A Summary of Observations of GioveA, taken from Mt Stromlo SLR Station

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Abstract

A summary of satellite Giove A SLR data taken at Mt Stromlo over the period from May to August 2006 is presented, and some factors affecting tracking productivity are discussed. Although in a high earth orbit, Giove A has a large optical back scattering cross-section, and this has provided data for an empirical analysis of link budget factors which has allowed potential productivity gains to be assessed.

Introduction

The new Mt Stromlo SLR station has been in operation since December 2004 and data production has been reasonable and overall performance has been very good. Mt Stromlo productivity levels often exceed many other SLR stations. Nevertheless, improvements can be always be made, and this paper describes an analysis of the potential increases to productivity levels that may result from increased laser output energy, particularly as it applies to tracking Giove A and other high earth orbit satellites.

Total number of passes	**77**	**100%**
Number low elevation	**11**	**14%**
Number weather affected	**33**	**43%**
Number available	**33**	**43%**
Number attempted	**21**	**27%**
Number tracked	**12**	**15%**
Tracked/Possible	**12/33**	**36%**

Table 1 *Productivity Metrics*

SLR productivity (i.e. detection of returns) of high satellites is particularly sensitive to environmental factors such as cloud, air mass water vapour content and photon noise during daylight hours. These high satellites include the Glonass and GPS satellites, Etalon 1 and 2 and the first Galileo test satellite, Giove A. Satellites such as Lageos 1 and 2 are also affected although to a lesser extent. To illustrate the relationships between laser energy and productivity from high satellites, an analysis of Giove A tracking at Mt Stromlo is presented, particularly taking into account actual availability of passes and their distribution with elevation.

Tracking Giove A

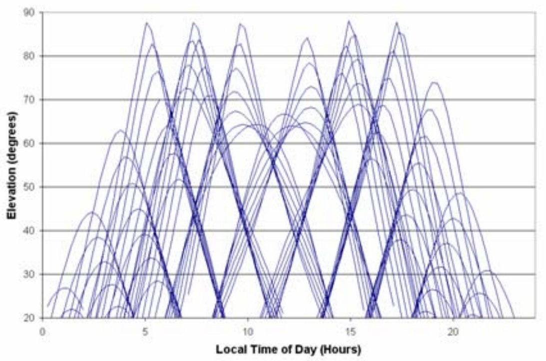

Figure 1: *Giove A passes, June 1 to August 9, 2006*

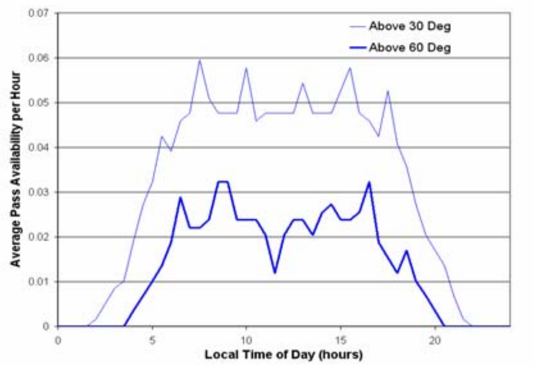

Figure 2: *Giove A Pass Availability*

Although Giove A was launched in December 2005, the ILRS was not requested to commence SLR tracking until late May 2006. The data from Mt Stromlo presented here are from observations taken from June 1st until August 9th (i.e. day 152 to 221). Table 1 summarizes the productivity statistics for this period and Figure 1 shows all of the available passes above the site's 20 degree horizon for this period.

By plotting pass elevations over 24 hour intervals, it was found that Giove A availability during the data period was on average not evenly distributed throughout the day. Figure 2 shows a frequency distribution plot (using time intervals of 0.1 hours) which indicated that there was a gap in passes during the period from approximately 18:00 to 04:00 local time (8:00 to 18:00 UTC) where passes were very sparse. There was also a significant reduction of very high passes in the middle of the day.

