

SLR2000C: AN AUTONOMOUS SATELLITE LASER RANGING AND SPACE-TO-GROUND OPTICAL COMMUNICATIONS FACILITY

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Abstract

The adaptation of NASA's SLR2000 satellite laser ranging station to a dual mode ranging and optical communications terminal for space-to-ground links is discussed. The SLR2000C concept assumes multiple communications channels near 1550 nm, which allows the use of commercially available fiberoptic communications components. Preliminary link calculations suggest that the 40 cm aperture of SLR2000 would permit several Gbps downloads per channel from geosynchronous or lower Earth orbits and several tens of Mbps per channel from lunar orbit with nominal spaceborne transmitter powers on the order of a few watts. A ground network of approximately 25 SLR2000C stations coupled into a ground-based fiberoptic network would meet most of the foreseeable needs of "instantaneous" high data rate space-to-ground communications, including Earth-orbiting satellites and Deep Space missions. A simple space architecture based on four interlinked geosynchronous satellites (plus up to four additional satellites for polar coverage), would provide greater than 99% link availability and permit instantaneous transfer of data between an airborne or spaceborne remote sensing terminal and any point on the ground that is connected to the fiberoptic network. A single 10 cm diameter cube on each of the GEO satellites would provide adequate cross-section for the ranging link.

1. INTRODUCTION

NASA is currently field testing a prototype fifth generation Satellite Laser Ranging (SLR) system at the NASA Goddard Space Flight Center in Greenbelt, MD. Unlike past manned systems, the photon-counting SLR2000 system, illustrated in Fig. 1, is designed to be fully automated and eyesafe [Degnan et al, 2003]. The transmitter produces low energy subnanosecond pulses at high repetition rates ($130 \mu\text{J} @ 2 \text{ kHz} = 260 \text{ mW}$), and the ranging receiver has single photon sensitivity. Eye safety is achieved through a combination of low pulse energies and large transmitted beam areas. Due to a unique and totally passive transmit/receive (T/R) switch design, the transmitter and receiver can simultaneously share the entire telescope aperture. Recent field experiments with the prototype have demonstrated the ability of SLR2000 to detect single photon returns from passive retroreflector arrays on satellites during both day and night tracking operations [McGarry et al, 2004]. The system has been designed to track the current constellation of retroreflector-equipped satellites at altitudes between about 300 km (LEO) and 20,000 km (GPS, GLONASS).

Recently, we investigated the possibilities for upgrading the SLR2000 system to permit high data rate laser communication downlinks and uplinks to and from Earth orbiting satellites in parallel with centimeter accuracy laser ranging operations. The marriage of the two applications is highly synergistic since the requirements for autonomous satellite laser tracking and communications overlap significantly. Specifically, the baseline SLR2000 system provides:

- Internet/modem/phone connections to support a variety of command and control functions (e.g. scheduling, updated orbital and time bias predicts, diagnostics, etc.), data transfer to a central processor, and internal instrument health and security monitors
- a “Smart” Meteorological Station which provides protection against local weather conditions (wind, precipitation, etc) and monitors ground visibility and cloud cover for efficient lasercom operations
- a GPS-disciplined Rubidium Time and Frequency Reference which yields accurate epoch times for reliable satellite acquisition as well as a stable clock reference for optical communications
- a 40 cm off-axis telescope with sufficient aperture to handle high bandwidth (2.5 Gbps per channel) optical com downlinks from Earth orbiting satellites using modest onboard laser powers (few watts at geosynchronous altitudes) but small enough to accommodate large phase front tilts due to the atmospheric effects or pointing errors in small aperture COTS lasercom detectors
- an arcsecond precision (command vs control) tracking mount augmented by automated star calibrations and a sophisticated 22 term mount model for high accuracy absolute pointing (~2 arcsec RMS over 66 stars)
- a photon-counting quadrant detector with pointing feedback capability for locking onto and maximizing both the ranging and optical com signals
- a unique transceiver design with a passive transmit/receive switch which allows the transmitter and receiver to simultaneously utilize the full telescope aperture without limiting the two-way data transfer rate and allows for improved eye safety margins and narrower transmit beams
- Communication satellites can be easily included in SLR constellation for automatic updating of orbit predictions by the central processor for rapid target acquisition



Figure 1: Prototype SLR2000 satellite laser ranging system undergoing field tests at the NASA Goddard Space Flight Center.

