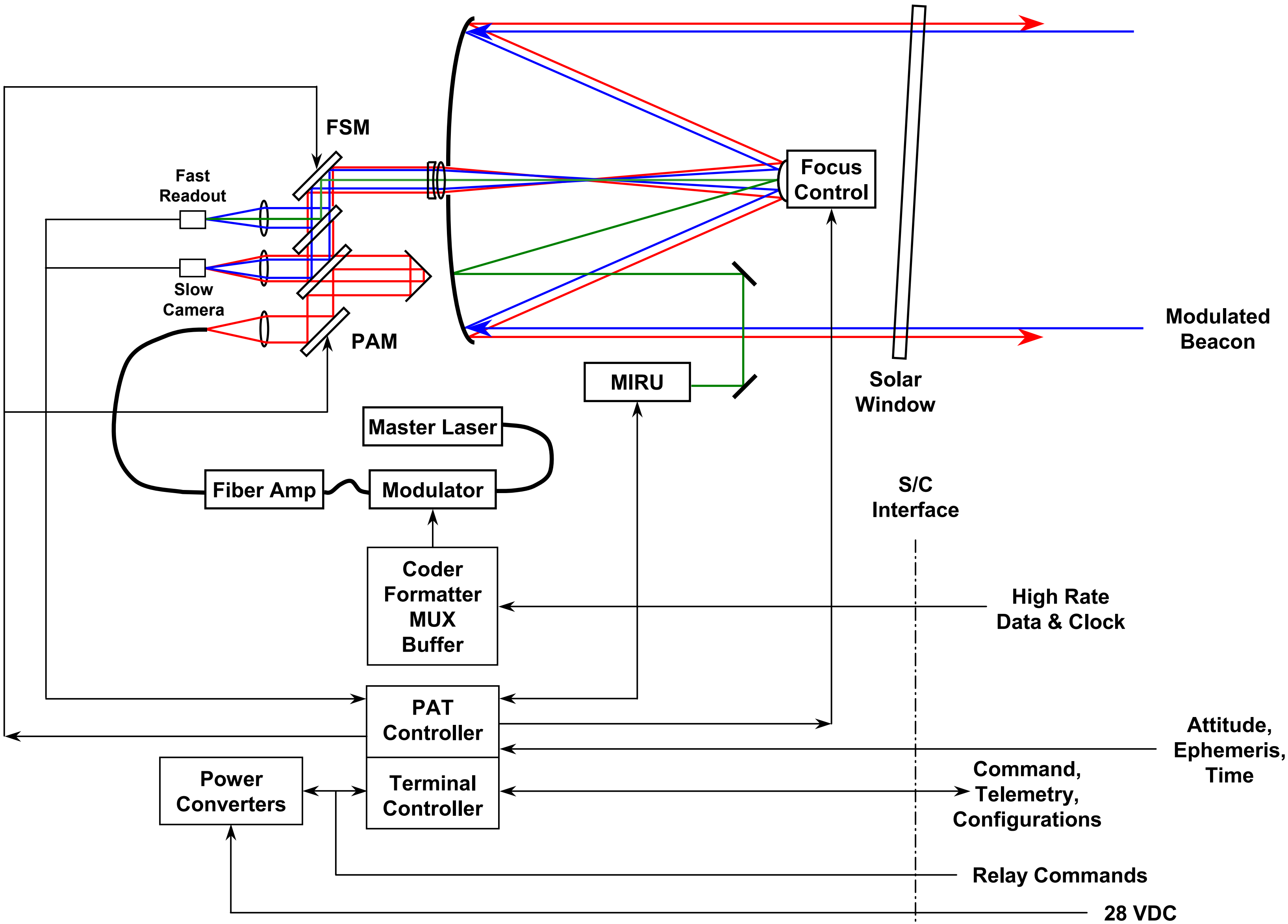
The Mars Terminal



- 5 W Ytterbium doped-fiber amplifier (1.06 mm)
- High order Pulsed Modulation with concatenated coding
- Hybrid inertial/beacon pointing & stabilization
- Approx 55 Kg and 130 Watts

Protective covers removed for clarity

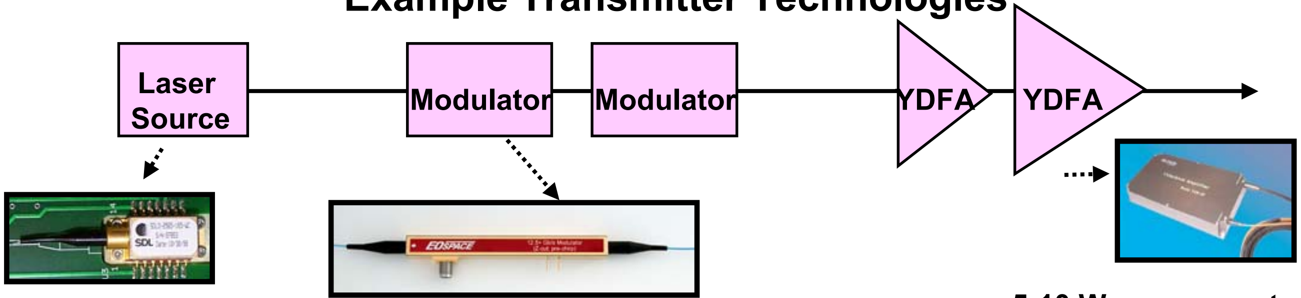
Flight Terminal Diagram



Transmitter

- Fiber-Coupled COTS Components for the Transmitter
- Photon Counting Detectors
- Pulsed Modulation with Near-Channel Capacity Achieving Codes
- Low Cost, Large Effective Area Receive Apertures

Example Transmitter Technologies



Semiconductor master laser
Fiber-grating stabilized

External modulator(s)
$LiNbO_3$ waveguide
Pulses < 1 nsec

5-10 W average output
Ytterbium Doped Fiber Amplifier
High peak power (300-1000 W)
~15% wall plug efficiency
Polarization-maintaining

- **1.06 μm is *currently* the best match of technology and system performance**
- **High peak power, space-ready amplifiers in ongoing development**

Ground Network

MLCD Ground Network Overview

OCTL
TMF

- Atmospheric Monitors
- Laser Safety System
- Monitor & Control

Hale
Palomar

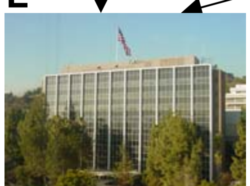
- Atmospheric Monitors
- Daylight Safety Assy.
- Monitor & Control

Array
TBD

LDES

- Atmospheric Monitors
- Daylight Safety Assy.
- Laser Safety System
- Monitor & Control

