SLR2000C: An autonomous satellite laser ranging and space-to-ground optical communications facility

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Motivation for SLR2000C

- New spaceborne remote sensing instruments generate huge amounts of data which must be transferred to the ground from space at high data rates. These include:
  - 3D Imaging Lidars/High Resolution Cameras
  - Synthetic Aperture Radars (SAR)
  - Hyperspectral Imagers
- SLR2000 can track satellites over a wide range of altitudes and can therefore support a wide variety of space lasercom architectures
- Preliminary link calculations indicate that SLR2000C can support multi-Gbps downlinks from Earth-orbiting satellites (up to Geosynchronous), 100 Mbps from the Moon, and some deep space capability.
- Multi-user support increases the likelihood for funding of a substantial global network which would benefit both geodesy and global communications

SLR2000/Lasercom Synergies

- **Shelter and azimuth tracking dome has internet connections for high speed ground data transfer and internal instrument health and security monitors**
- **“Smart” Meteorological Station provides protection against local weather conditions (wind, precipitation, etc) and monitors ground visibility and cloud cover for efficient lasercom operations**
- **GPS-disciplined Rubidium Time and Frequency Reference provides accurate epoch times for reliable satellite acquisition as well as a stable clock reference for optical communications**
- **Modest 40 cm off-axis telescope provides sufficient aperture to handle high bandwidth optical com from Earth orbiting satellites using modest spaceborne laser powers and is less sensitive to atmospheric perturbations than meter-class telescopes. No adaptive optics needed.**
- **Arcsecond precision tracking mount plus mount model provides high accuracy open loop pointing (~2 arcsec) to satellites**
- **Quadrant detector is expected to provide sub-arcsecond pointing corrections and closed loop tracking for optimizing both the ranging and optical com signals**
- **Ground-based ranging beam serves as a powerful beacon for the spaceborne lasercom system to lock onto and the returns from onboard reflectors provide accurate orbit information and independent verification of satellite “lock”.**
- **Communication satellites can be included in SLR constellation for automatic updating of orbit predictions by the central processor to expedite target acquisition**

SLR2000C Requirements

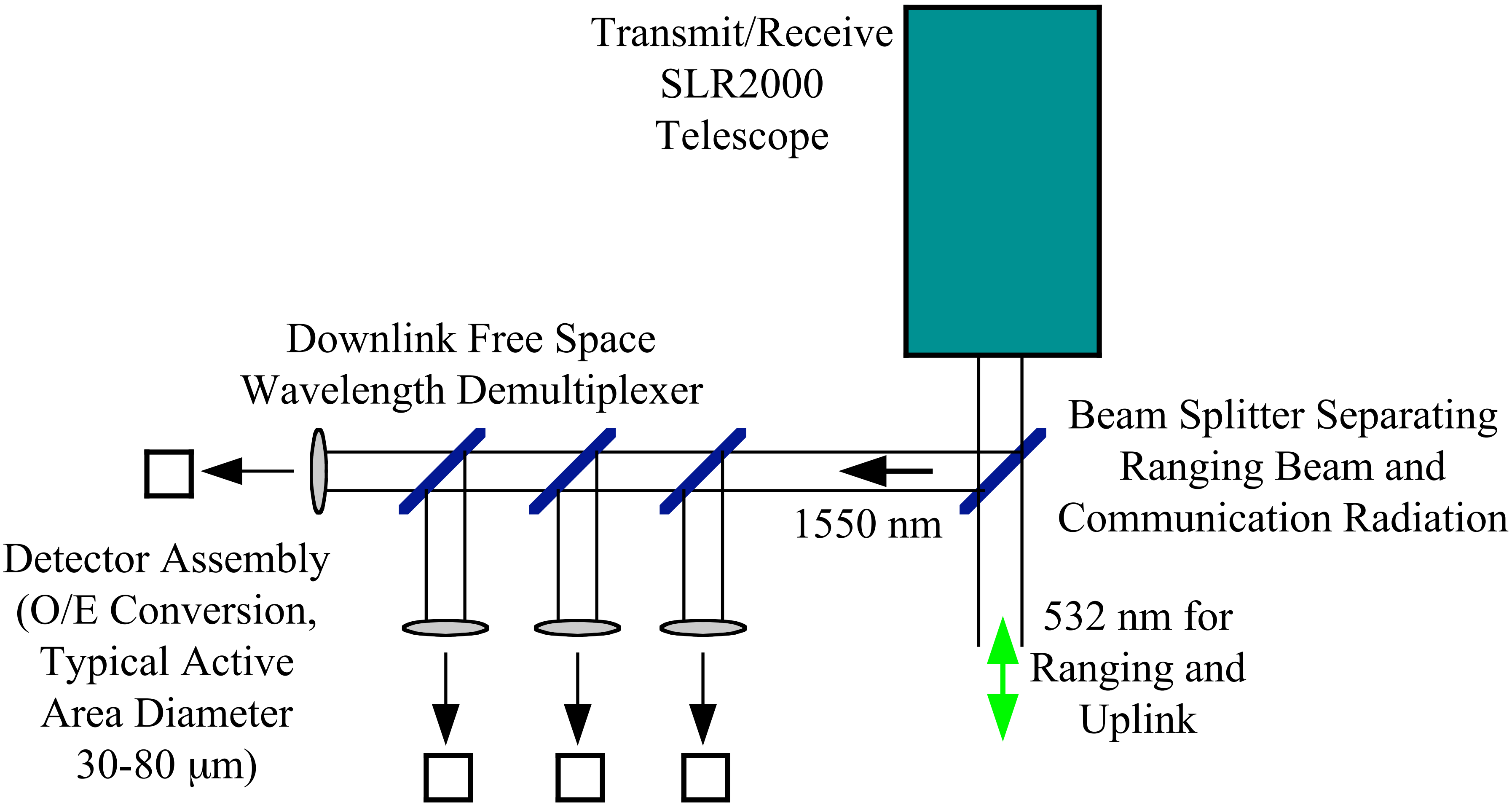
- Dual mode SLR and lasercom system
  - Sub-cm ranging
  - 10 Gbps downlink and 10 Mbps uplink
- 24/7 instant optical relaying of 10 Gbps data from any LEO remote sensing satellite or UAV (Point A) to any ground site (Point B) which is connected to a fiberoptic or other high speed hub.
  - Each SLR2000C site serving as a space-to-ground relay must have a direct fiberoptic or free space optical communications link to a hub.
- No lasercom/ranging operations below 20^{o} elevation
  - At sufficiently low elevation angles, differential refraction effects in the atmosphere cause the lasercom and ranging beams to follow different paths.
  - Atmospheric losses at the 532 nm ranging wavelength become more severe.
  - Satisfies FAA “startle” requirements at nearby airports

