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

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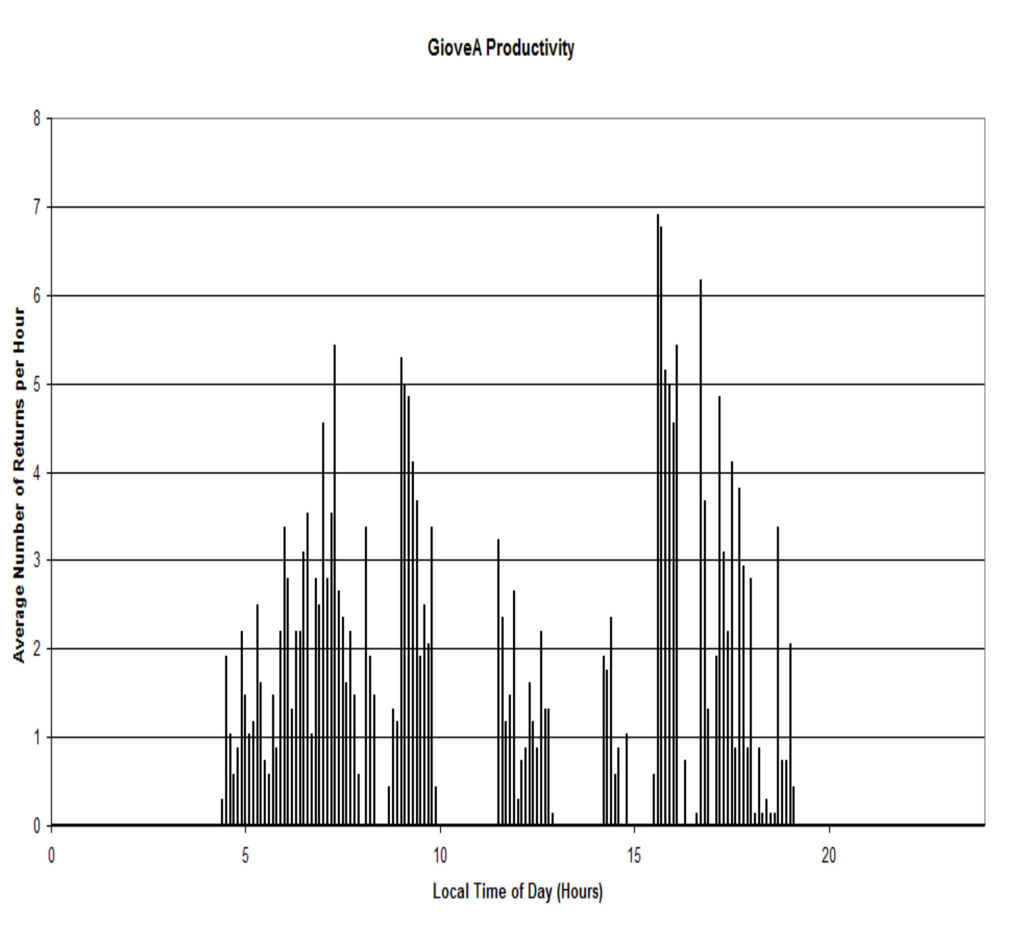
An assessment of satellite Giove A SLR data taken at Mt Stromlo over the period from May to August 2006 has identified some patterns that have impacted on tracking productivity. In addition, a high earth orbit satellite having a large optical back scattering cross-section has provided sufficient data for an empirical analysis of link budget requirements for tracking Giove A, Galileo and similar satellites.