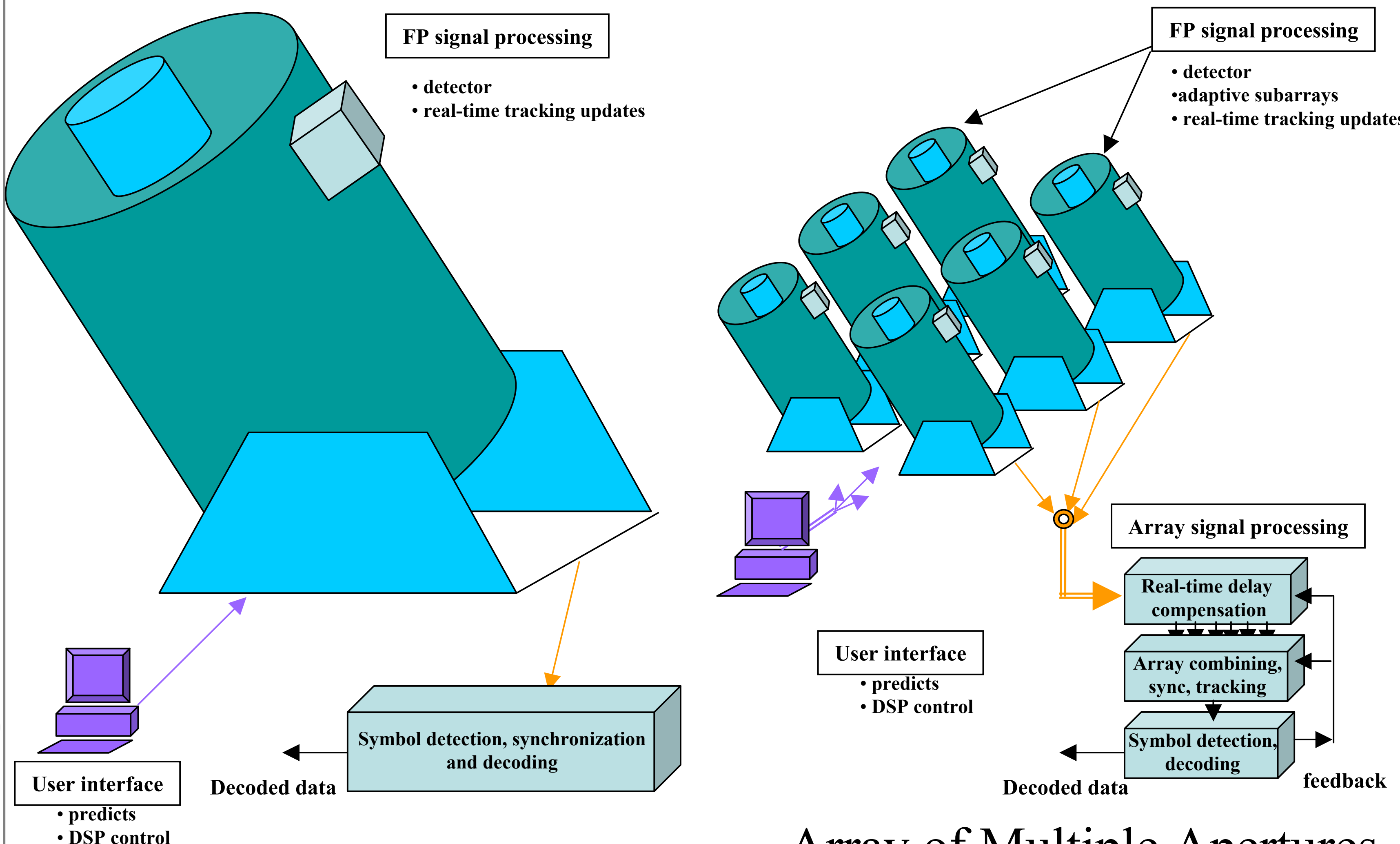
DCC
JPL



- MTO Ops
- DSN
- MIT/LL
- GSFC

- Provide MLT CMD/TLM processors and real-time displays
- Provide uplink Beacon for MLT
- Provide pointing data, sequencing information
- Provide ground terminal real-time displays
- Provide atmospheric monitors real-time displays
- Interface to DSN for science data readout
- Interface to MTO Ops for MLT CMD/TLM plus ops coordination
- Archive all received and monitored data
- Demonstration Lifetime Period: 2 years