Approach to SLR2000C Design

- KISS Approach (Keep It Simple, Stupid!)
- Minimal interference between the ranging and lasercom subsystems
- Use COTS components wherever possible
  - Adopted telecom industry components at 1550 nm
  - Large and competitive selection of transmitters, detectors, filters, splitters, etc
  - Eyesafe wavelength
  - Excellent atmospheric transmission and low solar scatter
- Keeps the differential replication cost between SLR2000 and SLR2000C relatively low (typically $500K to $700K depending on specific features)

10 Gbps Communications Downlink

(4 channels @ 2.5 Gbps per channel)



Satellite Architectures

- “Store and Forward” (e.g. A to Relay Satellite + delay to SLR2000C to B)
  - Does not meet instant relaying criteria due to forwarding delay
- “Bent pipe” (e.g. A to Relay Satellite to SLR2000C to B)
  - Can meet instant relaying criteria with enough ground stations and relay satellites
  - Number of required satellites and ground stations decreases with increasing altitude.
  - GEO constellation requires the fewest satellites (4) and ground stations (~ 28 for 99% availability). Polar coverage can be provided by two satellites in polar orbit
- “Intersatellite Crosslinks” (e.g. A to Relay satellite to Relay Satellite to SLR2000C to B)
  - Can meet instant relaying criteria with enough ground stations and relay satellites
  - Only 7 stations required for 99% availability and 10 stations for 99.9% availability assuming mean single station availability of 50% due to weather, cloud cover, equipment downtimes, etc
  - Number of required ground stations is independent of the satellite constellation altitude due to interconnectivity of satellites
  - Number of required satellites decreases with increasing altitude, however.

