Reduction of the Minimum Elevation Angle for NASA Satellite Laser Ranging Tracking Operations

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NASA Satellite Laser Ranging
and
Very Long Base Interferometry Program

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Introduction:

During the past few years, changing mission requirements have placed a greater need on increasing the amount of data observed from low earth orbit (LEO) satellites. One way to increase the data volume as well as increase the number of passes available for tracking operations, is to reduce the minimum elevation angle for satellite ranging operations. Presently, NASA Satellite Laser Ranging (SLR) systems are not permitted to track lower than an elevation angle of 20 degrees. However, for systems occupying the Goddard Geophysical Astronomical Observatory (GGAO), the elevation restriction increases to 30 degrees between the local hours of 6:00 A.M. and 9:00 P.M. (Reference NSLR Network Operating Procedures, NSLR-05-001 Revision 7). The following investigation analyzes the possible operational gains, scientific contributions, tracking capabilities and associated safety concerns of the NASA SLR Mobile Laser Ranging System (MOBLAS) for providing safe ranging operations at low elevations.

Operational Gains:

Satellite Support and Orbital Perigee

Presently, the NASA SLR network routinely supports 19 different satellites, with orbital altitudes ranging from 650 kilometers to more than 20,000 kilometers. The NASA SLR network has in the past, and will again in the future, track satellites with orbital altitudes of 400 kilometers and lower. Half of these satellites have a perigee of less than 1,500 kilometers, all of which rank in the top ten of the International Laser Ranging Service (ILRS) tracking priority list. Low orbital satellites are very short in pass duration. Additionally, they are more difficult to acquire as they move rapidly along the orbital arc and are perturbed more easily by the earth's atmosphere and gravity field. Reducing the elevation limit would allow the operator to initiate tracking efforts earlier in the satellite's orbit where the azimuth angular velocity of the tracking mount is less.

Satellite Availability

With reduced tracking elevation limits, satellite availability will be dramatically increased. Entire passes and portions of passes that are presently below the 20 and 30 degree limits would become available. The increased availability would translate into an increase in the number of passes available as well as an increase in duration spent on a particular pass. As an example, five days of tracking opportunities for the Lageos 1 and GFO-1 satellites were examined for May of 1998. Schedule lists with a minimum elevation angle of 30 degrees and 10 degrees were computed for the MOBLAS 7 system, located at the GGAO in Greenbelt, Maryland. A reduction in the elevation angle from 30 degrees to 10 degrees increased the pass count from 23 to 26 for Lageos 1 and from 11 to 22 for GFO-1. Summing the duration of all the available passes in this five day period resulted in an approximate increase of 98% for Lageos 1 and 316% for GFO-1. Figures 1 and 2 are graphical representations of this data.