Laser ranging off passive retroreflectors placed on the nadir-viewing face of communications satellite also provides: (1) a highly accurate orbit which implies less search time and faster target acquisition during subsequent orbits; (2) independent verification that the satellite has been acquired by the ground station; and (3) a bright beacon at 532 nm for the spaceborne lasercom terminal to lock onto.

The conceptual design of the proposed global network of upgraded SLR2000C (C = Communications) station, which will be described in the present paper, has followed the same developmental principles as the baseline SLR2000 system, i.e. maximum use of Commercial Off The Shelf (COTS) components, long life and reliability, and simplicity of operation. In particular, the proposed design leverages heavily off near-IR lasercom components being developed by the telecom industry at wavelengths near 1550 nm. The inclusion of a 10 Gbps (4 channels at 2.5 Gbps per channel) downlink and a 10 Mbps uplink lasercom capability is expected to increase the replication cost by less than \$700K, or about 30% of the baseline station cost of approximately \$2M. Current applications under active investigation include a global space-to-ground optical communications network and a lunar mapping mission.

2. SLR2000C TECHNICAL GOALS AND CONSTRAINTS

In considering the dual application SLR2000C system, we set the following goals for the overall lasercom space architecture and ground network:

- Dual mode SLR and two-way lasercom system with minimal interference between the two subsystems
 - Sub-cm ranging at 532 nm
 - 10 Gbps downlink and 10 Mbps uplink communications at 1550 nm

- 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. Thus, each SLR2000C site serving as a space-to-ground relay must have a direct fiberoptic or free space optical communications link to a ground communication hub.

- Reduce non-recurring engineering and replication costs by using COTS optical telecom 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)

In addition, we constrained operations above 20° elevation for a number of reasons:

- At sufficiently low elevation angles, differential refraction effects in the atmosphere cause the lasercom and ranging beams to follow different paths thereby destroying their coalignment.
- Losses due to atmospheric transmission and scintillation become more severe
- Even though both beams meet OSHA eye safety standards, operating above 20° elevation helps satisfy FAA “startle” requirements at nearby airports.

3. LASER COMMUNICATIONS AT 1550 NM

Fig. 2 shows a block diagram of a typical four channel lasercom receiver configured from existing COTS telecom parts. A simple dichroic mirror, inserted into the existing SLR2000 optical train, separates the ranging photons at 532 nm from the lasercom photons at 1550 nm in both transmit and receive mode. It is assumed here that each lasercom channel can carry 2.5 Gbps of downlinked data for a total of 10 Gbps as is typical in ground-based fiberoptic links, and the question that must be answered is whether or not these components can be utilized successfully in a free space optical communications link with reasonably powered space-qualified laser transmitters. When compared to a fiberoptic link, the free space atmospheric channel is significantly less benign due to scattering and turbulence effects which lead to beam attenuation, spreading, wander, and scintillation of the laser beam [Degnan, 1993]. In addition, one must consider optical losses due to imperfect pointing of both the transmitter and receiver. Preliminary link calculations suggest that a 3 W transmitter on the GEO satellite (which already exists in the laboratory) with simple OOK modulation can easily downlink a few Gbps to an SLR2000C station with bit error rates of less than 1 pps. Additional link margin can be obtained by employing more sophisticated laser modulation and/or coding schemes.