Actual Productivity of Giove A Passes During the Day

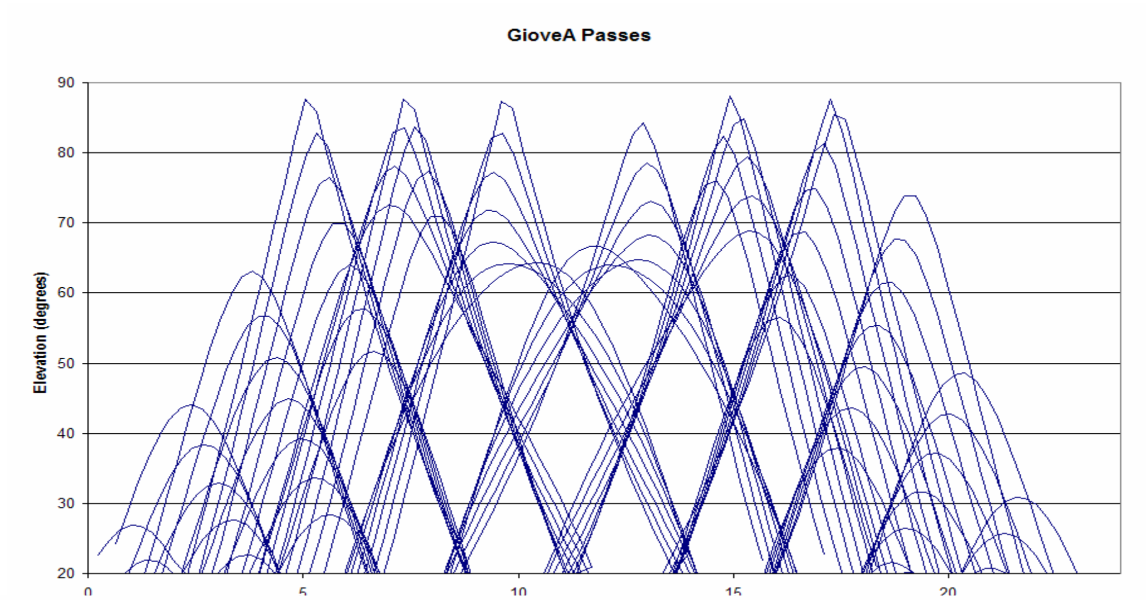


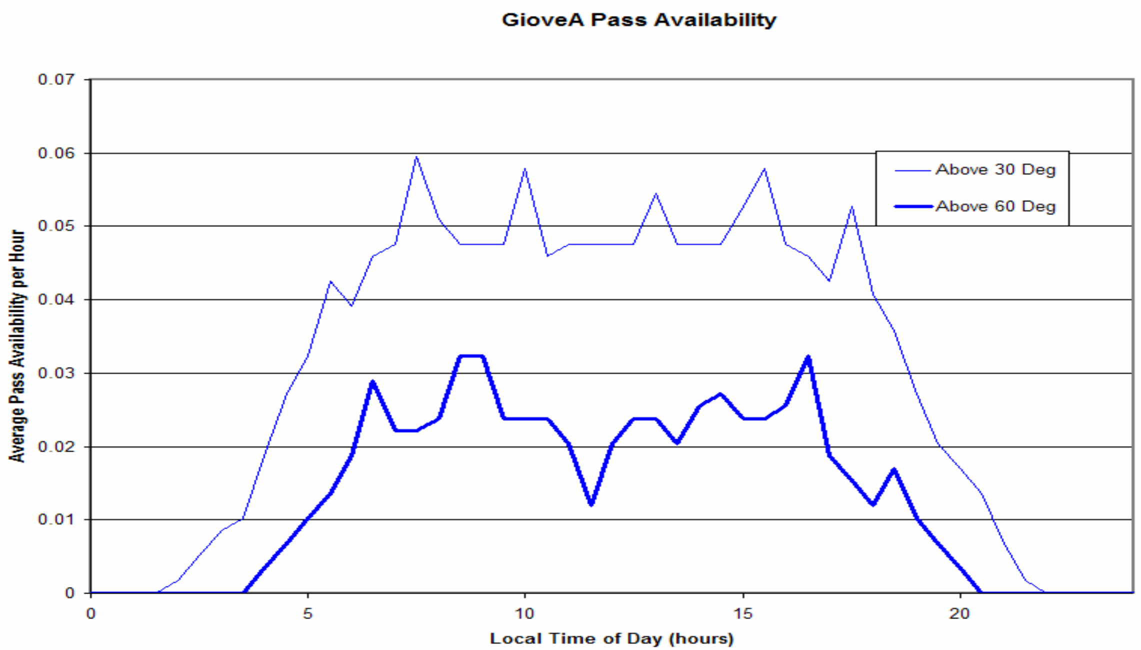
Actual Productivity at Stromlo

While there are many factors affecting successful SLR tracking, it does appear that the distribution of available passes has influenced actual productivity of Giove A.

This figure shows the average distribution of number of successful (single-shot) returns over the course of a day, and as expected there have been no passes tracked during the middle of the night, and 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 also have an effect.

Availability of Giove A Passes During the Day





By plotting Giove A 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.

A frequency distribution plot (using time intervals of 0.1 hours) showed 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.