Satellite Pass Availability

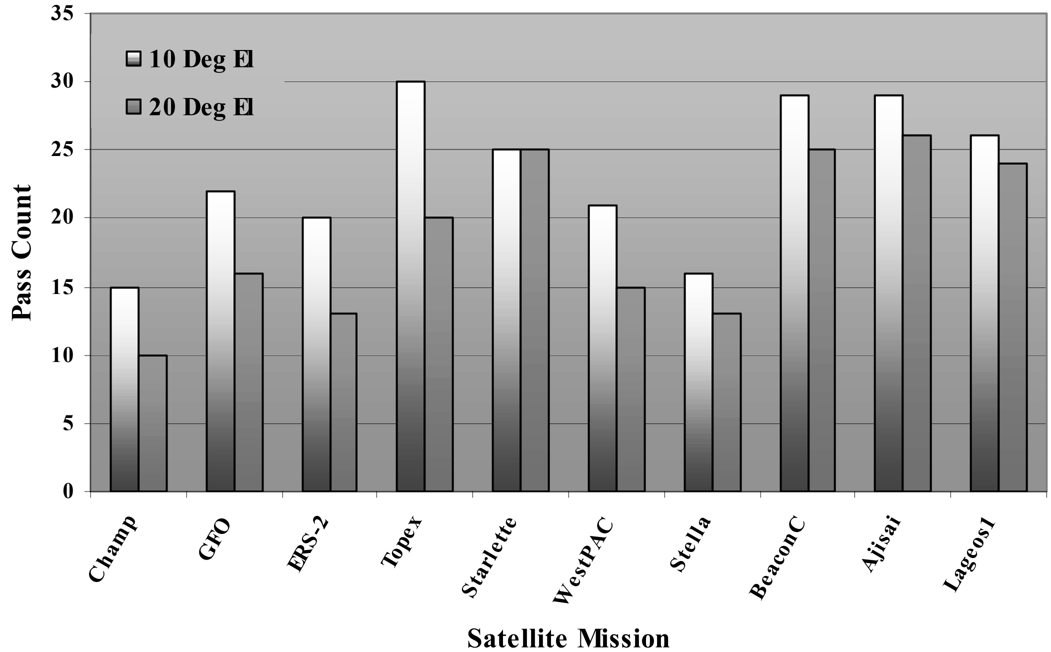

Figure 1

Satellite Pass Duration

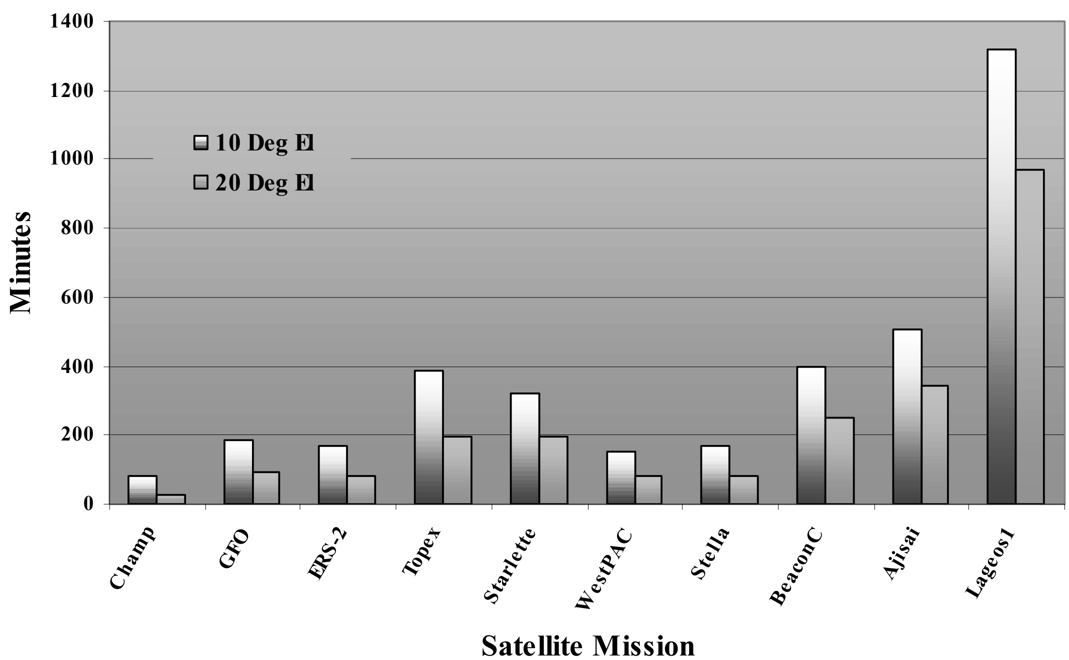

Figure 2

Satellite Array Capability

Not all satellite arrays are created equal. Spherical arrays such as those on Lageos and Starlette can be tracked at virtually any angle. However, arrays on satellites such as Topex/Poseidon and ERS-1 have limited tracking angles. As a result, some satellite arrays either may not be visible or the visibility may decrease considerably at elevations lower than 30 degrees. Table 1 describes the satellites tracked by the NASA SLR, noting the size and shape of the retroreflector array.

Priority as of 2-22-00	Satellite Name	Array Shape	Size (cm)	Number of Retroreflectors
1	SUNSAT	Annulus	26	8
2	Westpac	Sphere	24	60
3	GFO-1	Hemisphere	16	9
4	ERS-1	Hemisphere	18	9
5	ERS-2	Hemisphere	16	9
6	TOPEX/Poseidon	Annulus	150	192
7	Stella	Sphere	24	60
8	Starlette	Sphere	24	60
9	BE-C	Pyramidal		160
10	Ajisai	Sphere	215	1436
11	LAGEOS I	Sphere	60	426
12	LAGEOS II	Sphere	60	426
13	GLONASS 72	Planar Square	120 X 120	396
14	GLONASS 79	Planar Square	120 X 120	396
15	GLONASS 80	Planar Square	120 X 120	396
16	GPS-35	Planar Rectangle	24 X 19	32
17	GPS-36	Planar Rectangle	24 X 19	32
18	Etalon-1	Sphere	130	2140
19	Etalon-2	Sphere	130	2140

Table 1. Satellite Arrays

Data Quantity

With the increased safety and ranging capabilities provided by the Mount Observer Automation (MOA) system and High Sensitivity Laser Receiver (HSLR) system respectively, many of the satellites presently tracked by the MOBLAS can be observed well below the 30 to 20 degree elevation limit. A decrease in the tracking elevation limit will permit increased dwell time on a particular satellite and will inherently increase Normal Point (NP) data quantity. On the other hand, the return rate may decrease for some satellites as the increased atmospherics will attenuate the transmit signal causing the receive signal to fall below the threshold for the receive electronics.