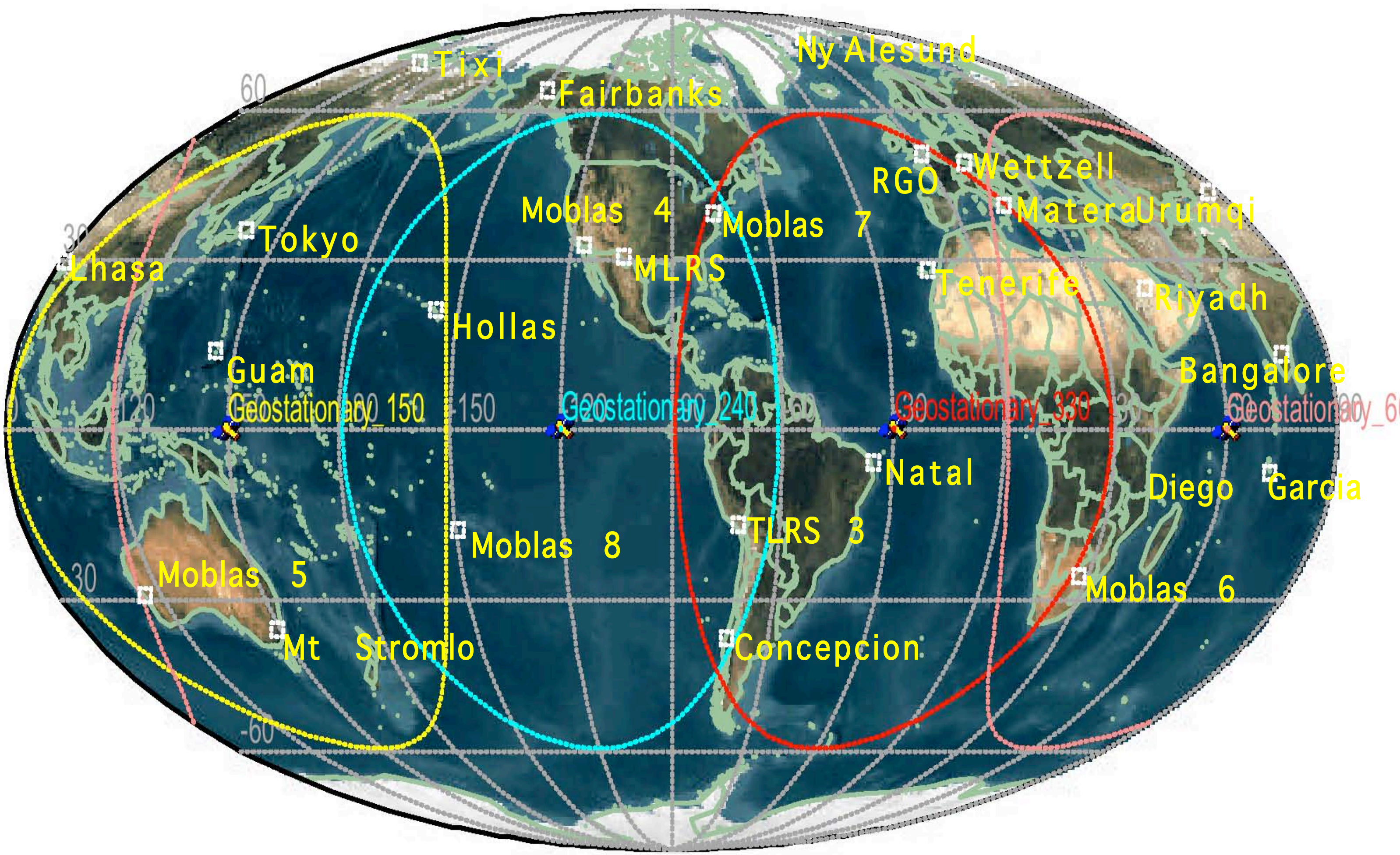
GEO Satellite Constellation

- **Advantages**
  - Four satellites provide total coverage for latitudes between $\pm$ 48^{o} and partial coverage to $\pm$62^{o}
  - Coverage encompasses most of the world's population
  - 100% global coverage can be achieved with additional satellites in polar orbit
  - Stationary satellites are easier to acquire and track
  - We can use single large hollow reflector for ranging array
  - GEO constellation requires fewest ground sites in "bent pipe" mode (~25 for 99% availability)
  - Only 10 ground stations required for 99.9% availability of orbit to ground communications if we include intersatellite crosslinks
- **Disadvantages**
  - Longer range to ground increases laser power requirements for a given data and bit error rate (com signal varies as R^{-2})
  - Requires large cross-section array for ranging (ranging signal varies as R^{-4})