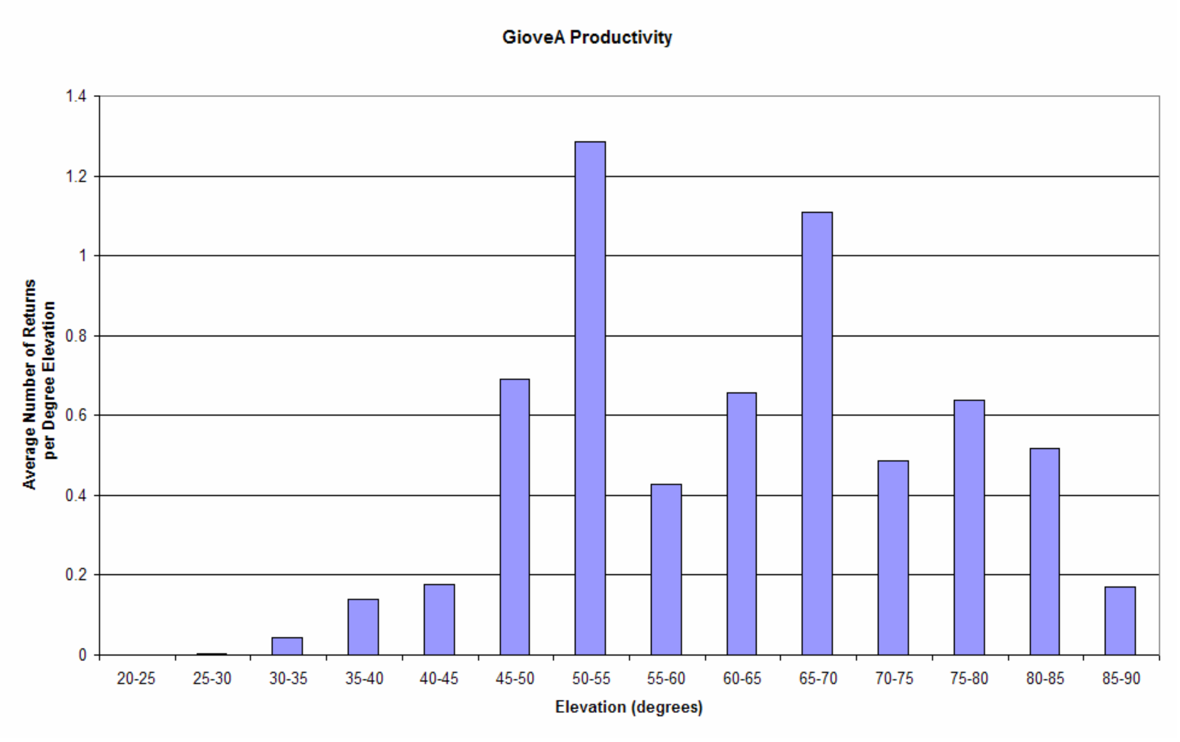
There was also a significant reduction of very high passes in the middle of the day.

Elevation Analysis – Actual Productivity

The second plot shows actual productivity against elevation.

Clearly the productivity falls with low elevation (low link budget due to increasing range) and high elevation (due to low availability of passes).