Earth Receive Terminal(s) Options



Single Large Aperture

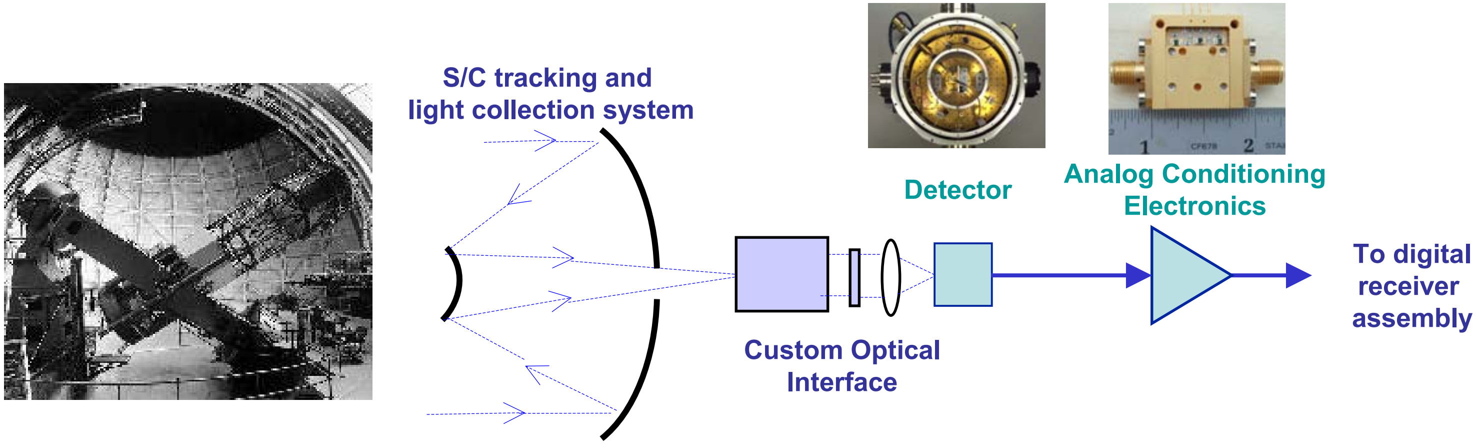
Array of Multiple Apertures

Detectors

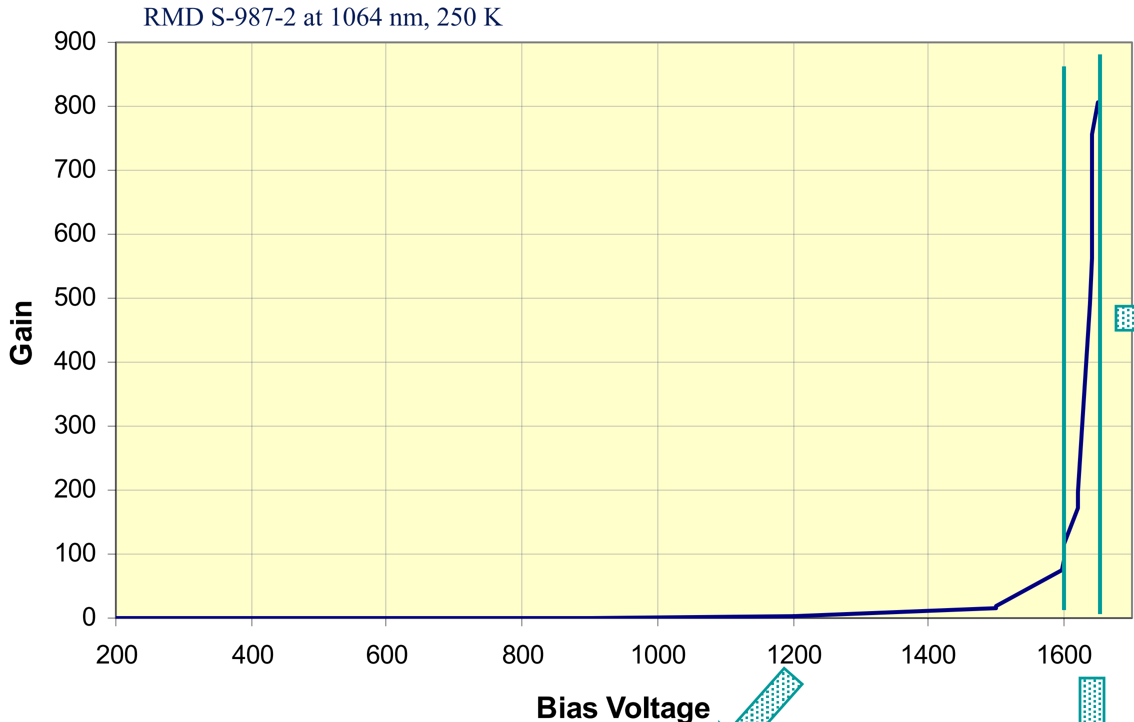
Mars Laser Communication Demonstration

MLCD

- Typical operation is in “photon starved” mode so need photon counting approach
- Avalanche Photodiode (APD) is detector of choice
  - Important parameters are detection efficiency and bandwidth
- Detector must match flight transmitter wavelength
  - presently near 1064 nm
- Must meet PPM link operational requirements
  - 1 ns minimum slot width
  - must operate in presence of high optical background

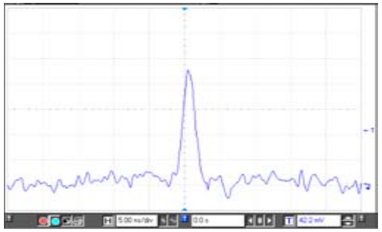


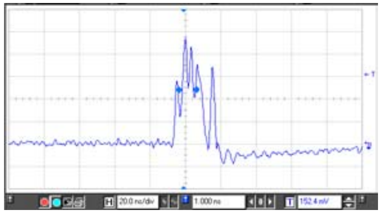
APD Operational Regimes



Geiger Mode
- typical gains > 50000
- longest pulsewidth (determined by external circuit)
- nonlinear signal response only good for photon counting

Linear Mode
- typical gains < 100
- lowest pulsewidth
- small signal pulsewidth has little dependence on gain
- presence of excess noise implies lower gains for optimal SNR

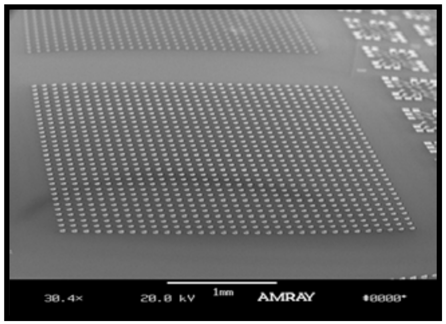




Sub-Geiger mode Mode
- typical gains between 500 and 5000
- mean pulsewidth relates to a gain-bandwidth product
- high gain is required for high detection efficiency,
  but execss noise is not a major factor for ‘photon counting’ operation
- local ionization assumption of standard McIntyre model is violated

Photon-Counting Detectors

- The ability to count individual photons is the key to making the system work efficiently

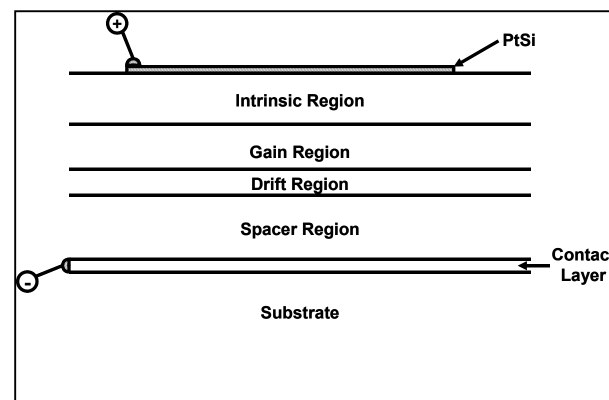


MIT/LL Geiger-Mode APD Detector

- < 1 nsec resolution
- Low noise (10 Khz, TE cooled)
- Detection efficiency .5-.8
- Refresh time limitation ~ 1 μsec
- Arrays up to 32x32

- **DRS VLPC detector** with increased PDE is the best candidate single element detector for use with the Hale telescope

- Undertake development to increase Visible Light Photon Counter (VLPC) Si:As device PDE @ 1064 nm to 50-60%
  - Fabricate* devices with platinum-silicide Pt-Si absorption layer
  - PDE scales with $1/\lambda^2$



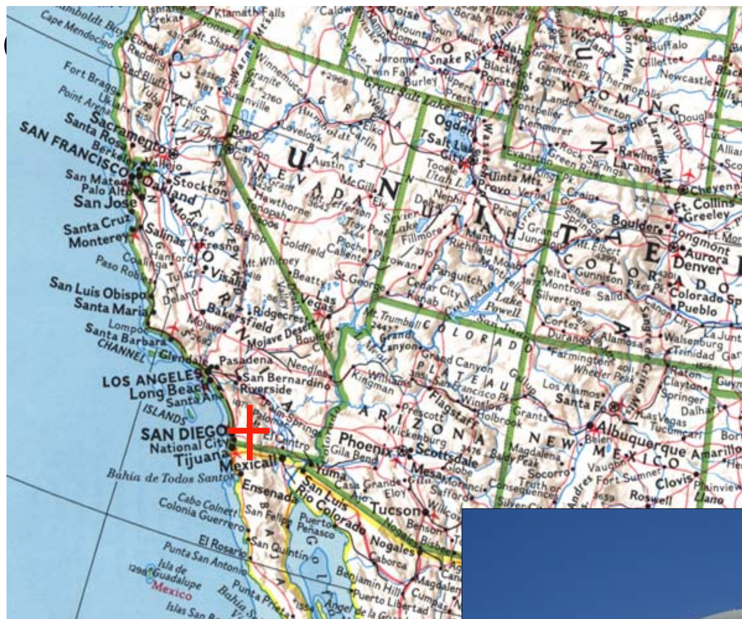
Proposed Near infrared photon counter device structure