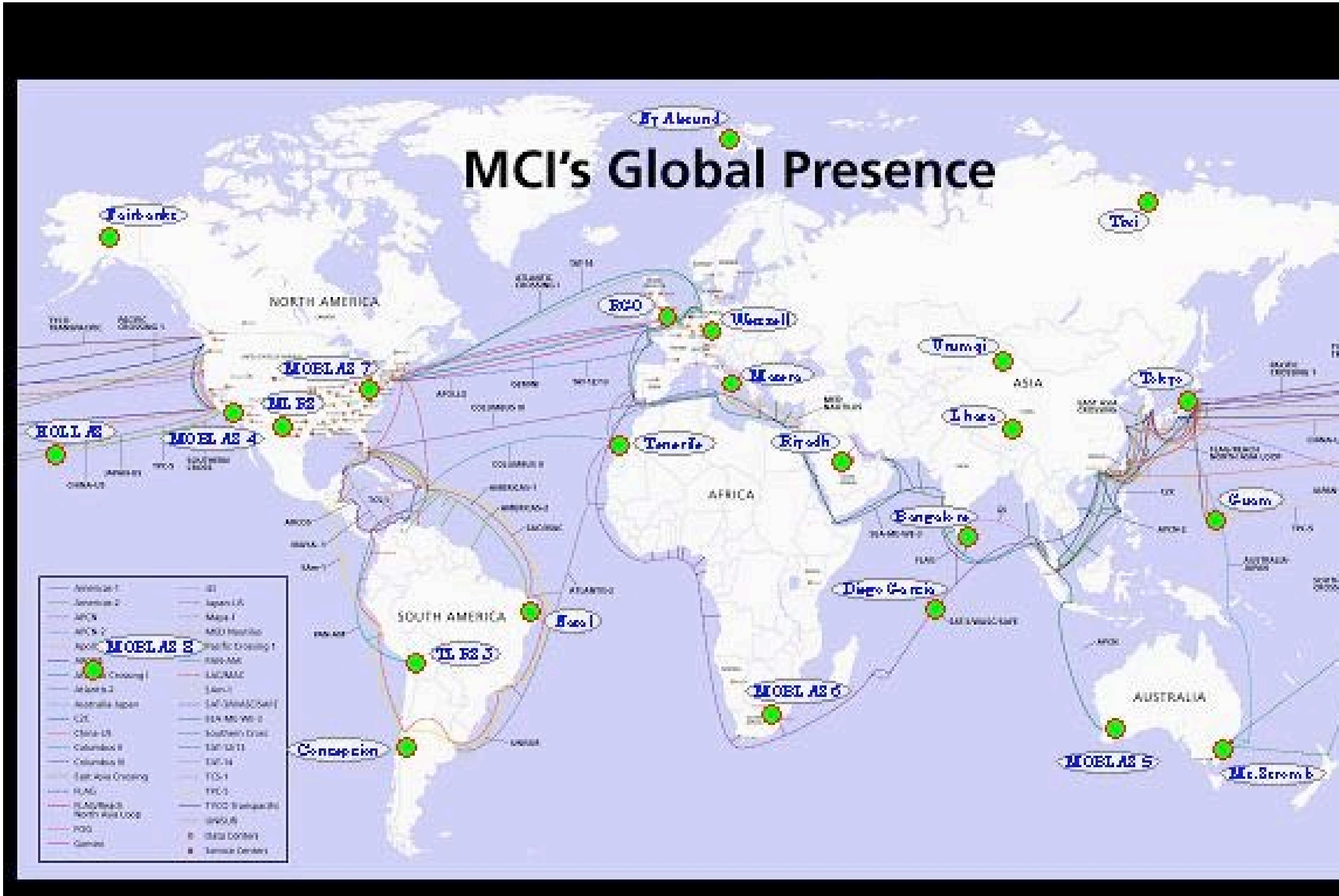
SLR2000C Siting Considerations

- **Good weather site**
  - Beneficial to both geodesy and lasercom
  - Improves single station availability
- **Quasi-uniform global distribution**
  - Weather diversity increases overall availability
  - Permits global “bent pipe” operation
  - Multiple stations in view for lunar and deep space missions that can’t benefit from satellite relays
- **Connected to fiber-optic based communications hubs**
  - Required for instant relay of space-to-ground data
- **Must have sufficient number of ground stations to support the various space architectures**
  - A minimum of 12 stations required to support continuous LAGEOS tracking and architectures using intersatellite links
  - 25 to 30 sites needed to support bent-pipe GEO and lunar/deep space links

Geosynchronous Coverage
(>20^o elevation, 25 ground stations)