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



Potential Productivity Gains

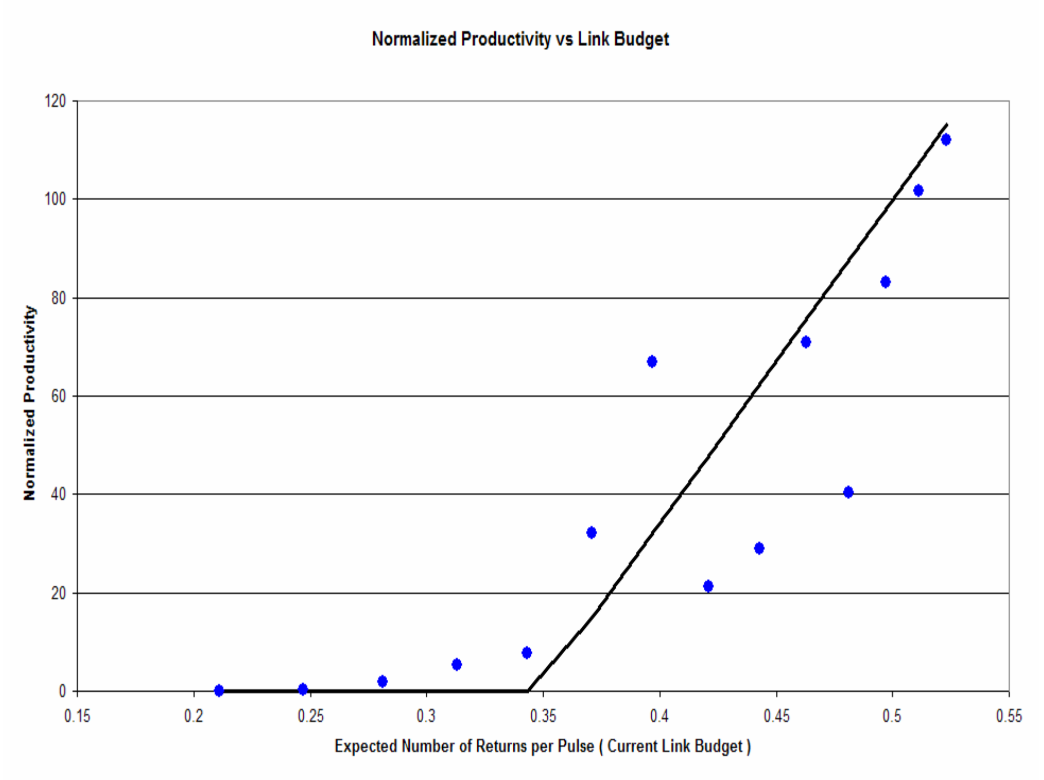
The mapping between link budget estimates and elevation allows normalized productivity to be compared with link budget estimates for each elevation interval, as illustrated in this figure.

It appears that for link budget estimates below 0.35 there is little or no productivity – i.e. no returns can be detected. For levels above 0.35, normalized productivity (η) appears to increase linearly with link budget values. A regression equation gives

$$\eta = 660 \times N_{pe} - 230 \quad N_{pe} > 0.35$$
$$\eta = 0 \qquad\qquad\qquad N_{pe} < 0.35$$

Of course ideally, it should be expected that actual return rate is proportional to expected return rate. In practice, it appears that this is the case once the link budget is sufficiently large.

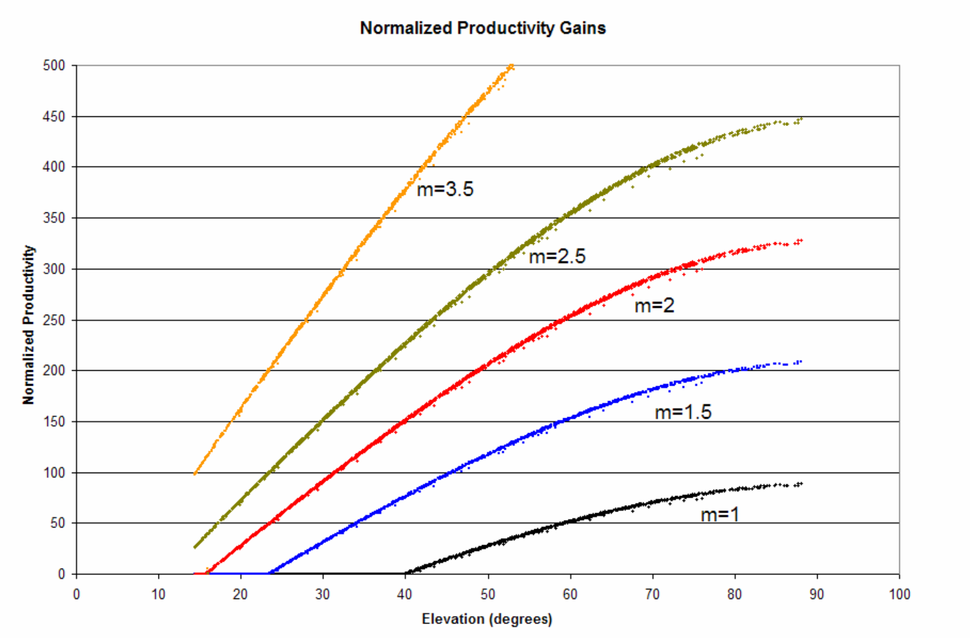
This regression equation suggests that increasing the link budget (say by increasing laser power) to values less than 0.35 will give little or no improvement to productivity levels. However there should be significant gains by increasing link budget levels that are currently below 0.35 to values in excess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