Actual Productivity of Giove A at Mt Stromlo

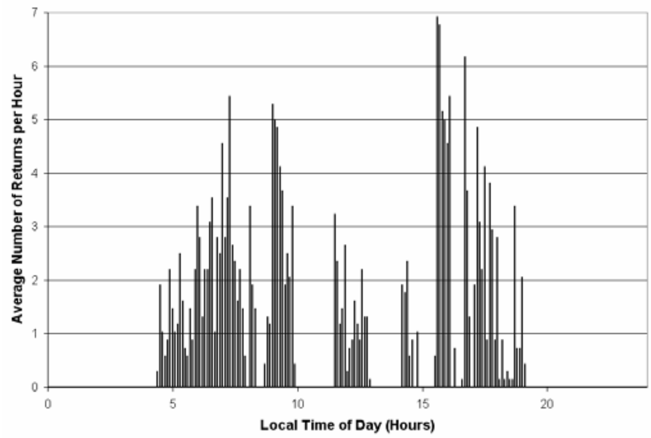

Figure 3: *Giove A Productivity*

While there are many factors affecting successful SLR tracking, it does appear that the distribution of available passes had influenced actual productivity of Giove A. Figure 3 shows the average distribution of number of successful (single-shot) returns over the course of a day, and as expected there were no passes tracked during the middle of the night. The impact of a reduced number of very high passes in the middle of the day is also apparent. However other factors such as sun avoidance and increased daylight noise would have also contributed to reduced productivity.

Figure 2 illustrates that SLR returns were being obtained from a wide range of target elevations (and thus ranges). To assess how productivity was dependent on target elevation a link budget analysis was performed. The following sections describe this analysis and results obtained.

Link Budget Analysis

Estimation of the SLR link budget was made using the standard link budget formulae which determines the average number of detected photons (returns) per laser pulse, N_{pe}, as [1],

$$N_{pe} = \eta_q E_T \frac{\lambda}{hc} \eta_T G_T \sigma_{sat} (4\pi R^2)^{-2} A_T \eta_R \tau_A^2 \tau_C^2 \qquad (1)$$

The transmit gain, G_T is given by $G_T = \frac{8}{\theta_K^2} \exp\left[-2\left(\frac{\theta_P}{\theta_K}\right)^2\right]$

For Giove-A and Mt Stromlo SLR laser we set the detector quantum efficiency, η_q, to 20%, the transmit and receive path efficiencies, η_R, η_T, to 90%, the laser pulse energy, E_T, to 13.5 mJ, the receive aperture area, A_T, to 0.7 m^2, the beam spread,

θ_P, to 1 arcsec, the pointing accuracy, θ_K, to 2 arcsec and the usual values to wavelength, λ, Planck's constant, h, and speed of light, c. The atmospheric transmittance, τ_A, was determined from an elevation dependent model [2] which gives transmittance at zenith of approximately 81% reducing to 72% at 20 degrees. Clear skies were assumed, so that cloud transmittance, τ_C, was set to 100%.

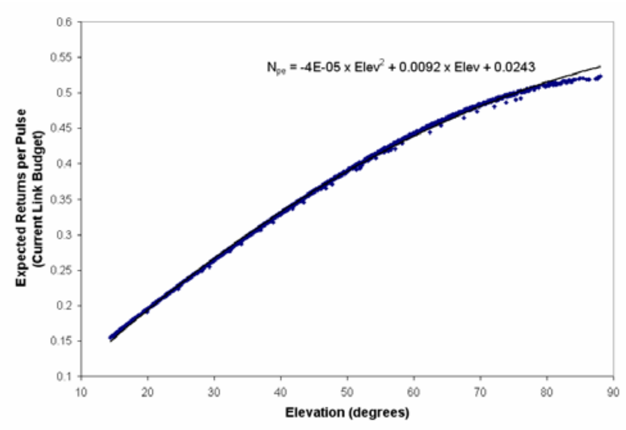

Figure 4: *Link Budget versus Elevation*

The Satellite back scattering cross section, σ_{sat}, for Giove A has been estimated to be in the order of $46 \times 10^6\, m^2$ (Dave Arnold, private communication). R is the distance from station to satellite (in meters) and is determined from orbit predictions.

The absolute value of estimated link budget is not critical and errors due to these assumptions do not affect this analysis. However, using these values, the average link budget estimates for Giove A against satellite elevation was calculated as shown in Figure 4. The polynomial regression line fitted to the average link budget estimates allows conversion or mapping between elevation, link budget estimates and hence laser energy. This equation is

$$N_{pe} = 0.0243 + 0.0092 \times Elev - 4 \times 10^{-5}\, Elev^2 \qquad (2)$$

where the elevation, *Elev*, is valid over the range 15 to 85 degrees.

Elevation Analysis

The mapping between link budget estimates and elevation allowed elevation to be used to provide a relationship between link budget estimates (i.e. laser power) and productivity. This analysis presents statistical analysis based on 5 degree elevation intervals from 20 degrees (the site horizon) to 90 degrees. For each elevation interval, the actual number of returns achieved (productivity) was normalized by the number of available passes in each interval to give the number of returns per pass.