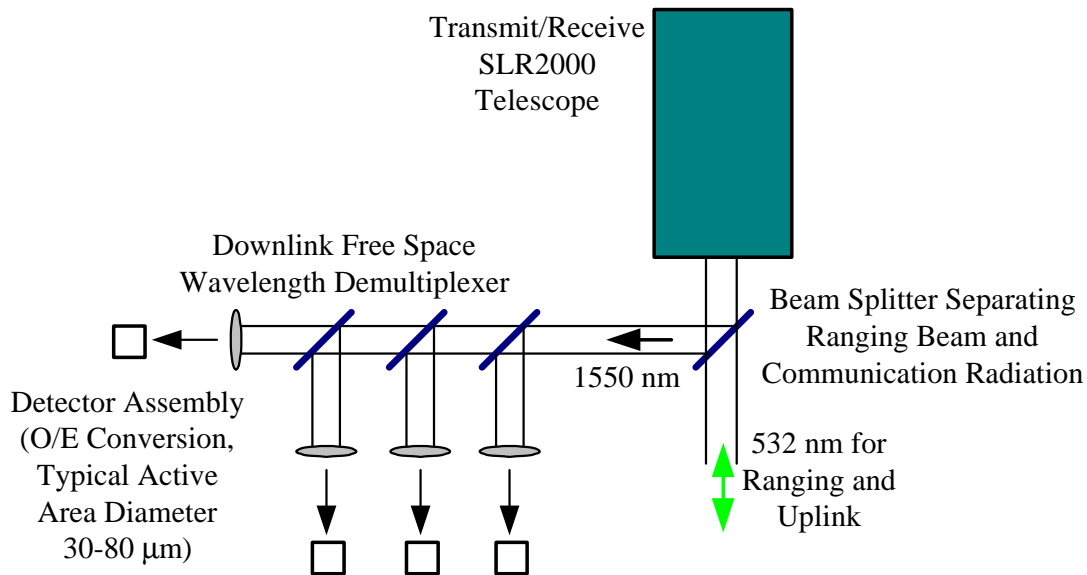


Figure 2: Block diagram of a four channel downlink each having a 2.5 Gbps capacity. The ranging/beacon and lasercom beams are separated by a simple dichroic mirror in both transmit and receive mode.

4. SATELLITE CONSTELLATION ARCHITECTURES

Let us assume that we wish to transfer large quantities of data “instantaneously” from lasercom terminal A on an Unmanned Aerial Vehicle (UAV) or Low Earth Orbiting (LEO) satellite via one or more relay satellites and/or a direct link to an SLR2000C ground station to a Ground User Terminal B where that data will be analyzed and used. Independent of the space architecture, both the SLR2000C and Terminal B must be interconnected by either a high capacity ground fiberoptic network (as provided by commercial or military users) or a “last mile” free-space communications system between SLR2000C and a fiberoptic hub. If an

individual station has a 50% average availability (due to local weather, scheduled maintenance and repairs, etc.), the active relay satellite would require 7 ground stations in its field of View (FOV) for 99% availability of a clear link. Ten such stations in view would provide 99.9% availability.

There are three types of space architectures routinely used for spaceborne communications: (1) Store and Forward, (2) Bent Pipe, and (3) Intersatellite Crosslinks. In a general “Store and Forward” architecture, a UAV or LEO would beam data to a relay satellite which would then store the data onboard until it could downlink it to a waiting SLR2000C ground station. Such an architecture clearly does not meet our 24/7 “instant” relaying criteria unless the ground network of SLR2000C stations was so dense that one was within view, both geometrically and optically, at all times. At lower relay satellite altitudes, the spatial correlation of weather patterns would greatly reduce the probability of an available link and or delay data delivery (high latency) even for a high concentration of ground stations.

A “Bent Pipe” architecture, in which the LEO transmits data to a clear SLR2000C site via a single intermediate relay satellite, can meet the 24/7 instant relay requirement provided there are enough ground stations and single-hop relay satellites in the constellation. The required numbers of ground stations and satellites decrease dramatically with an increase in the relay satellite altitude

With “Intersatellite Crosslinks”, one can use multiple linked relay satellites to transfer the data from Terminal A to any available SLR2000C station in the world. Thus, a global network of only 10 ground SLR2000C sites would provide 99.9% availability of a clear space-to-ground channel from any UAV or LEO location, independent of the satellite crosslink architecture. However, as in the “Bent Pipe” case, the number of required relay satellites decreases dramatically with increasing altitude of the relay constellation.