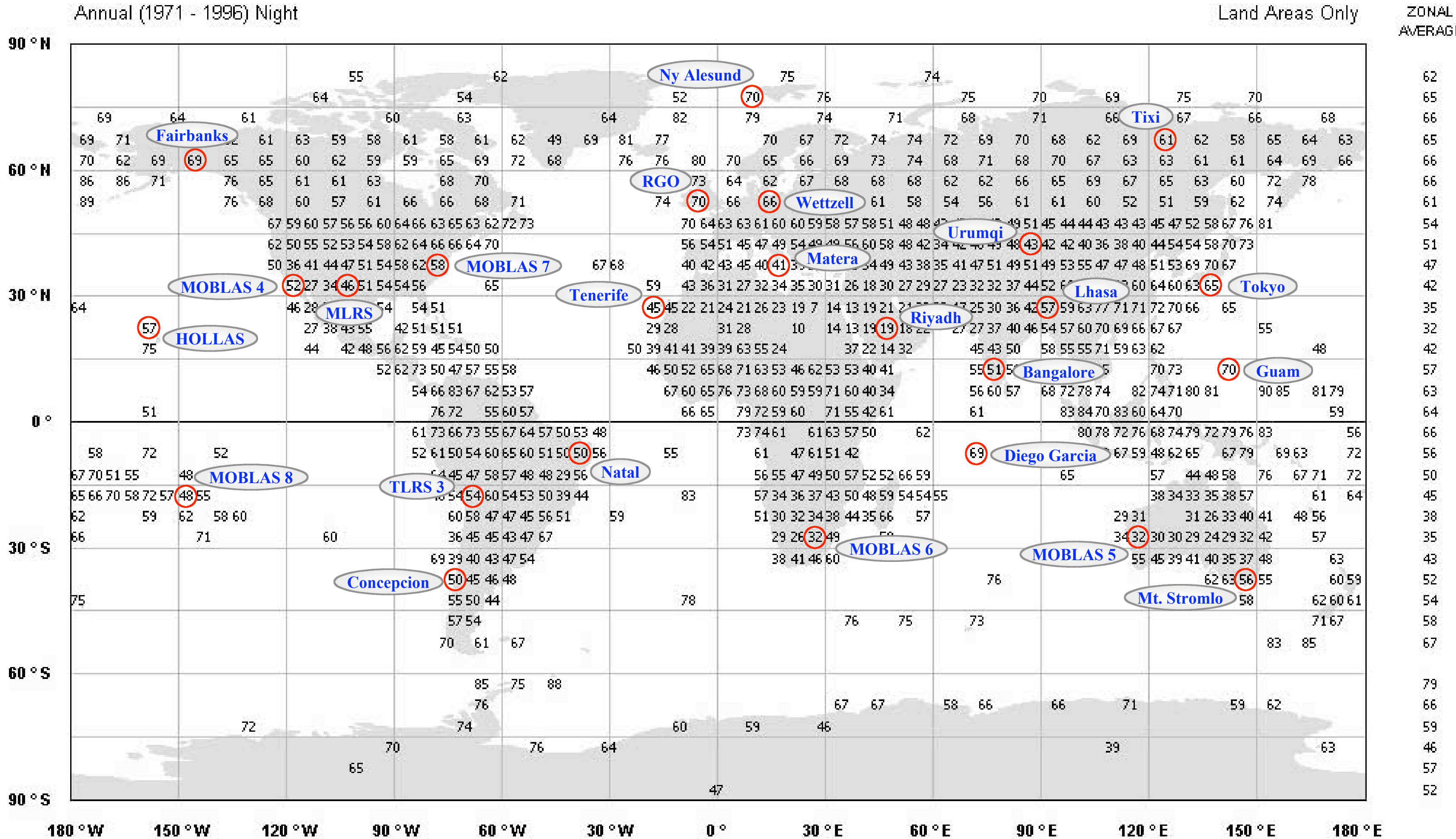


Access of Sites to MCI Hubs



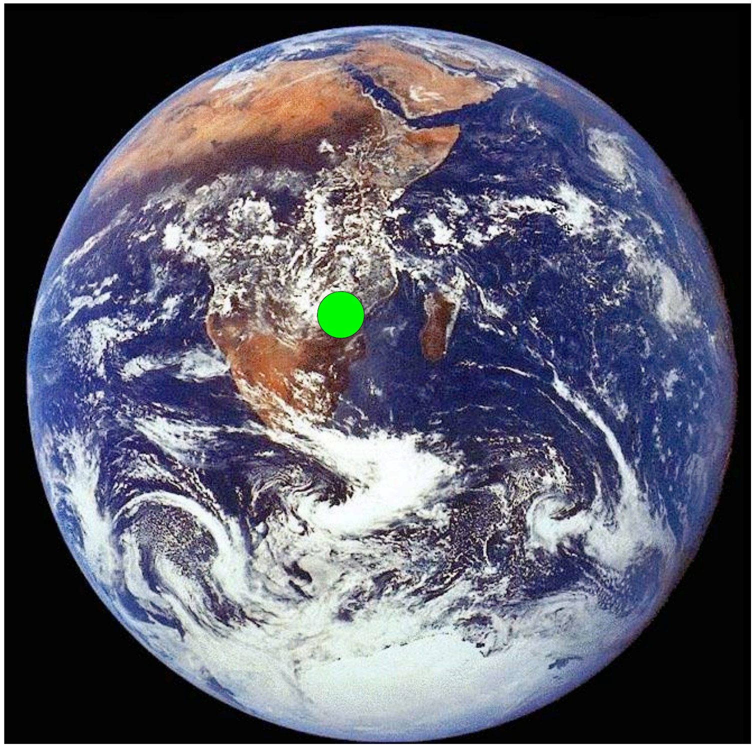
Total Cloud Cover

Average Cloud Amount (%)