The number of available passes per elevation interval is shown in Figure 5 and the productivity data for each elevation interval is shown in Figure 6. The second plot clearly illustrates that productivity falls with lower elevations (due to a decreasing link budget from an increasing range) and higher elevations (due to a lower number of available passes).

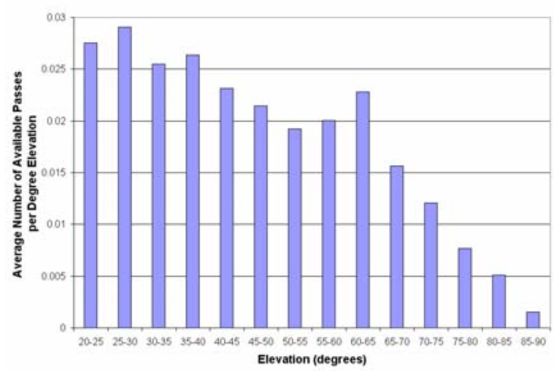

Figure 5: *Available Giove A Passes versus Elevation*

Hence a normalized productivity can be determined by dividing actual productivity data by the data availability. The results for Giove A are shown in Figure 7.

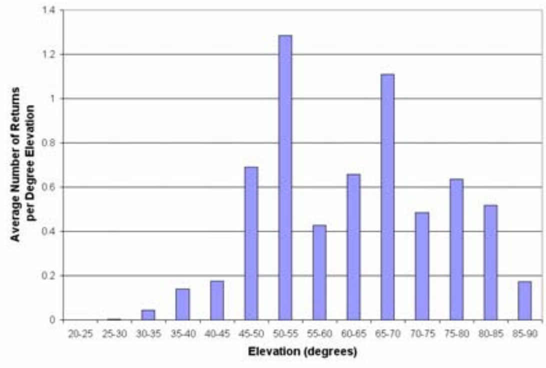

Figure 6: *Giove A Productivity versus Elevation*

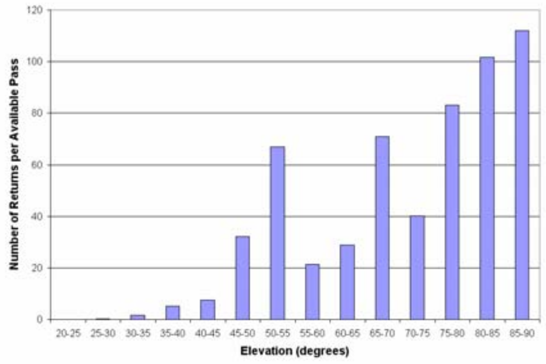

Figure 7: *Giove A Normalized Productivity versus Elevation*

Normalized Productivity

Figure 7 illustrates that, all else being equal, more returns are expected when the satellite is at a higher elevation. Scatter in this data indicates that in practice other factors such as weather are influencing productivity. It also appears that below approximately 40 to 45 degrees elevation, few returns were being detected with the given laser power levels.

When returns were detected at the lower elevations, observation logs indicated that the atmosphere was particularly clear and clean of particles, and that a strong signal had already been detected, and the satellite was being tracked as it descended in elevation.

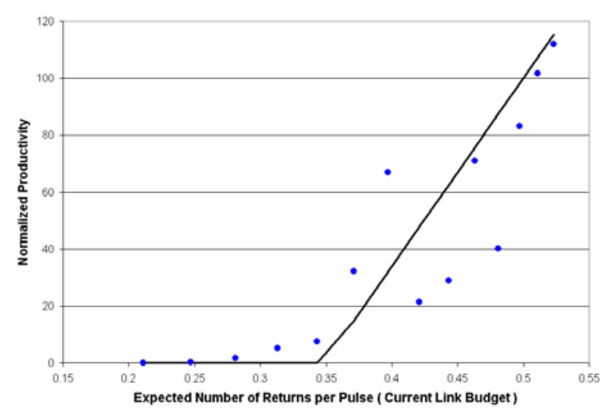

Figure 8: *Normalized Productivity versus Link Budget*

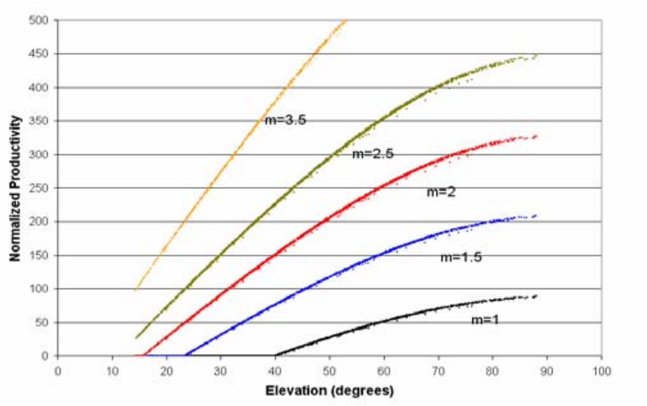

Figure 9: *Normalized Productivity Gains*

Using the conversion equation (2), normalized productivity can be compared to estimated link budget for each elevation interval. The results are shown in the Figure 8.