5. GEOSYNCHRONOUS INTERSATELLITE RELAY EXAMPLE

It is well-known that operating at Geosynchronous (GEO) altitudes offers several distinct advantages. Fig. 3 shows the global communications coverage provided by four geosynchronous satellites with a ground station elevation cutoff of 20°. There is full coverage between latitudes of $\pm 48^\circ$ and partial coverage up to $\pm 62^\circ$ latitude, and the satellites can be positioned longitudinally to service most of the populated regions of the Earth. If necessary, full polar (and therefore global) coverage can be obtained through the addition of up to four complementary satellites in high polar or Molniya orbits. Because they are stationary with respect to a ground site, GEO satellites are relatively easy to acquire and track. Furthermore, they require no transmitter point-ahead correction or velocity aberration correction in the passive retroreflectors used for ranging. In addition, a GEO constellation requires the fewest ground sites when operating in “bent pipe” mode (~25 stations for 99% availability). As mentioned previously, with intersatellite links between GEO's, only ten ground stations would provide 99.9% availability.

On the negative side, the longer slant range to the ground from GEO altitudes reduces the signal levels for both the ranging and lasercom links for a given laser power-telescope aperture product. The lasercom signal varies as R^{-2} whereas the reflected signal strength from a given passive reflector array varies as R^{-4} .

In designing a ground network, one must clearly:

- **Choose good weather sites**
 - 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/or deep space missions that can’t benefit from satellite relays
- **Choose sites connected to or near fiber-optic based communications hubs**
 - Required for instant relay of space-to-ground data
- **Provide a sufficient number of ground stations to support the various space architectures and applications**
 - 12 stations would support continuous LAGEOS tracking for geodesy and high availability (>99.9%) lasercom architectures using intersatellite links
 - 25 to 30 sites would be needed to support bent-pipe GEO and lunar/deep space links

Fig. 3 shows 25 globally distributed SLR2000C sites, most of which are currently occupied by internationally manned SLR stations operated on behalf of the International Laser Ranging Service (ILRS) to support geodetic and other Earth and lunar science measurements. Since in this example 3 of the sites service the polar regions, each GEO satellite can typically view 6 meteorologically diverse ground stations on multiple continents. Fig. 4 shows the site locations relative to a global fiberoptic grid operated and maintained by MCI.

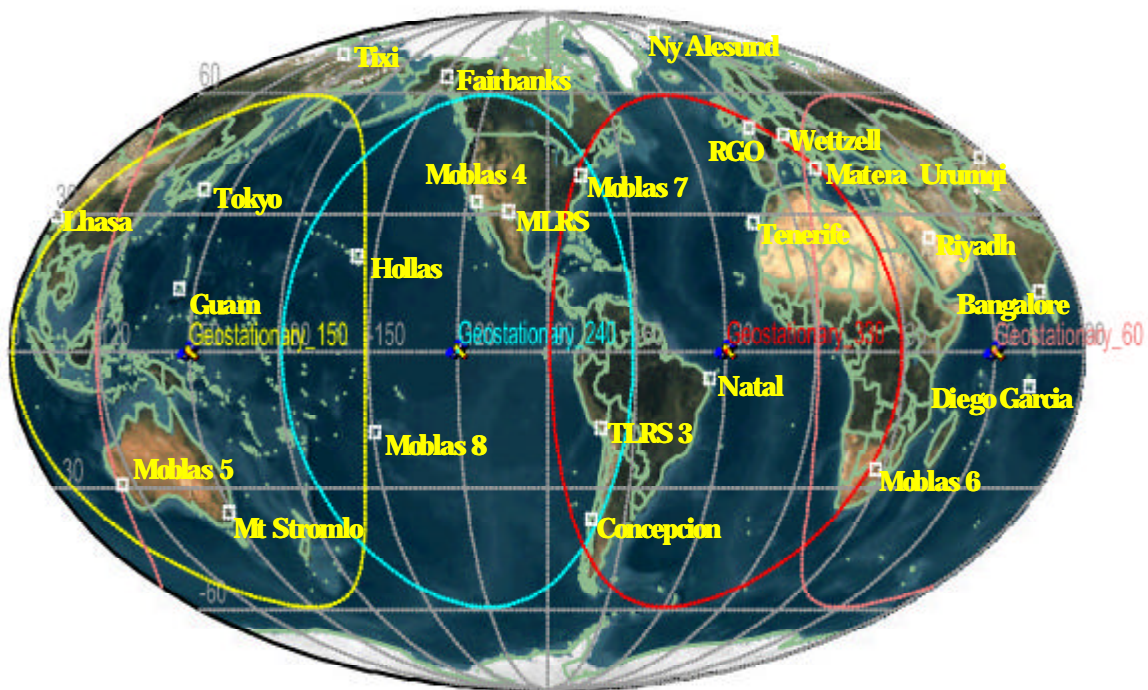


Figure 3: Global map showing geosynchronous satellite coverage for a four satellite constellation. Also shown are 25 potential SLR2000C ground sites which would largely meet the space-to-ground needs of global Earth, lunar, and deep space communications.