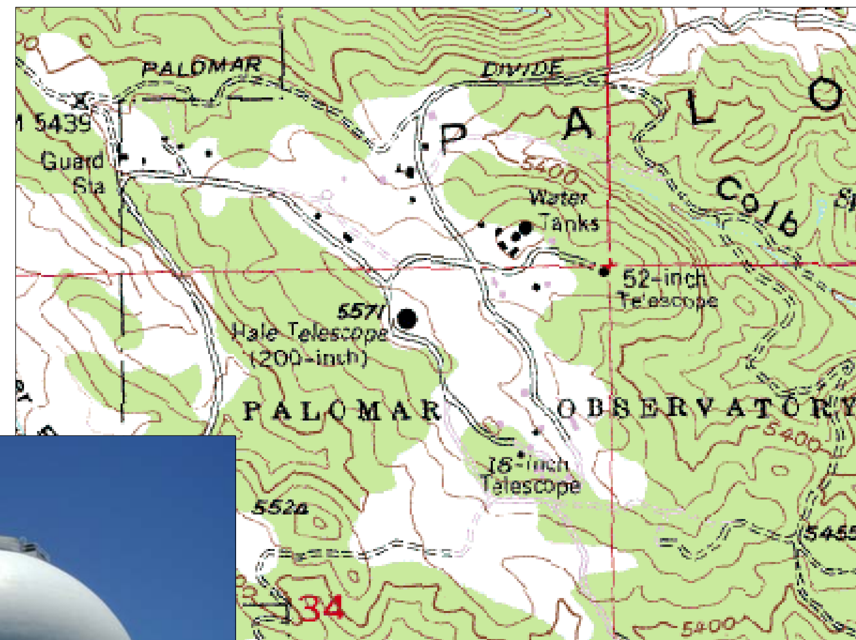
Introduction to Hale Telescope

Mars Laser Communication Demonstration

MLCD

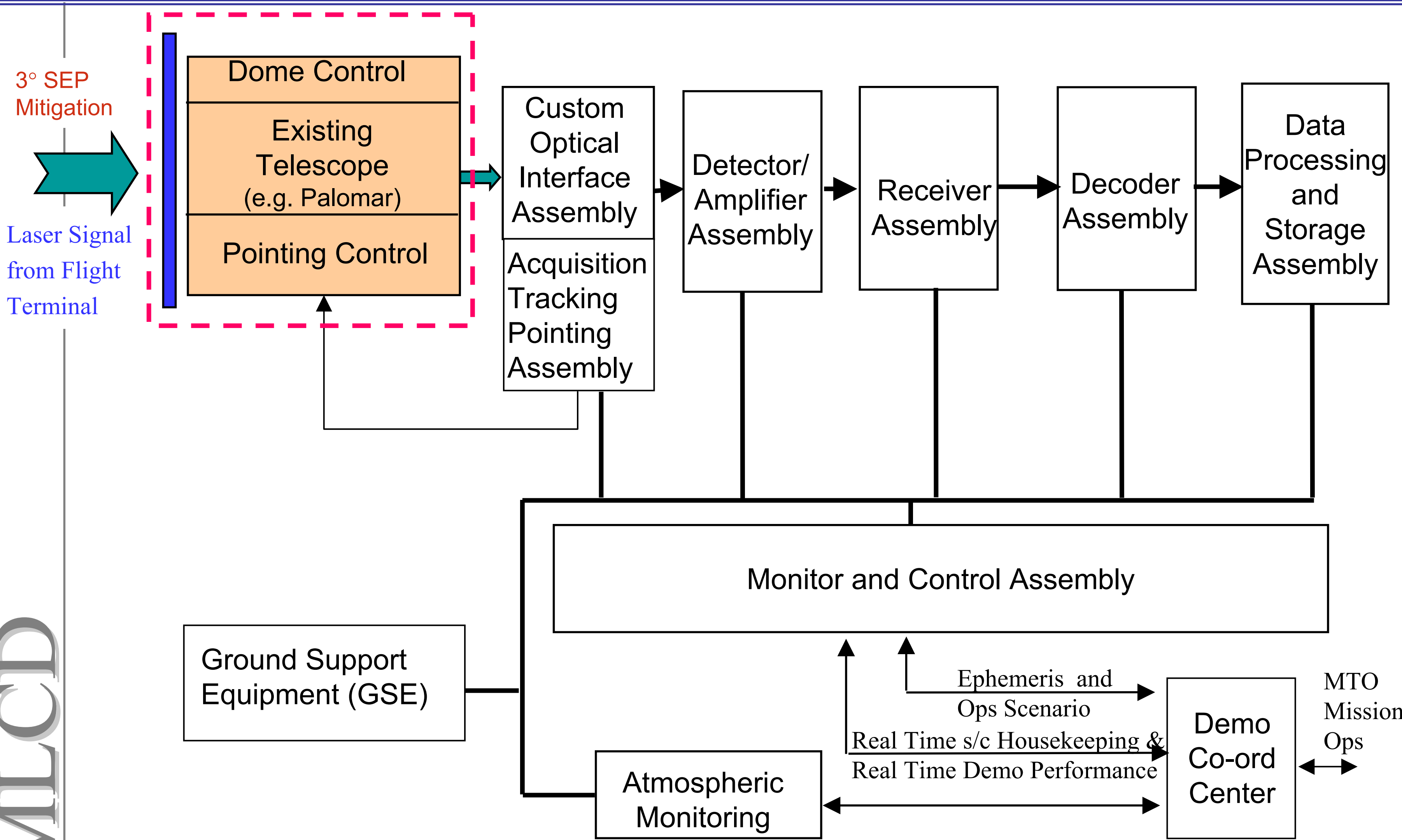
- **Base-lined 5-m diameter Hale telescope for receiving downlink laser**
- **Located at altitude of 1800 m above mean sea level in California**
- **Good** availability - 60-90% of the time**
- (