It appears that for link budget levels below 0.35 there is little or no productivity. For levels above 0.35, normalized productivity (η) appears to increase linearly with estimated link budget. A regression equation gives

$$\begin{aligned} &\eta = 660 \times N_{pe} - 230 \quad && N_{pe} > 0.35 \\ &\eta = 0 && N_{pe} < 0.35 \end{aligned} \qquad (3)$$

Of course ideally, it should be expected that actual return rate is proportional to expected return rate. In practice, it appears that this may be the case once the link budget reaches some "threshold" value.

Potential Productivity Gains

Equation (3) suggests that increasing the link budget (say by increasing laser power) to values less than 0.35 will give little or no improvement to productivity levels. However there should be significant gains by increasing link budget levels that are currently below 0.35 to values in excess of the 0.35.

Consider an increased link budget $N'_{pe} = mN_{pe}$ which is a result of multiplying current levels by a factor of m. From equation (3) the actual normalized productivity rate is expected to be now η', where

$$\begin{aligned} \eta' &= 660 \times mN_{pe} - 230 \quad & mN_{pe} > 0.35 \\ \eta' &= 0 & mN_{pe} < 0.35 \end{aligned} \tag{4}$$

Figure 9 shows plots of increased normalized productivity depending on the link budget multiplier, m.

Using the data gathered on Giove A pass availability, as shown in figure 5, the effect of link budget increases on actual productivity can be determined. Figure 10 shows such productivity plots for various values of m. The heavy line with m =1 is a smoothed curve using current data and is effectively equivalent to the plot shown in Figure 6.

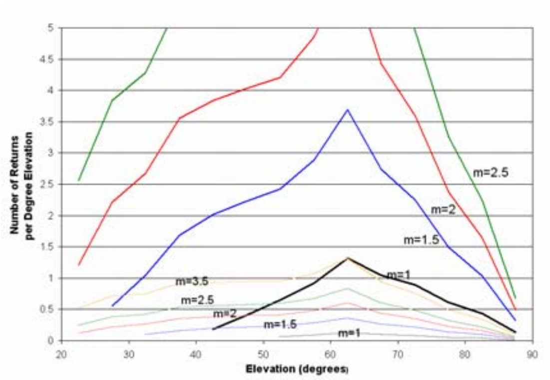

Figure 10: *Productivity Gains*

There are two sets of plots shown in Figure 10. The darker lines represent productivity increases based on current data while the lighter lines represent productivities assuming a factor of 10 (or 1 ND) loss in the number of returned photons. This factor is chosen to represent the loss when the enclosure glass window is installed and to account to some degree the effect of less than ideal sky conditions. The next section describes an analysis on the effect of the enclosure window, and for weak signals, it appears that a factor of 4 in link budget is required to compensate for the glass window.

It is clear that based on current data, increasing the link budget by 50% or 100% should make a substantial improvement to productivity including the possibility of obtaining reasonable number of returns from Giove A at elevations below 30 degrees. However, it is important that improved productivity levels can be maintained when the enclosure window is in place or when sky conditions deteriorate. Assuming a 1 ND loss, the second figure shows that an increase in link budget by a factor of 2 or more will be sufficient to maintain productivity at levels at least as good as current levels, and probably better at elevations below 40 degrees.

Effect of Enclosure Window

The Mt Stromlo SLR station is designed to allow continuous and unmanned operations in all weather conditions. This is in part achieved by having a weather-proof telescope enclosure incorporating a glass window. Such a window has many advantages for operations, but will also attenuate the transmit and receive beams. An assessment of the net impact from operating through the glass window is presented from comparisons made with data obtained when there was no glass window in place, i.e. the glass window is exchanged with an “air window”.

Near Field Target

A comparison of measurements to calibration pier (at a range of approximately 92m) with and without the glass window in place are shown in the Figure 11. The mean difference between the signals is approximately 0.061 ns (in two way time of flight) consistent with having a window with glass thickness of 18.3mm.