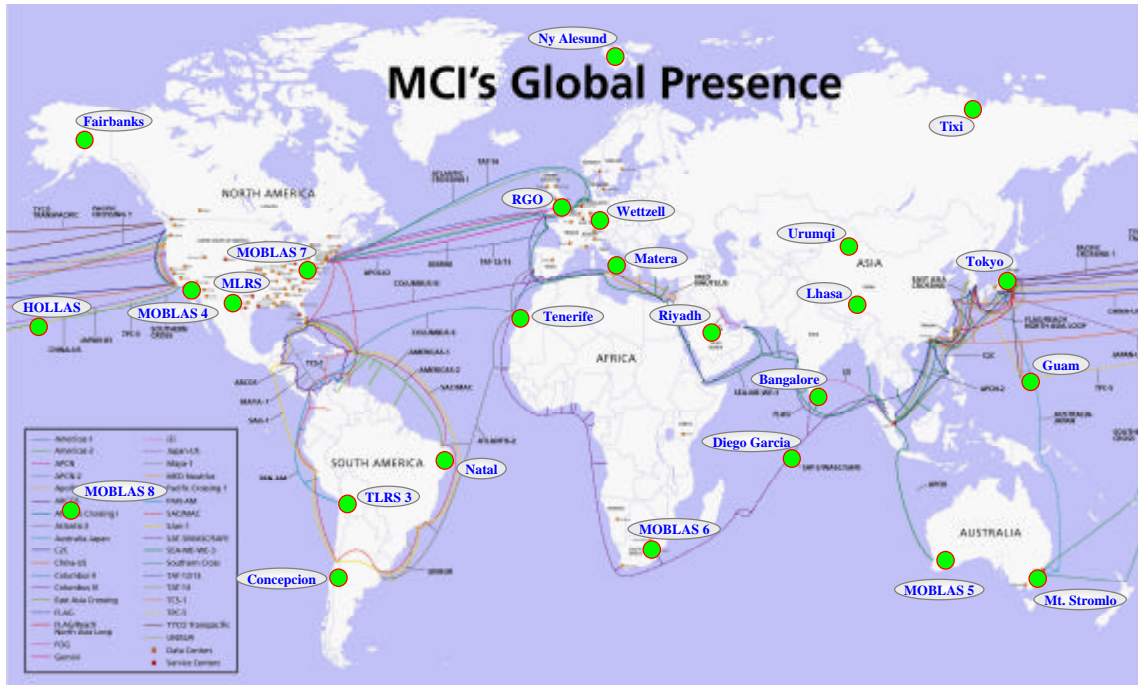


Figure 4: Candidate SLR2000C site locations relative to global MCI fiberoptic net.

6. GEO-TO-GROUND TERMINAL ACQUISITION SEQUENCE

The ground-based laser ranging beam from SLR2000C provides a strong beacon which, when viewed through a narrowband (0.3 nm) spectral filter, would appear as a bright pixel in a monochromatic CCD array (256x256 or greater) viewing the entire Earth disk. The location of the pixel immediately identifies the “clear” or “active” station and negates the need for separately transmitting ground terminal information to the GEO satellite. Assuming a 15 cm diameter telescope on the GEO satellite and operation at elevation angles above 20°, between 0.03 and 0.1 nW of beacon laser power at 532 nm would be absorbed by the onboard detector, corresponding to several tens of thousands of photoelectrons generated in the detector per ranging pulse at a 2 kHz fire rate.