** Detail provided in backup charts

Ground Receive Terminal Conceptual Block Diagram



Mars Laser Communication Demonstration

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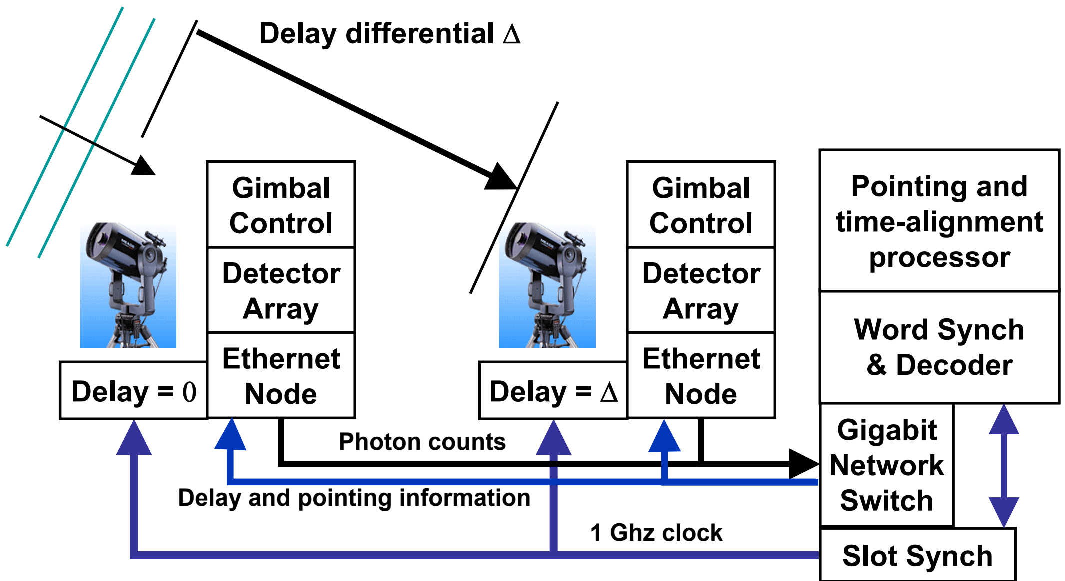
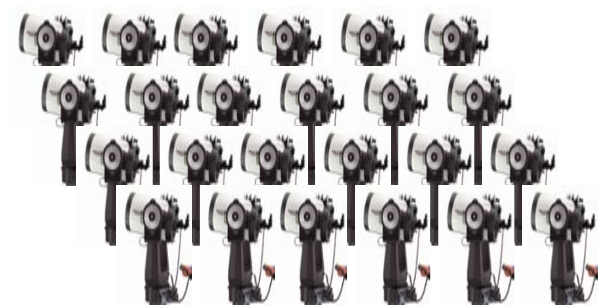
A Networked Array of Small Telescopes



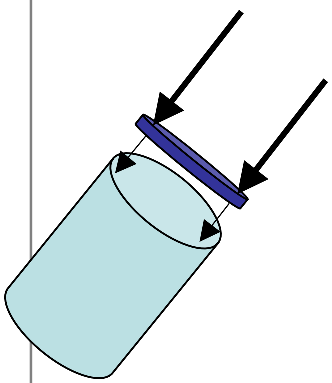


Concerns:
- Diagnostic testing, upkeep, and maintenance for a large array.
- Effectively combing the individual signals.

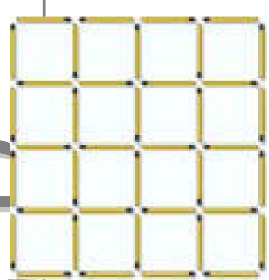
Lincoln Distributed Optical Receiver Architecture (LDORA)

- **Individual near-COTS telescopes**
  - ❑ 22 @ 16” supports 1 Mbps at Maximum Range from Mars (75 @ 16” supports 3 Mbps)
  - ❑ Could go with fewer, but larger size telescopes. Decision would be based on cost.
- **Shed-like housings for small groups with a sun shade on each telescope**
  - ❑ Sun shade is straight forward due to each telescope’s small aperture
- **Matched well to the Geiger Mode APDs detector array.**
- **Digital network connections**

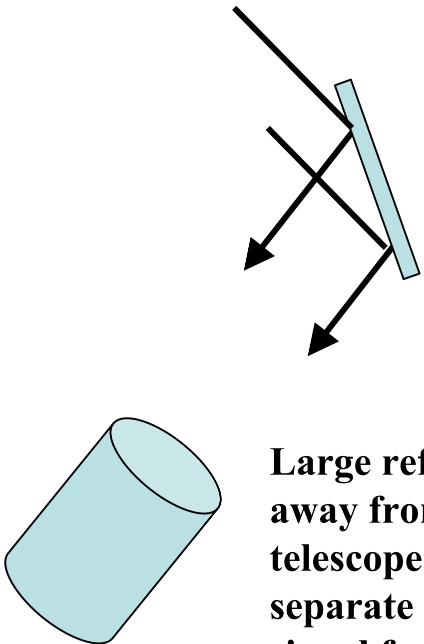
Possible Mitigation Techniques



Large 1064-nm narrow-bandpass pre-filter array.

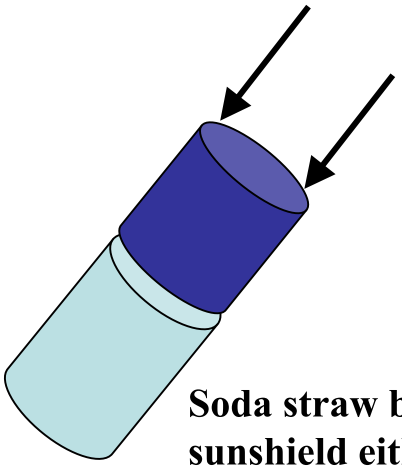


Concerns:
- Need panel sizes between 0.5-1 m
- Overall weight and size
- Aberrations caused by filter and mount

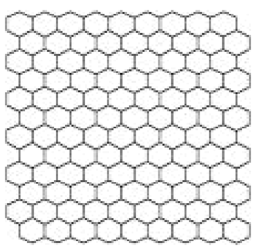


Large reflector away from the telescope to separate Mars signal from Sunlight.

Concerns:
- Implementation w/ existing telescopes
- Daytime background light entering telescope
- Scattering due to mirror contamination
- Wind-loading effects



Soda straw bundle sunshield either internal or external to telescope.



Concerns:
- Anticipate major implementation problems with existing telescopes
- Overall weight and size
- Heat buildup and removal

Near Sun Pointing of Telescope

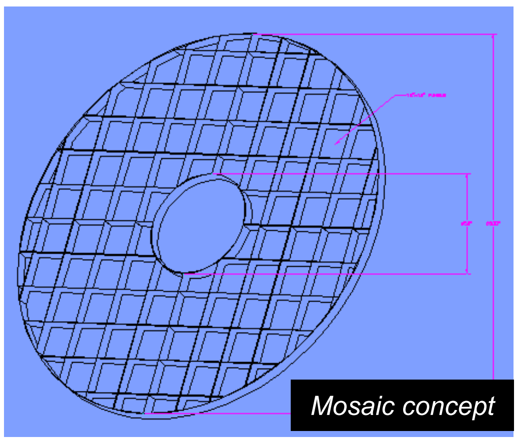
Solar Filter Options & Stray Light

Mars Laser Communication Demonstration

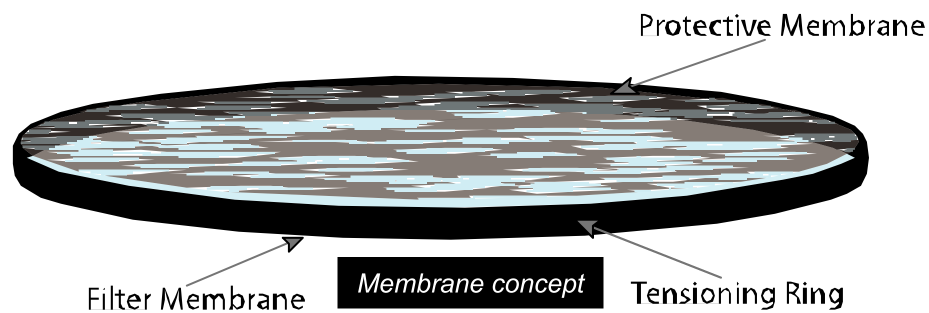
MLCD

- Selected solar filter approach to mitigating structural overheating for further study
  - 55-fold reduction in incident solar power with 30-nm bandpass filter centered at 1064 nm
  - 90% transmission at 1064 nm