Orbital Arc Coverage

Lowering the elevation limit would increase the tracking coverage of the satellite orbital arc. For a satellite which passes directly over an SLR system, lowering the elevation limit from 30 degrees to 10 degrees will increase the orbital arc coverage by approximately 48% for the Lageos 1 satellite and approximately 92% for the GFO-1 satellite. For ease of calculation, satellite orbits were considered to be circular.

Scientific Contributions:

Blue Ribbon Panel Report

In 1996, NASA assembled a panel of world renowned experts to make recommendations as to the fate and direction of NASA satellite laser ranging activities. The expert panel published a the SLR Review Committee Report in April of 1997, which has come to be known as the Blue Ribbon Panel Report. The panel concluded that NASA should continue to play a strong role in the global SLR network. More germane to this report however, the panel recommended that "NASA with its international partners should direct strong efforts toward validating and refining the troposphere refraction model so that it is essentially unbiased and the residual errors are mainly random from pass to pass." (Reference SLR Review Committee Report, April 1997, section labeled Committee Recommendations, paragraph 3b). Lowering of the elevation limit angle would be in compliance with the committee's recommendations.

Scientific Community

In order to understand the scientific contribution that may or may not be realized by lowering the tracking elevation limit, three scientists in the field of SLR were requested to provide their comments. Below are their inputs.

> **Dr. Michael Pearlman, Smithsonian Astrophysical Observatory**
>
> "The operations at the satellite laser ranging stations are currently limited to elevations above angles currently specified locally or by convention. The minimum elevation has been set for aircraft safety, in the belief that the traditional visual technique of aircraft spotting is unreliable at low elevations. For most of the stations, the minimum elevation has been set at 20 degrees, but some stations such as GSFC do not operate below 30 degrees at times due to the high incidence of air traffic. A few other stations, in areas of very low air traffic, have at times lowered the limit to 15 and even 10 degrees. It has long been recognized that the low altitude data contains information useful to both science

and instrument performance, but the issue of safety overshadowed any serious consideration of its acquisition.

Many stations have now been equipped with radars and other sensing devices that have greatly improved aircraft detection, and other stations have plans to do so. In addition, some stations are using daytime constraints during nighttime hours, even though there is no air traffic.

The current NASA SLR program aggressively supports the completion of a geographically-distributed fiducial reference network of SLR stations. This network will probably include 12-18 high performance stations, while the remaining 20-25 SLR stations will be available for lower level participation in more specialized, regional applications. To increase the cost effectiveness of the fiducial network, we should be trying to maximize geographic coverage with as little increase in cost as possible.

Lowering the elevation limits (e.g. 20 degrees to 10 degrees) at the fiducial network stations, will:

1. increase orbital cover coverage by 50 - 100% (depending upon satellite altitude) without adding any new stations, thereby providing:

    a. improved definition of LAGEOS orbits for better separation of dynamic (GM) and kinematic (ae) scale;

    b. longer tracking arcs on altimeter satellites for better orbital height interpolation between ground stations;

    c. longer tracking arcs on low earth orbiting satellites for better determination of the intermediate terms of the gravity field; and

    d. better definition of the low order/low degree tesseral harmonics for better identification of time varying effects;

2. provide a better understanding of the influence of the atmosphere on range measurements, which could provide a means of improving data quality through real-time observations;

3. improve system performance evaluation through:

    a. better separation of range bias from station height; and

    b. increased overlap between stations for geometric data quality tests

The largest systematic ranging error for high performance SLR systems today is the estimation of the refraction delay due to the atmosphere. Current models assume a spherically symmetric atmosphere whose characteristics are fully determined by ground based meteorological data. Analysis of range residuals down to low elevations, where the atmospheric delay increases rapidly, will provide information to better understand the influence of the atmosphere. A real-time estimate of the zenith delay along with some measure of azimuthal dependence could improve data quality."

Dr. Richard Eanes, University of Texas, Center for Space Research

"I think that data below 20 deg would be nice to have. I have firm evidence that Marini-Murray needs to be changed even above 20 deg. All of the best SLR systems want to change the zenith delay by 3 mm when averaged over a number of years and adjusted simultaneously with bias, and height. Having the lower elev. data will help this type of study. And if you don't want to use it you don't have to!"

Dr. Ron Nooman, Delft University of Technology, Faculty of Aerospace Engineering

"We, both in our quick-look and "full-rate" analyses, always use a cut-off of 20 deg. The reason is simply the quality of the troposphere model (Marini Murray, for which we feel a value of 2-3 cm is the limit at these elevations). As it turns out, only few stations are affected by this (Graz is a notably one).
This may change, I understand....