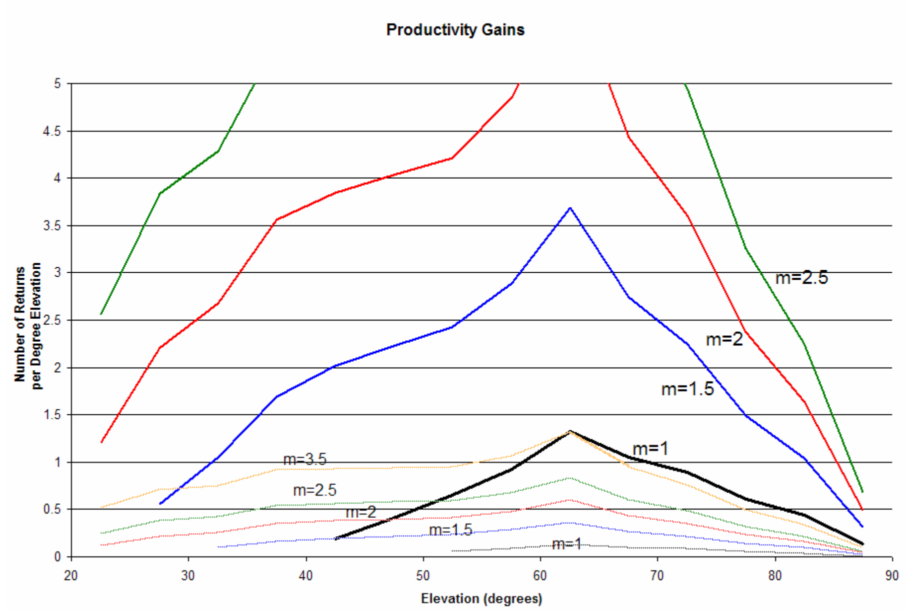


Therefore consider an increased link budget $N'_{pe} = mN_{pe}$ which will be the result of multiplying current levels by a factor of m. It is expected that in this case, the actual normalized productivity rate, η’, would increase according to the following,

$$\eta' = 660 \times mN_{pe} - 230 \quad mN_{pe} > 0.35$$
$$\eta' = 0 \qquad\qquad\qquad mN_{pe} < 0.35$$

Potential Productivity Gains





The first figure shows plots of increased normalized productivity depending on the link budget multiplier, m.

Using the data gathered on Giove A pass availability, the effect of increasing the link budget on actual productivity can be determined, and this is shown in the second plot 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 of current productivity.

The darker lines in the second plot represent productivity increases based on current data while the lighter lines represent productivities assuming a 1 ND loss in the number of returned photons. This factor is chosen to represent effect of less than ideal sky conditions and losses when the enclosure glass window is installed.

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.

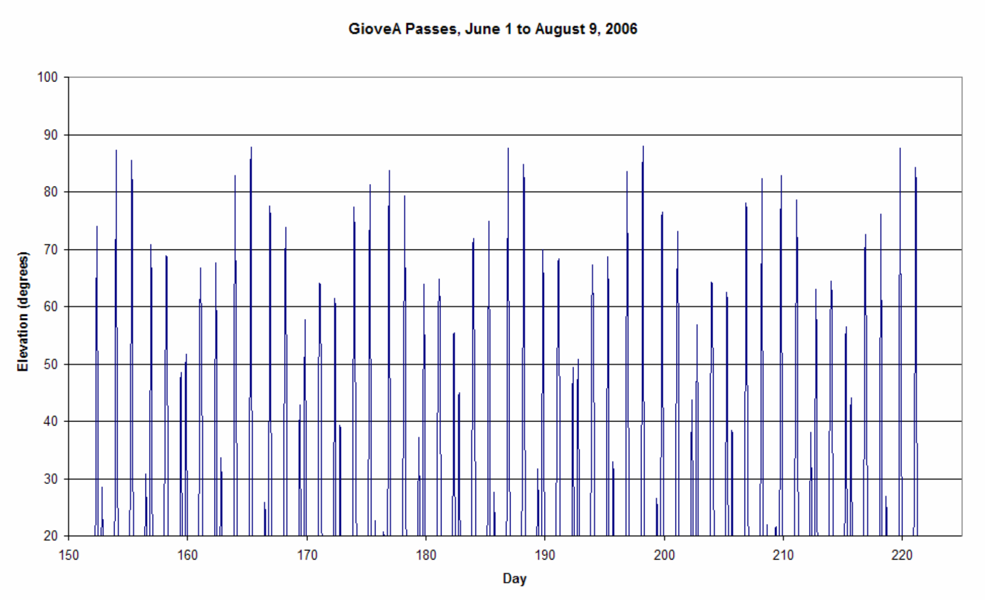
It appears that in good conditions, and no losses due to an enclosure window, a factor of 2 or more will provide good level of returns over the entire elevation range.