- Two implementation approaches being pursued
  - Mosaic of dielectric coated 0.5 x 0.5-m glass panels
  - Polymer membrane with dielectric coating



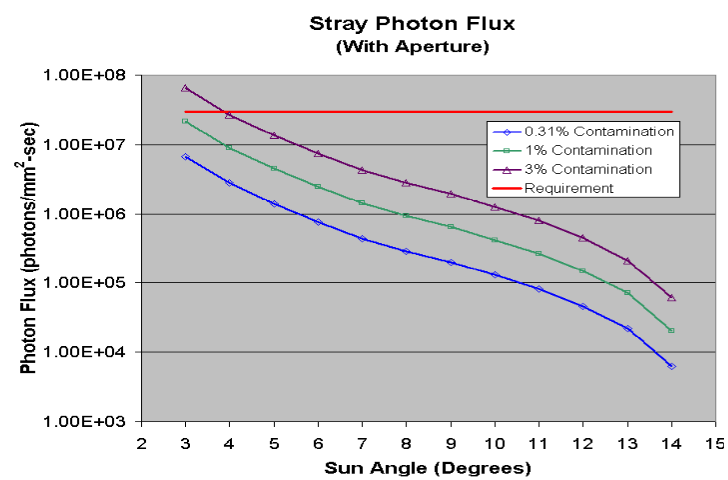
Mosaic concept



Membrane concept

- Determined that stray light from primary mirror restricted to ≤ 3E7 photons/mm^2-sec

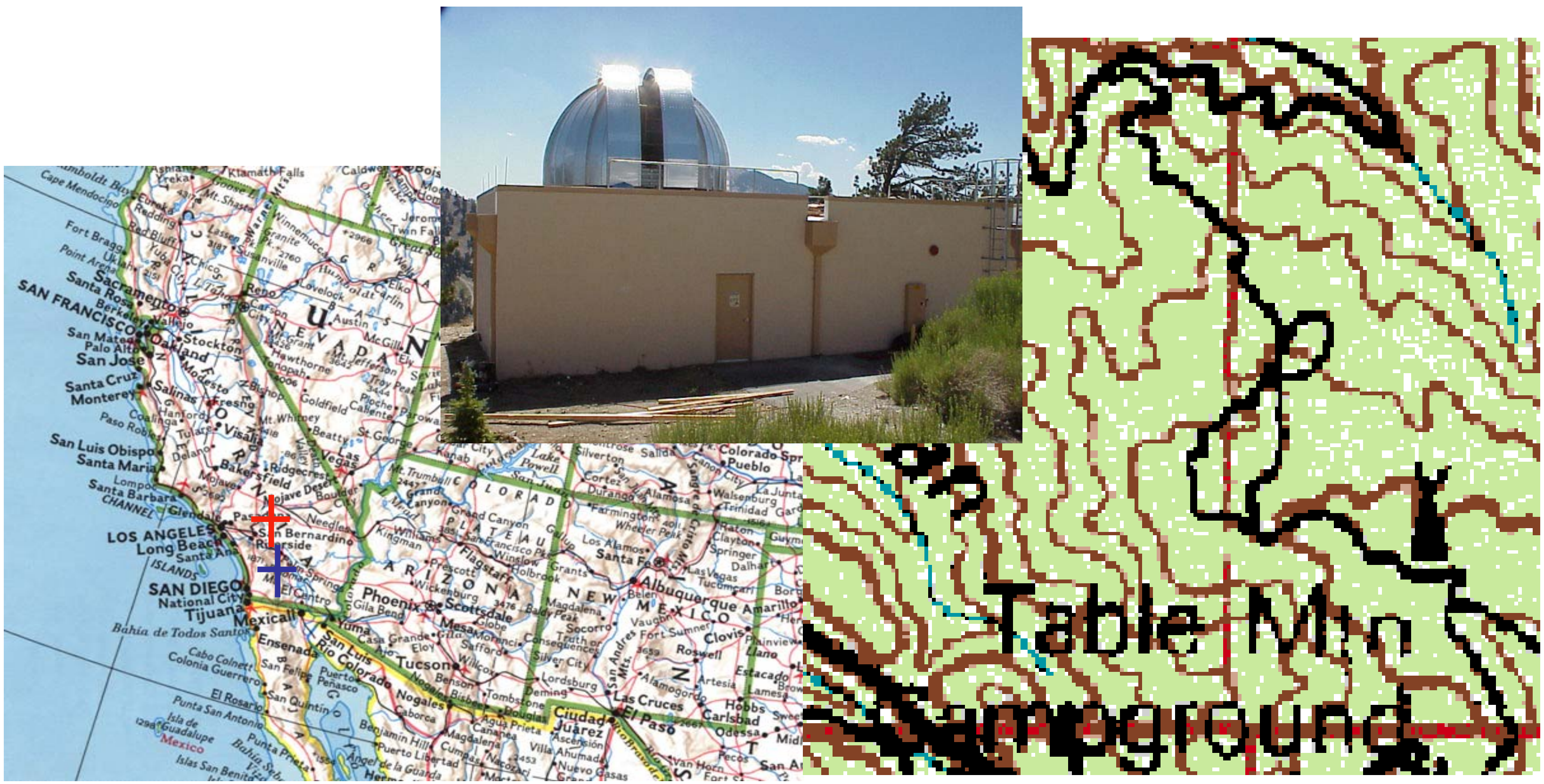
- Studying use of Lyot stops to restrict added stray light from mosaic filter support



Earth Transmit Terminals

Optical Communications Telescope Laboratory

- 1-m diameter dedicated optical communications telescope under development by NASA/JPL
- Located at Table Mountain, CA, 2200 m above mean sea level
- Good weather availability and “seeing”