Personally, I am not very convinced of the use of going further down. The quality of the troposphere model will remain an issue, and if analysts (not one, but all of them) choose to stay on the safe side there's no point in doing all of the effort to acquire the data. In addition, from an analyst point of view: what makes SLR unique? I think this is absolute coordinates, and in particular the vertical and the geocenter. Adding observations at very low elevations will not contribute much to the vertical. You may argue that it will add to the quality of the horizontal position, but considering the additional uncertainty because of tropo I have my doubts about this. More data is not always better.

As for the geocenter, both vertical and horizontal contribute here. I do not see the improvement in this parameter going to another elevation. One might address the issue in a very pragmatic way: do a test with a selected data set (e.g. 1993-1995 or so) and see how quality varies if the minimum elevation is changed. For instance, do the analysis with 20 deg, and repeat it with a cut-off of 30 deg (there's no point in going down to 10 deg in this test, because stations are not focused on this; there will be little data). Nice test, but I do not have the opportunity to do it...."

Tracking Capabilities:

Optically Low Linked Satellites and Long Time of Flights

In recent years the capabilities of the MOBLAS have been upgraded to better support the needs of the SLR community. The recent installation of the High Sensitivity Laser Receiver (HSLR) provides the MOBLAS with increased nighttime capability of tracking low optically linked satellites such as the GPS. The GPS satellite, orbiting at altitudes of greater than 20,000 kilometers, produces very long time of flights (TOF) for the transmitted laser energy. Until recently, the MOBLAS was not able to support a TOF greater than 150 milliseconds, which corresponds to approximately 30 degrees in elevation for the GPS satellite. However, upgrades to the controller computer software now allow support of TOFs of approximately 225 milliseconds. This is much greater than the TOF for the GPS satellite at 10 degrees elevation of 165 milliseconds.

Range Rate

Mr. John Seago, an orbital analyst for the NASA SLR network, offers the following observation about the potential use of satellite range rate information. "The uncertainty in troposphere model might be larger at low elevations, but the error difference between successive observations (used to make a RATE measurement) would be small. That is to say, systematic errors like refraction would tend to cancel in the formation of a rate observation. Needless to say, rate measurements are larger numbers at lower elevations (typically) so even small random errors may have less effect on the value of the measurement (but this is secondary and needs some investigation). Rate measurements could be a potential way to improve low elevation tracking quality until better refraction models can be established."

System Star Calibration Capability

The star calibration program used on NASA SLR systems has the capability of allowing the telescope to observe and model stars as low as 10 degrees in elevation. To accomplish this, parameters within a file called Mask would need to be modified to reduce the star calibration tracking elevation angle and the laser fire elevation angle. These modifications are simple and can be accomplished easily onsite and do not required recompiling of the software. Depending upon system location, optical background noise, atmospheric attenuation and star magnitude, observing stars at lower elevations is usually more difficult. Presently, the system operator observes about 50 stars between the elevations of 20 degrees to 85 degrees for the star calibration.

Satellite Tracking Schedule

A reduced tracking elevation limit may require adjustments to satellite tracking schedules. Increased availability, longer tracking opportunities and considerations with respect to the retroreflector array capability may need to be included in the scheduling parameters. The NASA SLR scheduling software does have the capability of selecting the minimum tracking elevation on a per satellite and a per station basis. Use of this feature will allow schedules to be adjusted to increase or decrease the number of available passes and pass duration for a particular satellite. Figures 1, 2 and 3 are the tracking schedules for the MOBLAS 7 with a 30 degree, 20 degree and 10 degree minimum elevation limit. As the tracking elevation is decreased, the number of passes increases, especially for the higher priority, lower orbital satellites. Likewise, as the tracking elevation is decreased, the number of minutes a satellite is visible increases, especially for the higher priority, lower orbital satellites. This value is represented by the numbers in the columns on the right-hand side of each figure.