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 3 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.

Introduction

Returns from all of the high satellites being tracked are very sensitive to environmental factors such as cloud and air mass water vapour content and photon noise during daylight hours. These high satellites include Glonass 87, 89, 95, GPS 35 and 36, Etalon 1 and 2 and the first Galileo test satellite, Giove A. To a lesser extent satellites such as Lageos 1 and 2 are also affected

To illustrate the relationships between laser energy and productivity (i.e. return rate or normal points produced) 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. Note that to maintain productivity in varying sky conditions, during this period Mt Stromlo SLR Station has been tracking high satellites through an open enclosure window.



Tracking Giove A

Although Giove A was launched in December 2005, the ILRS was not requested to commence SLR tracking until late May 2006. Results are presented from observations taken from June 1st until August 9th (i.e. day 152 to 221).

The following table summarizes the productivity statistics for this period and the plot shows all of the available passes above the site's 20 degree horizon for this period

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%**

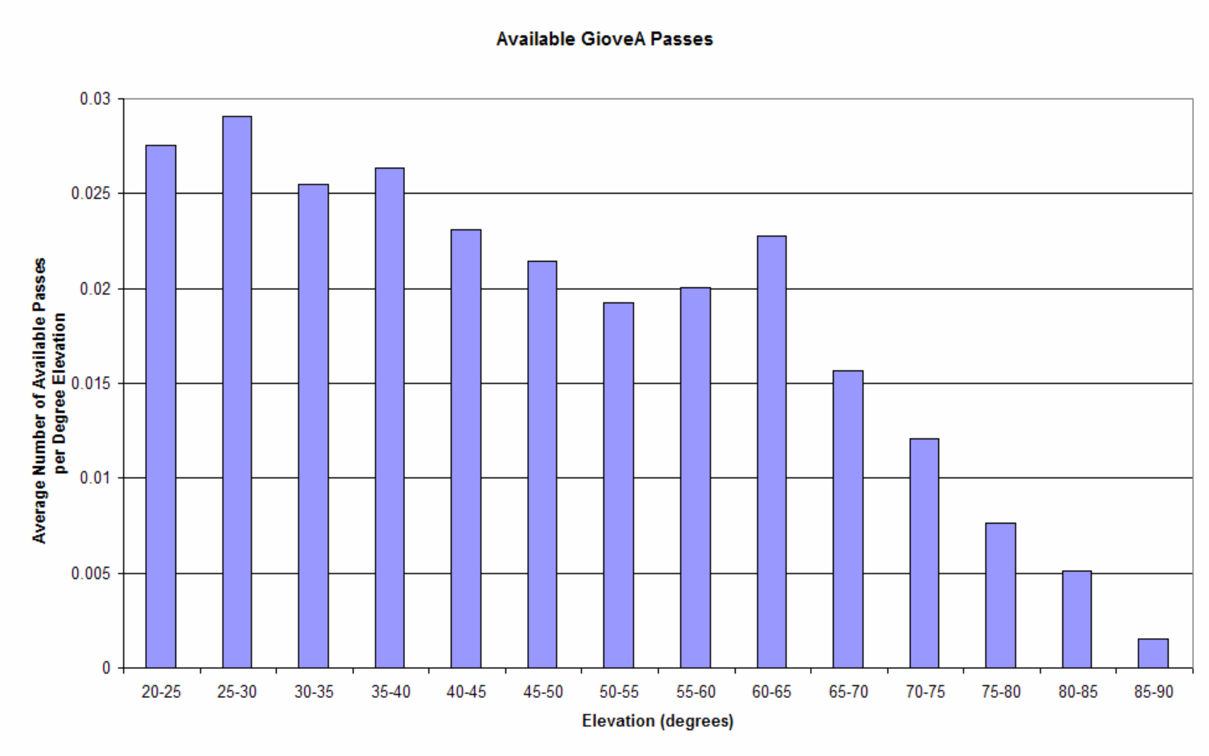
Elevation Analysis – Available Passes

The mapping between link budget estimates and elevation allows elevation to be used to provide a relationship between link budget estimates (i.e. laser power) and productivity.