Since there is no significant relative motion between the GEO satellite and ground station, there is no need to “spoil” the retroreflector dihedral angles as in lower satellites to compensate for velocity aberration effects. “Spoiling” typically reduces the natural optical cross-section by 1 to 2 orders of magnitude [Degnan, 1993]. Furthermore, the Earth disk subtends an angle of only $\pm 8.6^\circ$ at the GEO terminal, well within the $\pm 15^\circ$ angular field of view (FOV) of a hollow retroreflector [Degnan, 1993]. Thus, a single unspoiled 10 cm diameter hollow cube corner mounted to the nadir face of the GEO satellite has a huge optical cross-section (almost 2 billion square meters) and can provide a steady stream of ranging data to the ground station. Link analyses suggest 20 to 220 ranging photoelectrons per second at elevation angles between 20 and 90 degrees respectively resulting from this simple and compact GEO target. Using the reflected photons from the satellite and a photon-counting quadrant detector, the SLR2000C can acquire and lock onto the satellite reflector, totally independent of the lasercom system.

The proposed acquisition sequence follows:

1. SLR2000C initiates search for GEO satellite, acquires 532 nm returns from the onboard retroreflector, and locks onto the satellite using existing ground quadrant detector. It then informs the ground lasercom system, which is co-boresighted with the ranging system, of successful acquisition and lock. The ground lasercom goes into “ready to transmit or receive” state.
2. The onboard wide FOV CCD array with 532 nm filter constantly views the entire Earth disk (± 8.5 deg) through the pointing telescope and sees the active 2 kHz SLR2000 “beacon” as a bright pixel.
3. The onboard lasercom mount controller centers the bright pixel (“Coarse” pointing correction) which in turn brings the SLR2000C ranging beam into the much narrower FOV of an onboard 532 nm quadrant detector.
4. The onboard quadrant detector locks onto the ground ranging beacon, refines the lasercom pointing (“Fine” pointing correction), and informs the onboard lasercom system of successful acquisition and lock onto the ground terminal. 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 receive 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.

7. DOWNLINK BIT ERROR RATES FROM GEOSYNCHRONOUS ORBIT

Figure 5 shows the results of an optical communications downlink analysis to SLR2000C from geosynchronous orbit. The analysis was done for three popular wavelengths – 532 nm (green), 1064 nm (red), and 1550 nm (brown). A spaceborne transmitter with an output of 3 W, a full beam divergence of 4 arcsec between Gaussian $1/e^2$ intensity points, simple On-Off Keying (OOK) at 2.5 Gbps, and an on-off modulation depth of 10^3 was assumed. The transmitted power for 532 nm was reduced to 1.5 W to reflect a 50% power conversion loss in the frequency doubler, but, on the positive side, the modulation depth of the original 1064 nm transmitter is squared by the same process. In addition to this “transmitter noise” due to imperfect extinction of the 0’s, we assumed a worst case high noon scenario for solar scattering in the atmosphere. Detector dark counts were assumed to be negligible compared to solar scattering and were not included in the analysis. The best detector quantum efficiencies available were assumed for each wavelength. We also included the effects of the atmospheric turbulence including beam wander, spread, and scintillation. The scintillation indices used are plotted in Figure 5a and reflect both the increased atmospheric scattering at shorter wavelengths (green = 532 nm, red = 1064 nm, brown = 1550 nm) and the theoretical $[\sec(\theta_z)]^{11/6}$ power dependence of the index on the satellite zenith angle [Andrews and Phillips, 1998]. The goal of one bit error per second is indicated by the dashed horizontal line in Fig. 5b. Based on our atmospheric noise models, the detector threshold was varied with zenith angle to maintain a rate of false 1’s below the targeted bit error rate. However, the number of false 0’s (undetected 1’s) increases rapidly with zenith angle beyond some wavelength dependent break point due to scintillation-induced fading. That breakpoint was

37° at 1064 nm (but the BER goal was met up to 45°) and 55° at 1550 nm. The frequency-doubled laser was never able to meet the BER goals at the reduced power level. Increasing the transmitted power by 66% to 5 W allows the 532 nm wavelength (2.5 W) to meet the BER goals down to zenith angles of about 15° and only extends the breakpoint and BER limits at 1064 and 1550 nm outward by about 7° to 52° and 62° respectively. .