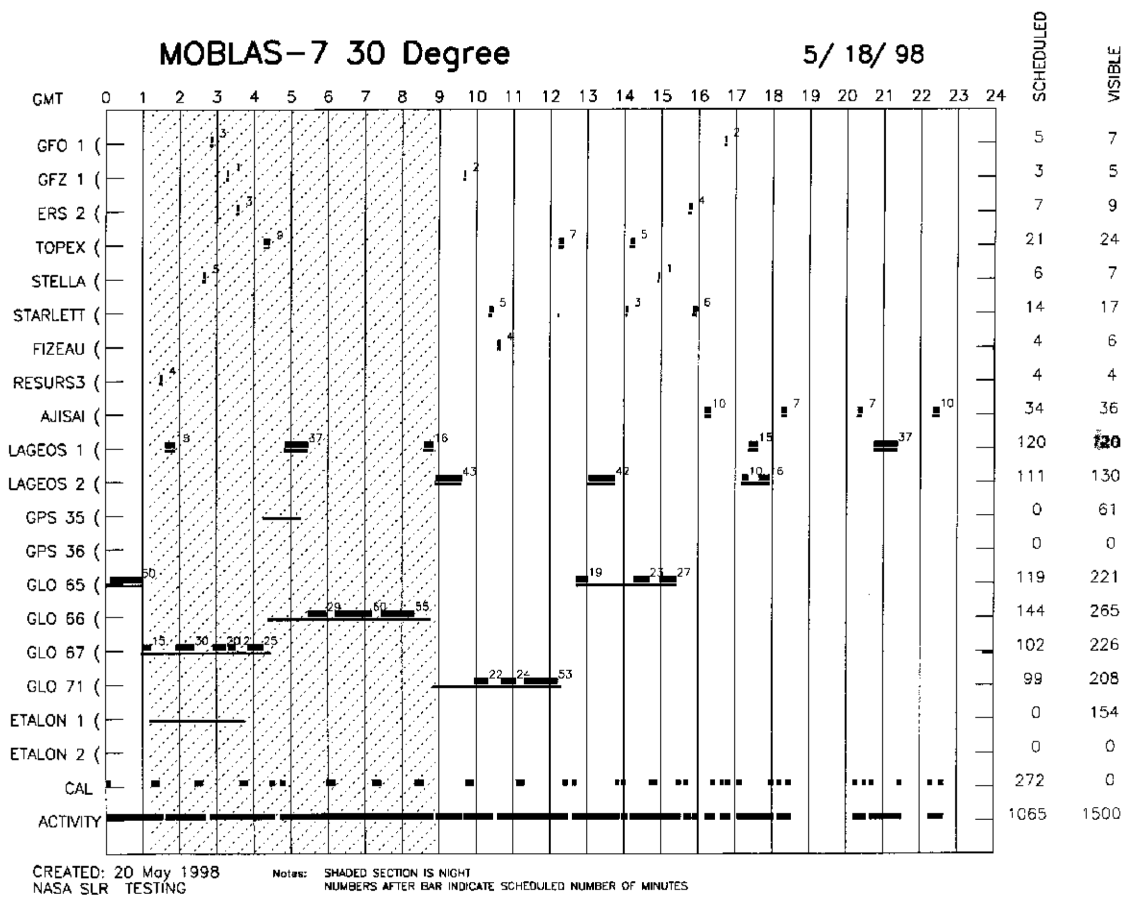

Figure 1. MOBLAS 7 Tracking Schedule for 30 Degree Elevation Limit

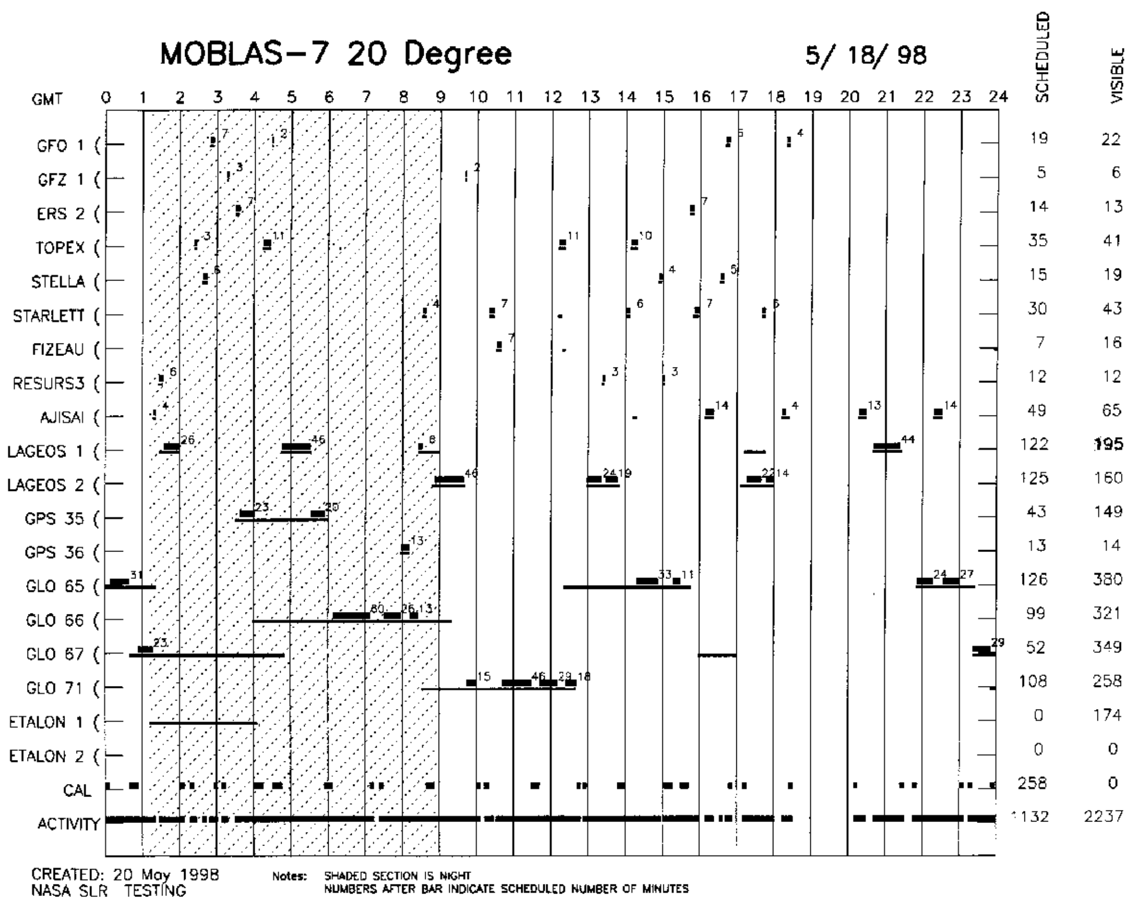

Figure 2. MOBLAS 7 Tracking Schedule for 20 Degree Elevation Limit

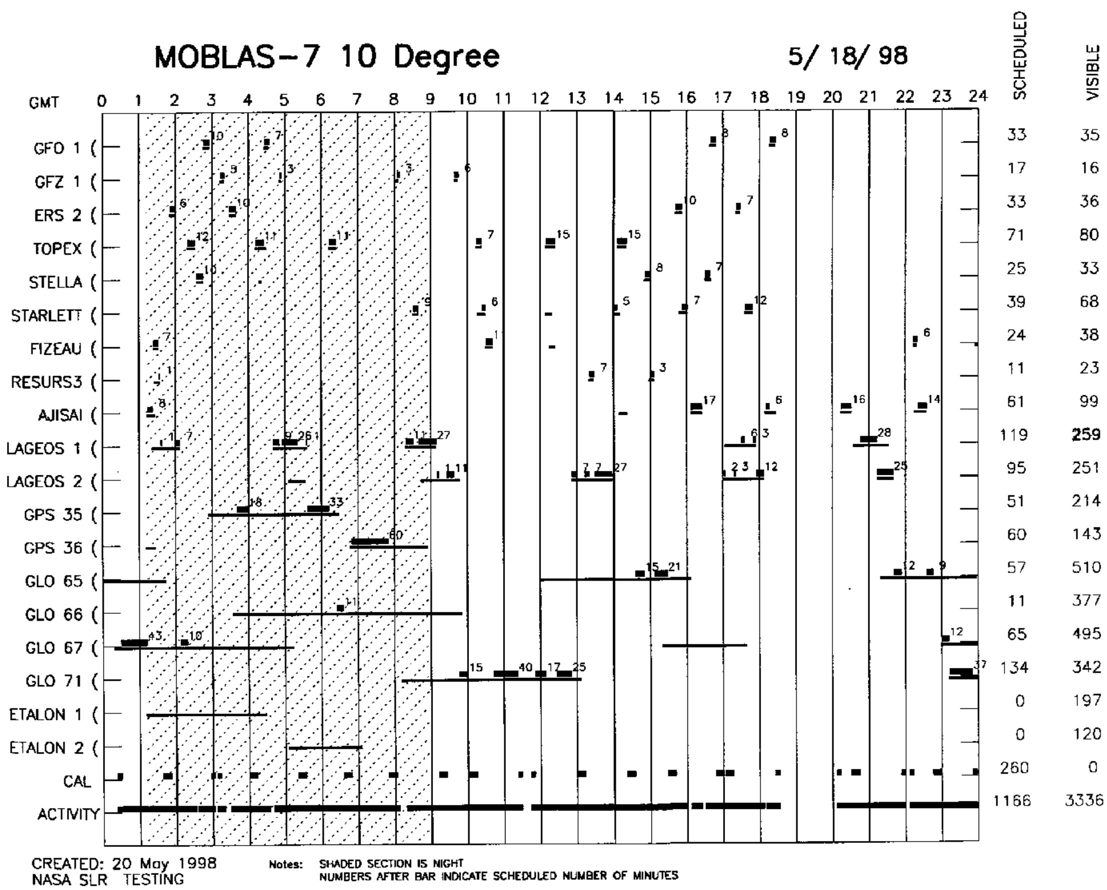

Figure 3. MOBLAS 7 Tracking Schedule for 10 Degree Elevation Limit

Tracking Safety Concerns

The main reason for not performing laser tracking operations below 20 degrees, and the reason a 30 degree limit was imposed at the GGAO facility, was the concern for safety. The primary job of the human observer is to prevent the illumination of airborne or ground based objects by the laser transmitter. Increased atmospheric attenuation, increased optical background noise from nearby cities and towns, and the decreased vertical spatial difference between aircraft make the human observer less effective at elevations below 20 degrees. In the case of an SLR system based at the GGAO, the light pollution and air pollution caused by local cities such as Washington DC, Baltimore and Laurel, coupled with the high humidity of the east coast, can make the viewing conditions for the human observer extremely difficult. In addition, the 4 major airports and 20 plus smaller airports located within a 30 mile radius of the GGAO produce a very large amount of air traffic, on the order of 2 million aircraft landings and take offs per year.