This analysis presents statistics based on 5 degree elevation intervals from 20 degrees (the site horizon) to 90 degrees.

This first plot shows the number of available passes per elevation interval.

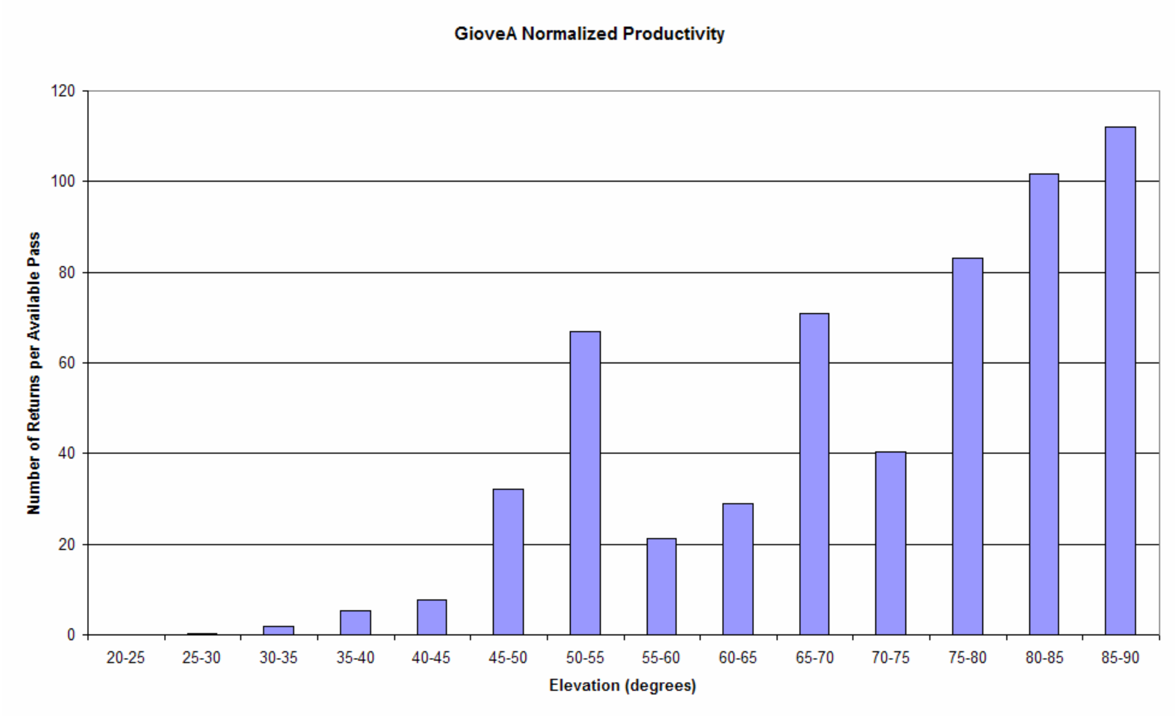
For each interval, productivity data must be normalized against the number of available passes at that interval.



Elevation Analysis – Normalized Productivity

This figure 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 40-45 degrees elevation, few returns are being detected with the current laser power levels.

Experience has shown that for the returns detected at these low elevations, the atmosphere has been particularly clear and clean of particles, and that a strong signal had already been detected, and the satellite is being tracked as it descends in elevation.



Link Budget Analysis

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

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

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

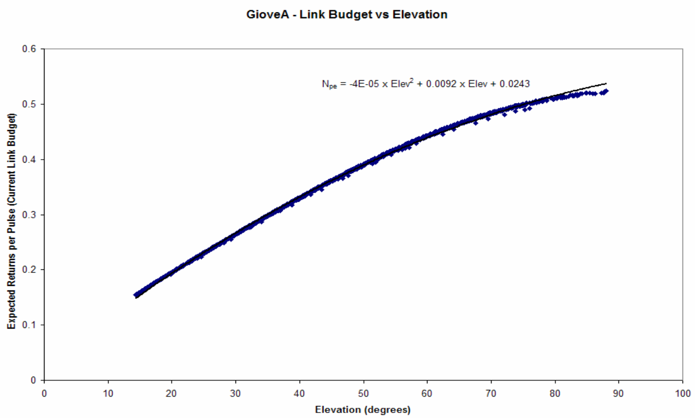
Definition of the remaining terms and the values assumed for Giove-A and Mt Stromlo station are as follows;
Detector quantum efficiency, η_q = 20%
Current pulse energy, E_T = 13.5 mJ
Transmit path efficiency, η_T = 90%
Receive path efficiency, η_R = 90%
Receive aperture area, A_r = 0.7 m^2
Beam spread, θ_P = 1 arcsec
Pointing accuracy, θ_K = 2 arcsec
Wavelength, λ = 532 nm
Planck's constant, h = 6.26×10^{-34} Js and speed of light, c = 3×10^8 ms^{-1}