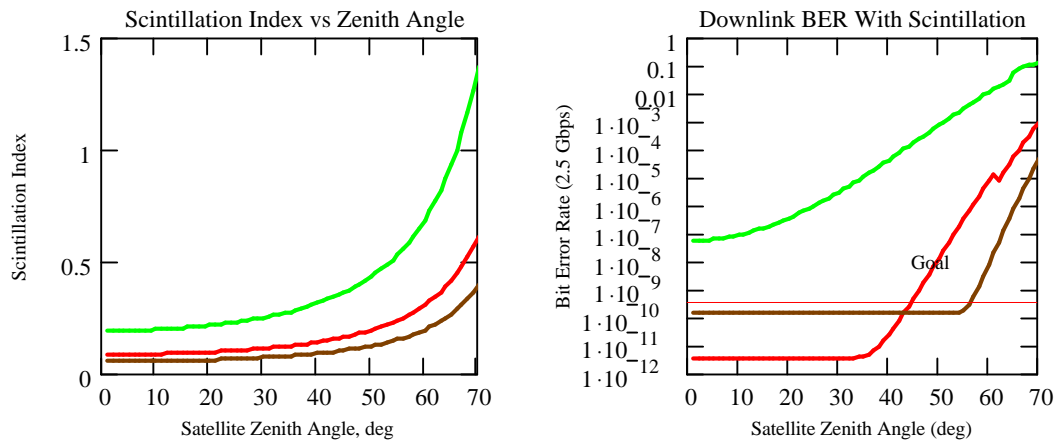


Figure 5: (a) Scintillation index used in the multiwavelength lasercom link analysis; (b) Computed daylight Bit Error Rate (BER) at 2.5 Gbps as a function of wavelength and satellite zenith angle. Goal (dashed red horizontal line) reflects one bit error per second.

8. LUNAR AND DEEP SPACE COMMUNICATIONS

Because the signal from a passive retroreflector target falls off as the fourth power of the range (R^{-4}), an active laser transponder would be substituted for the passive target when considering combined ranging and communications between SLR2000C and a spacecraft at lunar or interplanetary distances [Degnan, 2002]. Both the transponder and lasercom signals would now fall off as R^{-2} . Since a distant spacecraft sees half the Earth disk but is above 20 degrees elevation over only 33% of the Earth surface, we would need approximately $3 \times 7 = 21$ uniformly distributed stations for 99% availability or $3 \times 10 = 30$ stations for 99.9% availability, again assuming a mean single station availability of 50%

8. SUMMARY

We have argued that satellite laser ranging and lasercom applications are highly synergistic since most of the ground 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. The 1550 nm wavelength is not only eyesafe, but the high atmospheric transmission and low scatter combined with low solar output in this spectral region greatly improves the signal to noise situation for free space laser communications.

At geosynchronous altitudes, a single 10 cm diameter, unspoiled hollow cube corner is capable of satisfying the SLR2000C ranging link and contributes no error to the range measurement. Range returns from the passive reflector provide independent verification of satellite acquisition and lock and greatly simplifies terminal acquisition for lasercom. An onboard CCD array can view the upcoming ranging beacon through a 532 nm filter for initial

acquisition of the ranging beacon, in situ identification of the active ground station by its position on the Earth disk, and initial coarse pointing of the onboard lasercom terminal. Narrow FOV 532 nm quadrant detectors at both terminals can further refine the pointing at the sub-arcsecond level. For longer deep space links, active laser transponders can be substituted for passive reflectors. Both lasercom data rates and range returns will fall off as R^{-2} for a given transmitter power/receive aperture product.

A 12 station ground SLR2000C network can provide >99.9% availability for LEO to Earth communications using intersatellite relay links. A denser 25 to 30 site SLR2000C network would support both global "bent pipe" LEO to GEO to Earth communications and deep space coverage with > 99% availability. Preliminary link calculations suggest the feasibility of 10 Gbps near-Earth downlinks (4 channels @ 2.5 Gbps per channel) and a 70 Mbps downlink capacity from the Moon with achievable laser powers of a few watts per channel. It is hoped that multi-user support will increase the likelihood for funding of a substantial global network which would benefit both geodesy and global scientific space-to-ground communications

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