Transmit Terminal Concept

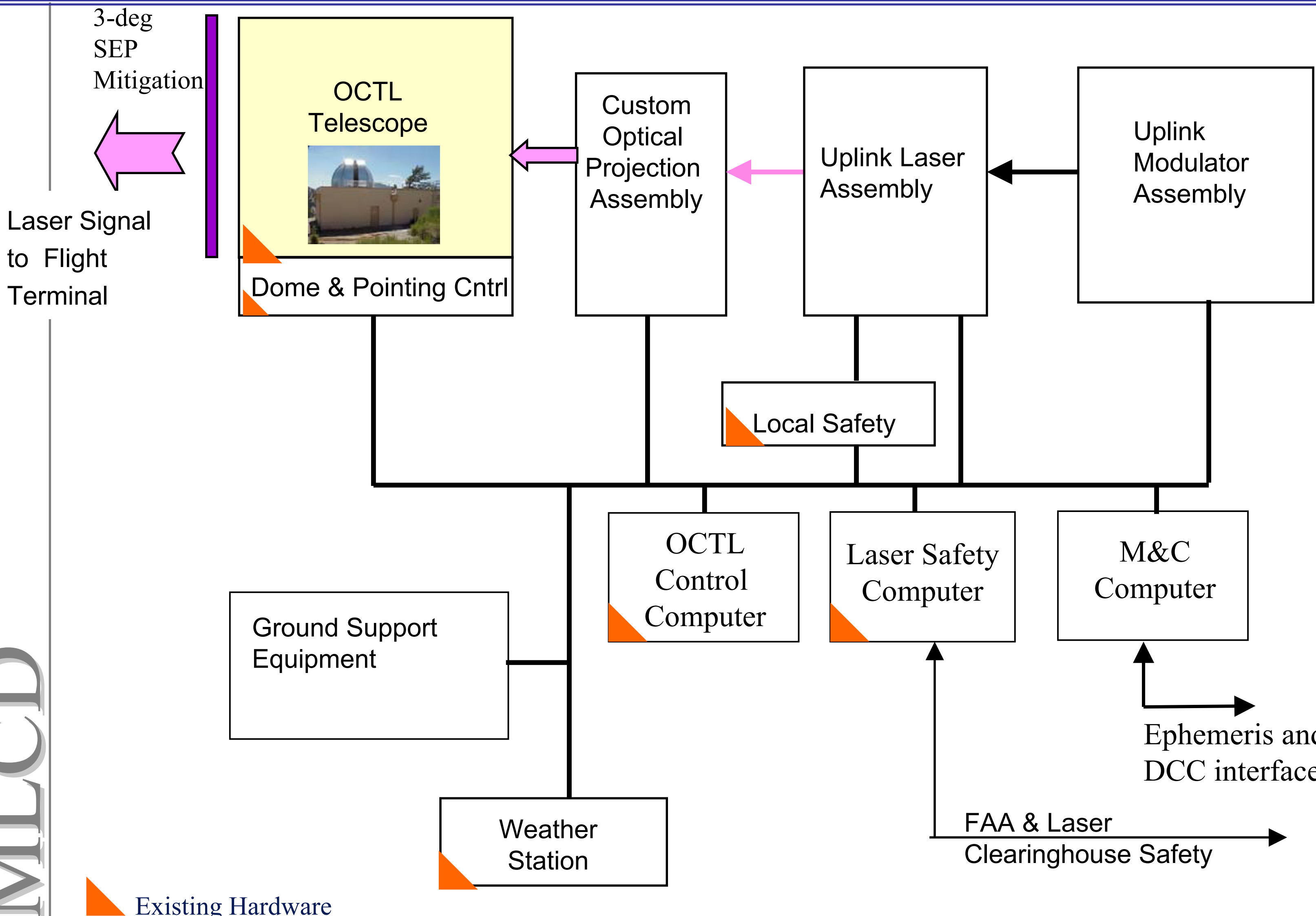
- Use Optical Communications Telescope Laboratory (OCTL) 1-m diameter telescope as uplink station
  - Good site availability
  - Laser safety will be built in

Optical Communications Telescope Laboratory

- Blind pointing with mount calibration adequate for pointing beacon
- Retrofit OCTL to meet 3 degree SEP pointing
  - Protect telescope structure from thermal damage
  - Minimize backscatter from solar filter
  - Hale telescope solution will work at OCTL
- Transmit multiple sub-aperture beams at selected wavelength
- Install laser and modulation system adequate for MLT needs