MOBLAS Safety System

In 1994, the Mount Observer Automation (MOA) system was first integrated with the MOBLAS 7, which is located at the GGAO site. The MOA is comprised of a radar system, sensors and safety devices that virtually eliminate the possibility of illuminating ground-based or airborne objects with the transmitted laser beam. Replacing the human observer, the MOA is an automated system, which is not affected by the conditions, which would impair the performance of the human observer. In 1995, the Safety and Environmental Branch of NASA accepted the MOA as a replacement for the human observer for the MOBLAS.

The main subsystem of the MOA is the Laser Hazard Reduction System (LHRS), also known as the radar. The LHRS is comprised of a radar system mounted on a pedestal that is position "slaved" to the MOBLAS optical transmitter. The 2.8 degree divergent RF transmit beam of the radar encompasses the 0.01 degree divergent laser transmit beam of the MOBLAS. Any aircraft that flies within the RF beam of the radar is detected by the LHRS, which in turn disables the MOBLAS laser subsystem. The delay time from when the LHRS has detected the aircraft and when the laser energy transmission is disabled is less than 50 milliseconds. The effective range of the LHRS is from 500 feet to more than 128,000 feet, or 24 statute miles. Since the MOBLAS Nominal Ocular Hazard Distance (NOHD) is 22 statute miles, the LHRS provides protection through all unobstructed elevation pointing angles.

Laser Hazard Reduction System Limitations below 20 Degrees Elevation

While the LHRS can detect objects greater than the NOHD of the MOBLAS laser, objects that are closer to the radar transmitter than 500 feet are offered no protection. Since the Federal Aviation Administration rules require aircraft to maintain a distance of 500 feet from all ground based objects during flight, there is no safety concern for airborne aircraft. However, ground based objects, such as buildings, towers, etc. do pose a problem. At each of the MOBLAS systems, elevation maps are periodically performed. This mapping of the elevation consists of using a small telescope co-aligned with the laser transmitter to detect whether or not the transmitted laser will illuminate any ground based object. A laser elevation horizon map performed at the MOBLAS 7 is shown in Figure 4. MOBLAS hardware and software safety devices are used to mask specific elevation and azimuth coordinates to prevent the laser from illuminating ground based objects, thus preventing satellite tracking in those areas.

Limitations also exist with the LHRS. Depending on the topography surrounding the system and location of ground based objects, this "ground clutter" can trigger the LHRS causing it to disable the laser. However, this is a benefit as it does prevent illumination of these ground based objects. An elevation map was developed using the radar to identify the ground clutter surrounding the MOBLAS 7. Performed in a similar fashion as an optical ground map, the radar is rotated in azimuth at discrete elevations and target detection is recorded. Figure 5 represents the MOBLAS 7 radar ground clutter map. Ground clutter associated with the LHRS, does not pose a safety problem however. It will simply cause the LHRS to disable the laser, thus preventing satellite tracking operations.