GLOBAL AVERAGE (LAND) 52 %

GEO/Deep Space Acquisition

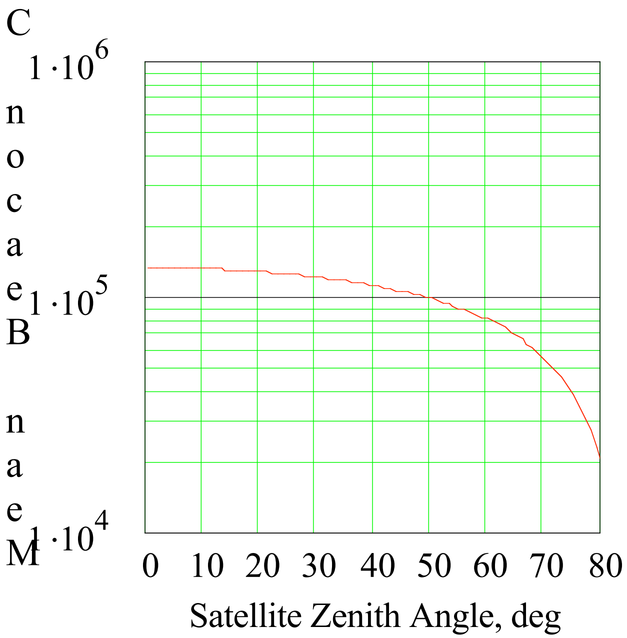


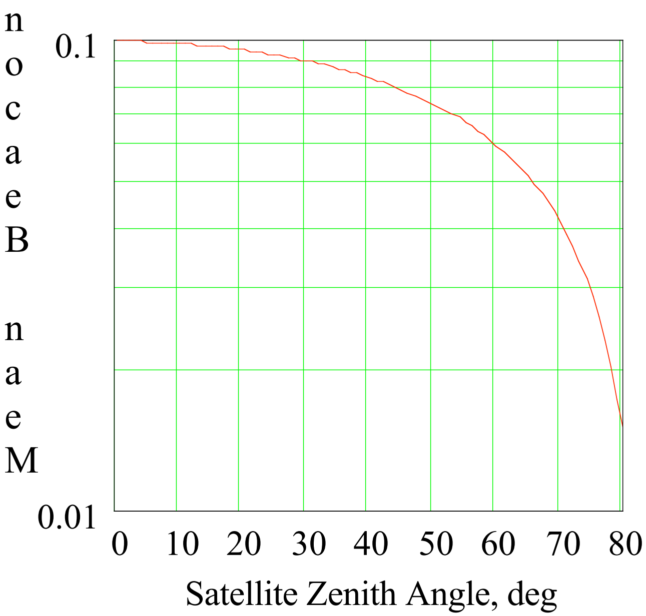
Earth and beacon as seen by CCD camera through a 532 nm filter

1. SLR2000 initiates search for GEO satellite, acquires retro returns, and locks onto satellite using existing ground quadrant detector. Informs ground lasercom system, which is co-boresighted with the ranging system, of successful acquisition. Ground lasercom goes into "ready to transmit or receive" state.
2. Onboard wide FOV CCD array with 532 nm filter constantly views entire Earth disk ($\pm$8.5 deg) through pointing telescope and sees 2 kHz SLR2000 "beacon" at 532 nm.
3. Onboard lasercom controller centers lasercom pointing system in CCD array bringing the SLR2000 beam into the much narrower FOV of an onboard 532 nm quadrant detector ("Coarse" pointing)
4. Onboard quadrant detector locks onto the ground beacon, refines the lasercom pointing ("Fine" pointing), and informs onboard lasercom system of successful "lock". Space lasercom system goes into "ready to transmit or receive" state.
5. At this point, the space lasercom terminal can either begin transmitting to the ground via the downlink or request an upload via the 10 Mbps uplink.
6. If the beacon link is broken, both terminals will lose 532 nm lock simultaneously and can stop send/receive operations until the link is re-established via steps 1 through 5.

SLR2000 Beacon at GEO Satellite

- **Used by spaceborne lasercom system to lock onto SLR2000C ground station via onboard CCD and then quadrant detector**
- **Received beacon power assumes SLR2000 values of 260 mW (130 μJ pulses @ 2 kHz) of transmitted power in ranging beam and 15 cm diameter lasercom transmit/receive aperture**