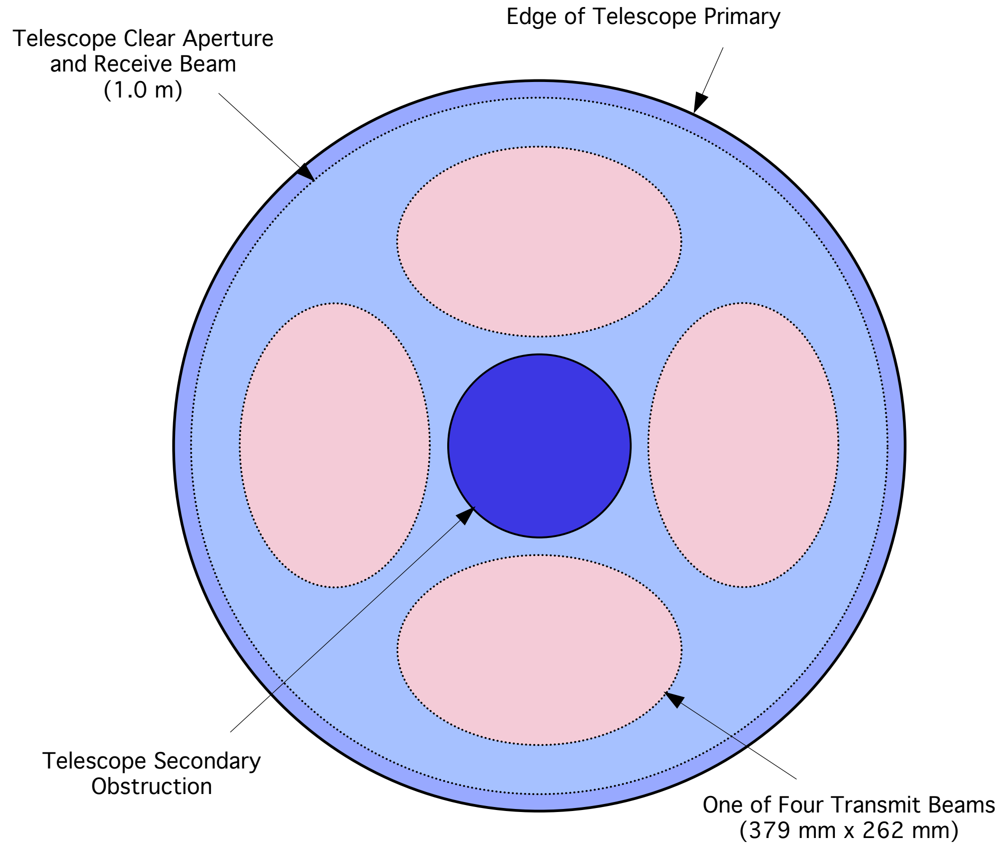
1-m diameter telescope system

Ground Uplink Transmit Terminal Block Diagram



OCTL High Power Laser Optical Projection Assembly

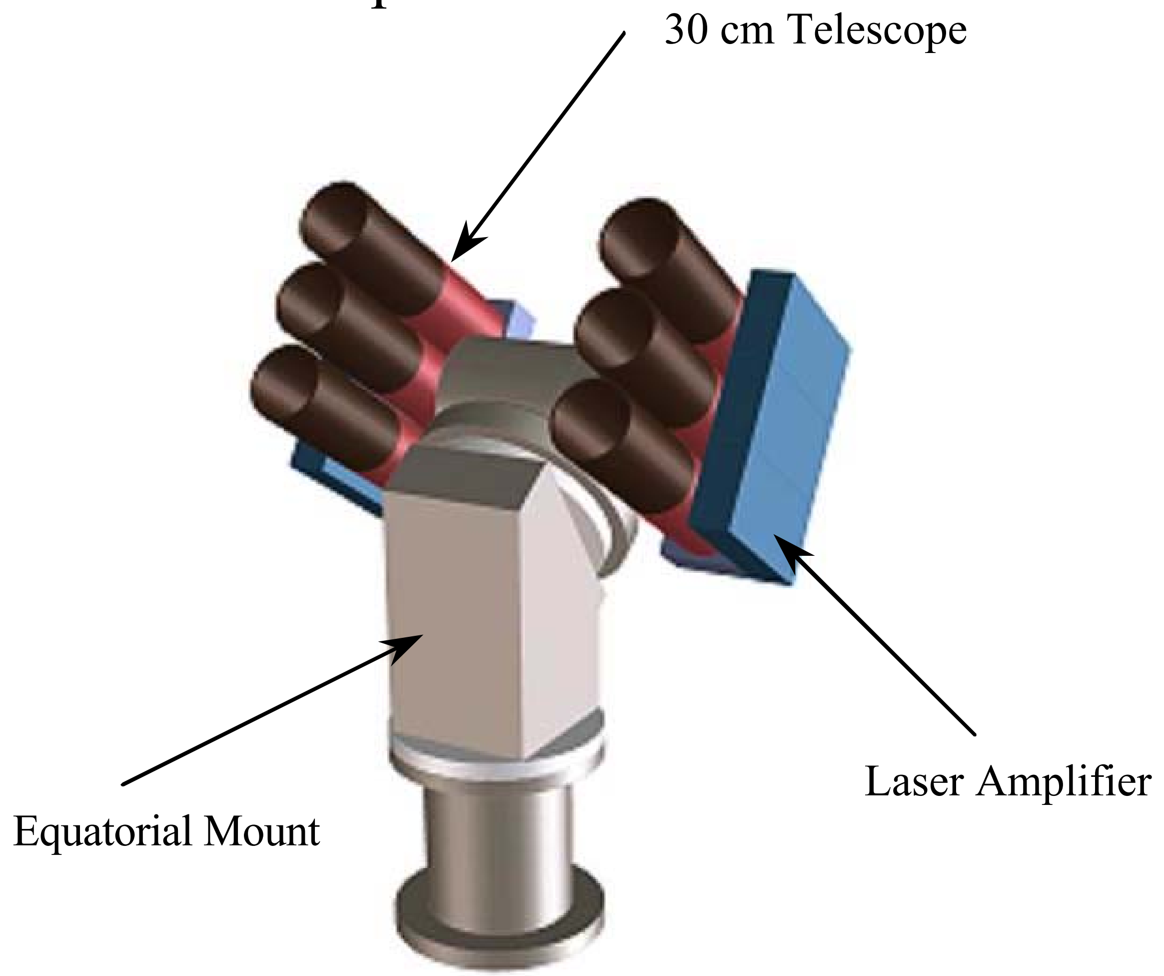
- Custom optical projection assembly to transmit multiple sub-aperture beams
  - Similar design implemented for GEO-to-ground link
  - 20-μrad beam divergence per beam
  - Sub-aperture transmit 4 non-coherent, co-aligned, phase retarded beams
  - Make up for uncompensated atmospheric tilt with adequate laser power



MULTIPLE BEAMS ON TELESCOPE PRIMARY MIRROR

Multiple Aperture Uplink Transmitter

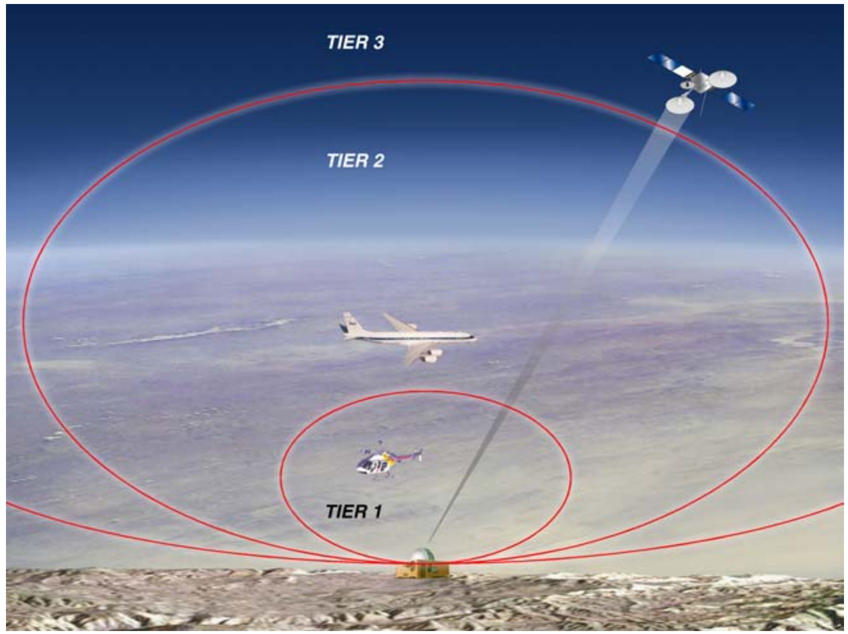
An option to using the 1-meter OCTL telescope is to use multiple small telescopes



Multi-Tiered Safe Laser Beam Propagation Assembly

Mars Laser Communication Demonstration

MLCD



- **Tier 0:** Confined within OCTL building under OSHA guidelines
- **Tier 1:** FAA controlled region ranging from dome out to 3.4 km
- **Tier 2:** FAA controlled ellipsoidal region ranging to 20km @ zenith and 58km @ 20° elevation
- **Tier 3:** Space Command region extends from near-Earth to the ranges of geo-stationary and high elliptical orbiting satellites

Summary

- MLCD is the first space-to-Earth deep space optical communications demonstration
- Provides experience
  - Systems and components in space
  - Operational procedures with ground-based receivers
- Pathfinder for future deep space optical communications systems
  - Potential for smaller size, lower mass and power relative to RF
  - Enabling high data rate missions of the future