The atmospheric transmittance, τ_A, was determined from the elevation dependent model described by J. Degnan, 1993 (AGU Geodynamics Monograph Vol.25, p.139-140). This model gives transmittance at zenith of approximately 81% reducing to 72% at 20 degrees.
Clear skies were assumed, so that cloud transmittance, τ_C = 100%.

The Satellite back scattering cross section, σ_{sat}, for Giove A has been estimated to be in the order of 46×10^6 m^2 (private communication from Dave Arnold).

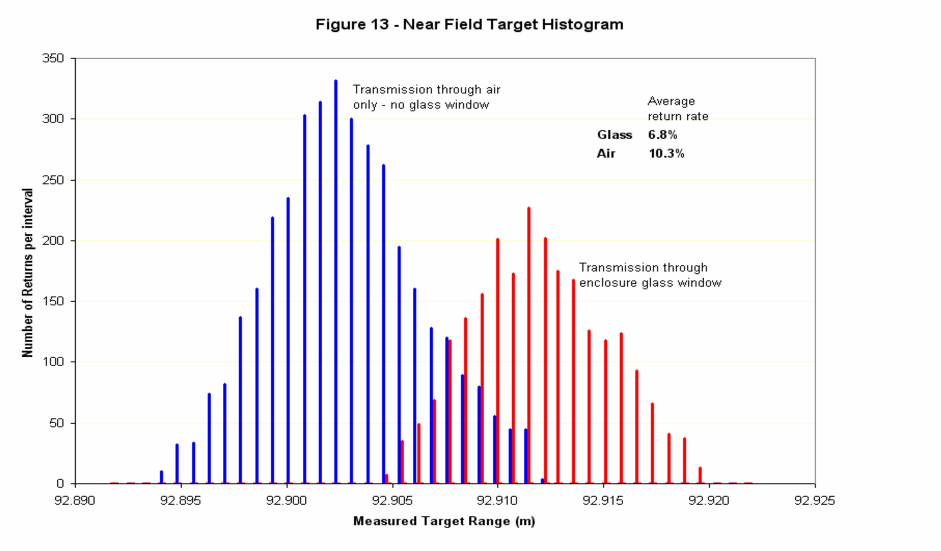
R is the distance from station to satellite (in meters) and is determined from orbit predictions.

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 can be calculated as shown in the following figure.



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 first figure.

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.

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%.

Effect of Enclosure Window

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.

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.

Conclusion

These two examples suggest there is a "threshold" effect occurring as link budgets are reduced (in this case by transmitting through a glass enclosure window). This is consistent with the link budget – normalized productivity plot using GioveA data and also indicates a rapid deterioration in detectable signal when return rates fall below approximately 3-4%.

Figure 14 - Lageos 1 Return Rate Distribution

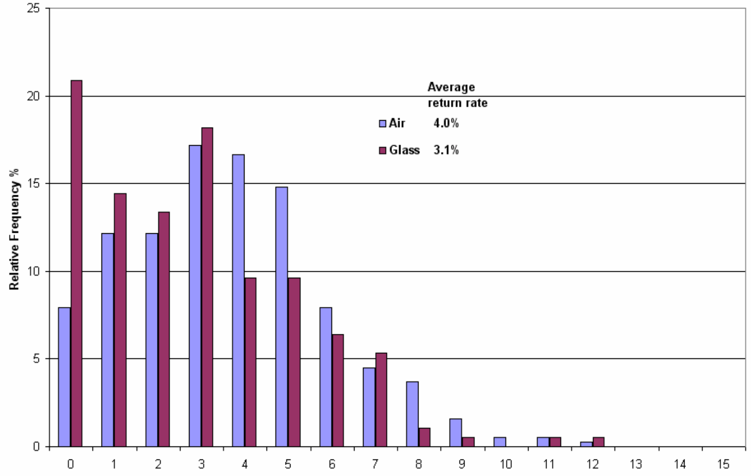


Figure 15 - Lageos 2 Return Rate Distribution