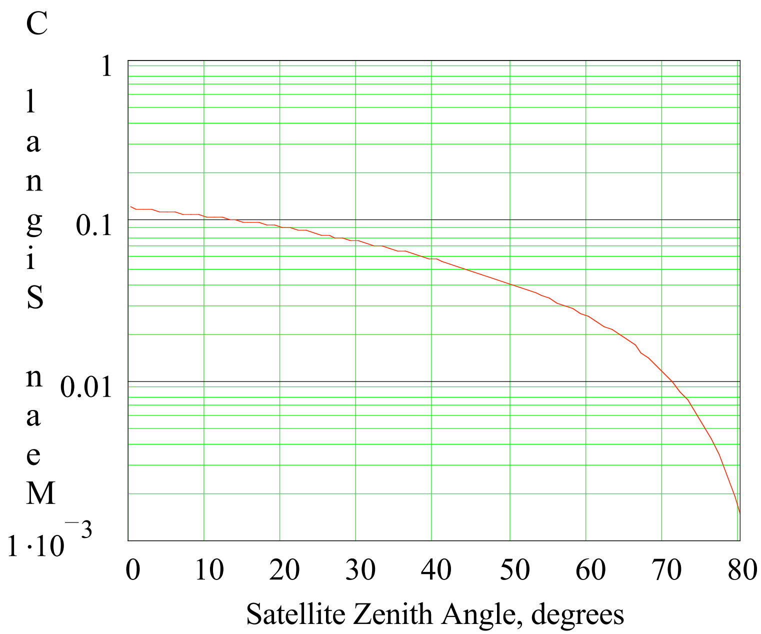


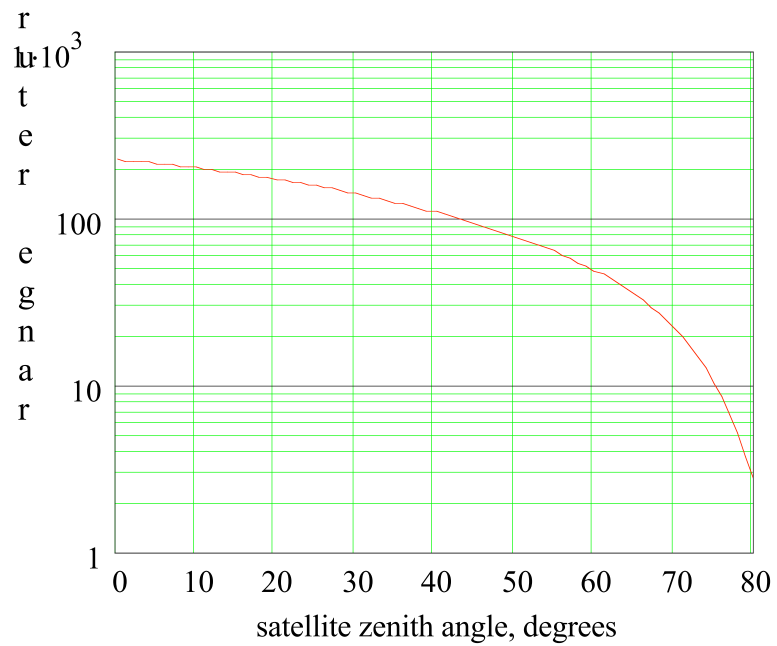
Simple GEO Retroreflector

- Single 10 cm diameter hollow retroreflector on nadir face of GEO lasercom satellite
  - Reflector can be unspoiled since there is very little relative motion between the station and the GEO satellite
  - Earth disk subtends $\pm$ 8.66^{o} cone at GEO satellite which is well within the nominal $\pm$ 15^{o} response angle of a hollow cube
  - Single hollow cube response is greater than 60% of the peak over the entire Earth disk and 100% near the equator
  - Acts as an ideal point reflector (no pulse spreading)

SLR2000 to GEO Ranging Link

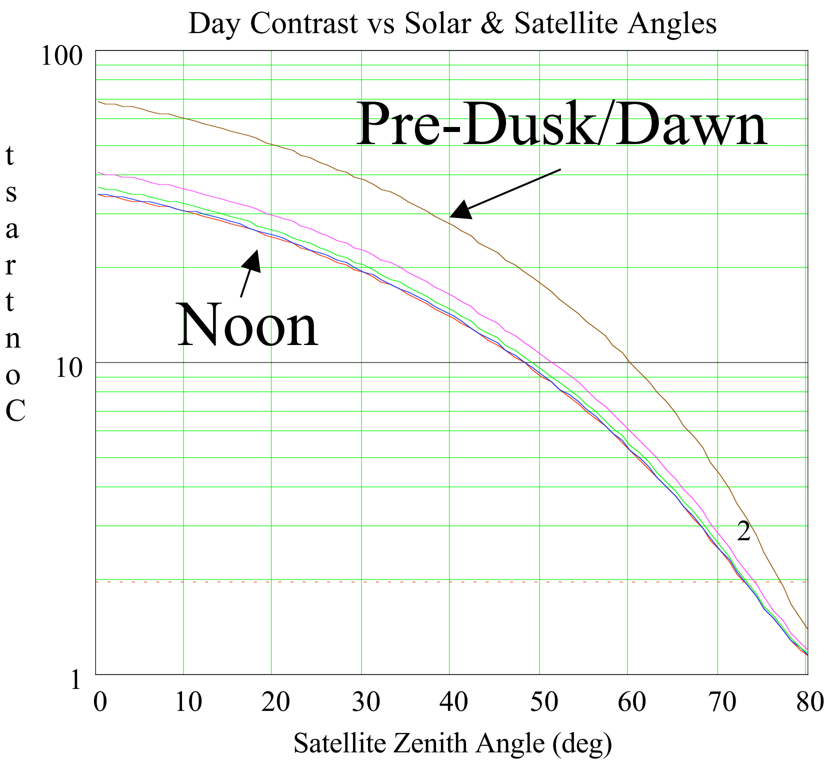
(standard clear atmosphere, 10 cm hollow retro, 10 arcsec divergence)