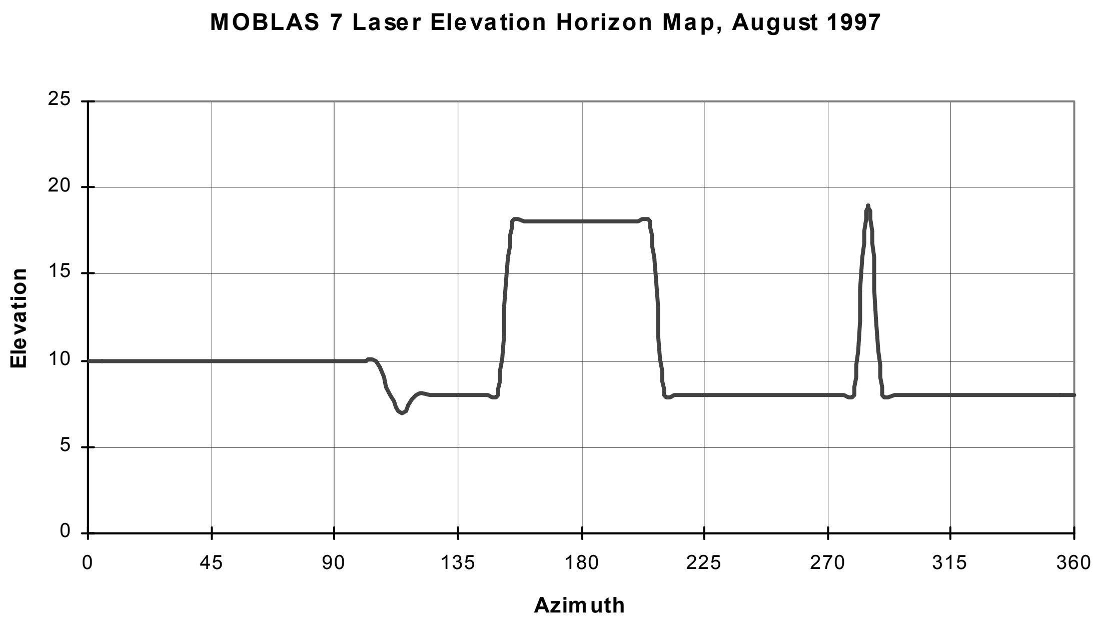

Figure 4. MOBLAS 7 Laser Elevation Horizon Map

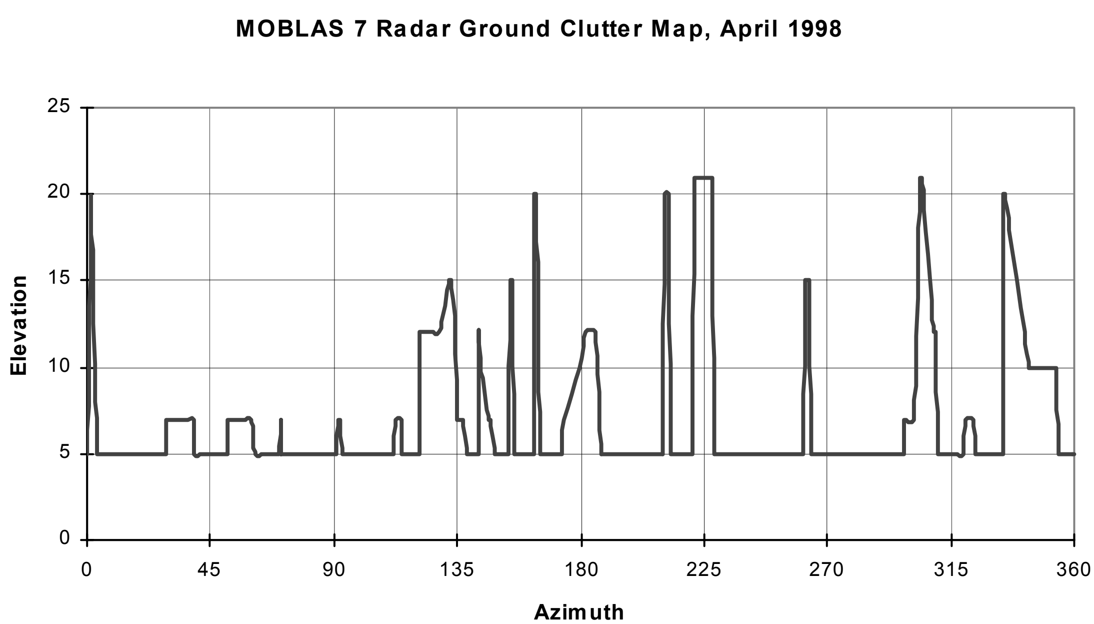

Figure 5. MOBLAS 7 Radar Ground Clutter Map

Conclusions:

After examining the possible operational gains, decreasing the elevation tracking angle to 10 degrees will increase the number of passes available for tracking (especially LEO satellites), increase dramatically the available orbital arc coverage and increase Normal Point data quantity (although exactly how much for this parameter is difficult to predict). Lowering of this angle will also allow the station operators to acquire signal returns from the satellites earlier in the pass duration. This is something that is highly desirable during the tracking operations of the very fast, and short pass duration, LEO satellites.

Reactions from the scientific community mostly favor reducing of the minimum elevation. Lowering the elevation tracking angle to 10 degrees will provide satellite laser ranging data useful for better defining the low order tesseral harmonics, for better orbital height interpolation between ground stations and for the refinement of atmospheric models. Additionally, refinement of the atmospheric model is a recommendation of the Blue Ribbon Panel Report. However, other scientists believe that the vertical and geocenter components derived from the data are what makes SLR unique. Data obtained from low elevations is not believed to strongly contribute to these elements.

The capabilities in both tracking and safety have been greatly increased since the inception of the 20 degree elevation minimum for SLR tracking operations. Star calibration software, controller computer ranging software, system tracking hardware and system ranging hardware all permit tracking operations down to 10 degrees elevation. The MOBLAS radar safety system that replaced the human observer has virtually eliminated the greatest concern of low elevation tracking, illumination of aircraft with the transmitted laser energy.