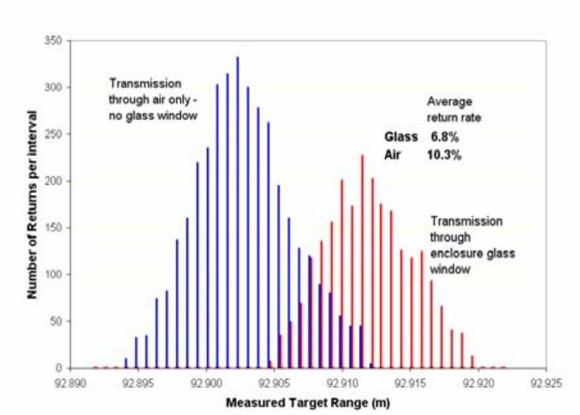

Figure 11: *Near Field Target Histogram*

For a given configuration (i.e. fixed laser power, ND filters etc.) and equal time periods the return rate with a glass window in place is 6.8% while in air the rate is 10.3%. Thus the difference in average return rate gives a loss of approximately 30%.

Far Field Targets

Data from far field targets at ranges of 6,100 to 10,000 km allows a comparison of results for relatively good signals (Lageos 1) and weaker signals (Lageos 2). These satellites are used since comparisons are difficult using much higher satellites when fewer returns are available when the glass window is in place. The second and third plots show average return rates and return rate (suitably normalized by tracking periods) distributions for the two signal levels.

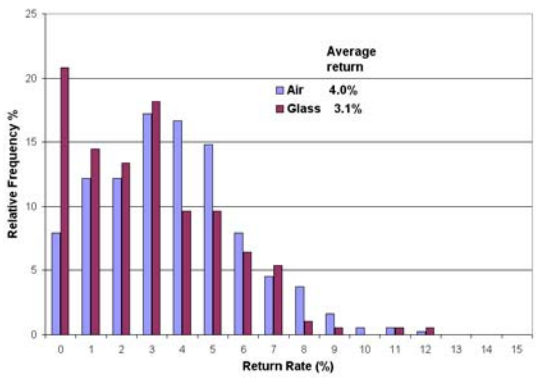

Figure 12: *Lageos 1 Return Rate Distribution*

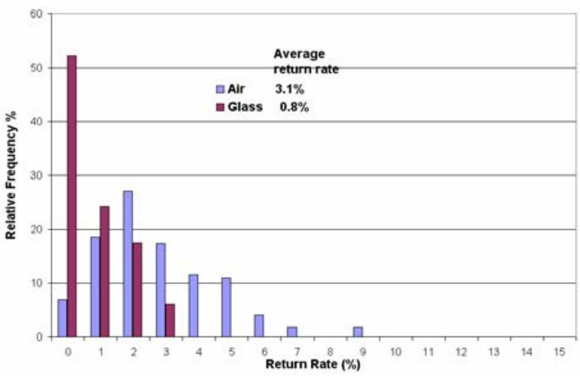

Figure 13: *Lageos 2 Return Rate Distribution*

Good Return Signal

When average return rate is relatively good, above 4% in air, the average return rate decreased to about 3% when the glass window was in place - indicating a 25-30% loss, similar to that for a near field target. The plot clearly demonstrates the relative decline in return rates above 3% when the window is in place and also the greater fraction of time there are no returns.

Weak Return Signal

When the return signal is weaker, in the case around 3% in air, the effect of the glass window is proportionally greater as illustrated in the third plot. In this case, the average return dropped to less than 1% when the glass was in place giving a loss of over 75%. Return rates with the glass in place do not exceed 4% and there are no returns for at least 50% of the time.

Conclusions

Mt Stromlo SLR station has successfully tracked Giove A for a number of months commencing in June 2006. A link budget analysis of the distribution of productivity data for this satellite with elevation has allowed an assessment of factors that may improve SLR productivity for Giove A (and other high earth orbit satellites).

Threshold effects associated with decreasing link budgets have been identified both during tracking of Giove A (e.g. with decreasing elevation) and also with Lageos 1 and 2 with transmission though air versus a glass enclosure window. Such threshold effects result in a rapid deterioration in detectable signal when return rates fall below approximately 3 or 4% for the current configuration at Mt Stromlo. Because of this threshold effect, it is possible that an increase in the link budget by a factor of two or better may lead to a substantial improvement in productivity. It is hoped that such an improvement can be demonstrated once the planned upgrade of the SLR laser power at Mt Stromlo has been implemented.

References:

[1] Degnan, J., Millimeter Accuracy Satellite Laser Ranging: A Review. Geodynamics Series 25.

[2] Degnan, J., 1993. AGU Geodynamics Monograph Vol.25, p.139-140