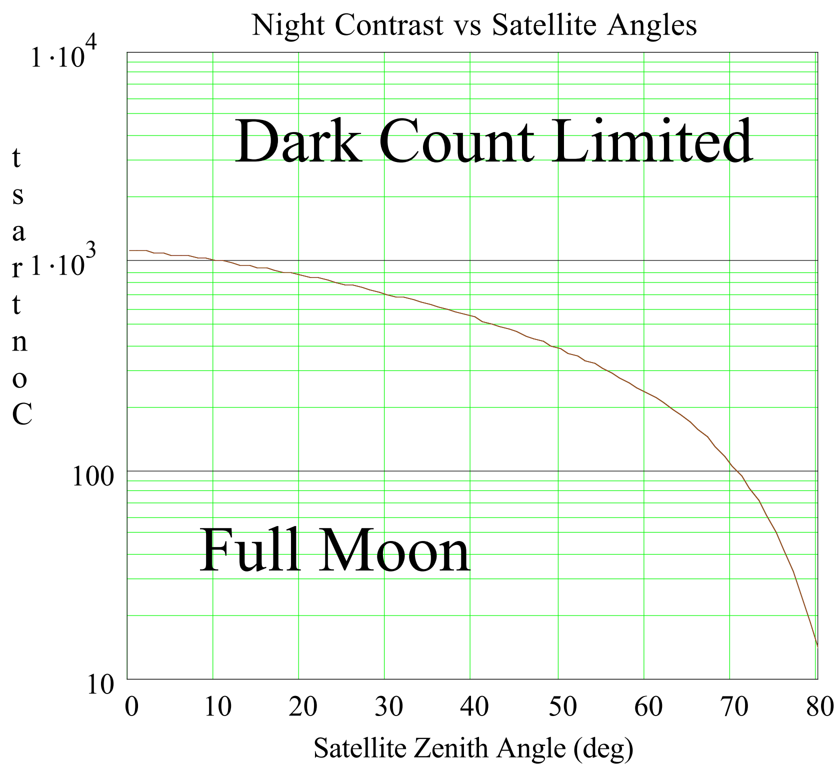


DAY/NIGHT SIGNAL CONTRAST

(should be greater than 2 for reliable signal extraction)

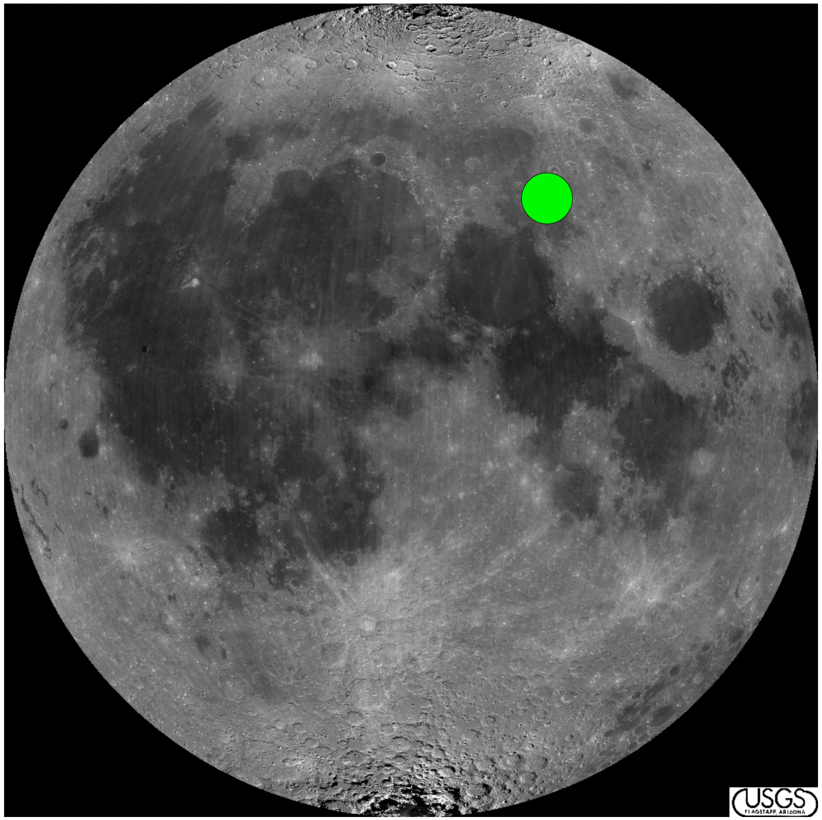


(a)



(b)

Lunar/Deep Space Communications



Moon and lunar transponder as seen from Earth through 532 nm filter

- Substitute a transponder for the passive reflector
- A distant spacecraft sees half the Earth disk but is above 20 degrees elevation over only 33% of the Earth surface
- If we assume a mean single station availability of 50%
  - Need approximately 3 x 7 =21 uniformly distributed stations for 99% availability
  - Need 3 x 10 = 30 stations for 99.9% availability
- So SLR2000C network of approximately 25 stations satisfies lunar and deep space needs as well!

Summary

- Satellite laser ranging and lasercom applications are highly synergistic since most of the support capabilities required for an automated ground lasercom station are provided by the baseline SLR2000 design
- A space-to-ground 10 Gbps downlink and 10 Mbps uplink lasercom capability can be added to SLR2000 for a differential replication cost of about $600K at an eyesafe wavelength of 1550 nm using COTS telecom parts.
- Excellent atmospheric transmission and low solar scatter at 1550 nm.
- Range returns from a passive reflector provide independent verification of satellite acquisition and lock.
- A single 10 cm diameter, unspoiled hollow cube corner should be capable of satisfying the SLR2000C ranging link at GEO distances.
- An onboard CCD array can view the upcoming ranging beacon through a 532 nm filter for initial acquisition of the ranging beacon, identification of the active ground station, and initial pointing of the onboard lasercom terminal; 532 quadrant detectors at both terminals further refine the pointing .
- Transponders can be substituted for passive reflectors over lunar and/or deep space links; both lasercom data rates and range returns will fall off as R^{-2} for a given transmitter power/receive aperture product. A 25 site SLR2000C network can downlink ~100Mbps from lunar orbit with > 99% availability.
- Multi-user support increases the likelihood for funding of a substantial global network which would benefit both geodesy and global communications