Some Early Results of Kilohertz Laser Ranging at Herstmonceux

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Abstract

As part of its support of an upgrade and expansion of capability at the UK Space Geodesy Facility, the UK Natural Environment Research Council has provided funding to enable in-house development of kHz-rate laser ranging at the site. The scientific justification for this upgrade included the expectation of an increase in single shot precision furnished by the much shorter laser pulse-length, an increase in normal point precision from compression of a greater number of raw data points and much more rapid target acquisition via rapid searching.

The upgrade has proceeded in stages. Before we were able to consider kHz ranging we needed an event timing device able to record epochs of multiple events at kHz rates. To this end we built in-house the Herstmonceux Event Timer (HxET), which is based on three modules supplied by Thales. Following completion of HxET in August 2006, the device was thoroughly tested and found to agree with expectations in terms of linearity and precision. With HxET in place we were able to make our first tentative steps by late September into kHz calibration and satellite ranging. This paper presents some of our early problems and successes.

Basic Requirements for Kilohertz ranging

- A kHz laser
- An event timer to record epochs of laser firing and detector triggering. This must be able to record epochs to an accuracy of a few picoseconds.
- A computer system(s) able to read ET, control the laser, display data and archive the data at kHz rates
- Software to extract weak return signals from the higher noise levels generated by a C-SPAD running at kHz rates.
- Reduction software that can cope with the new features displayed in kHz data.

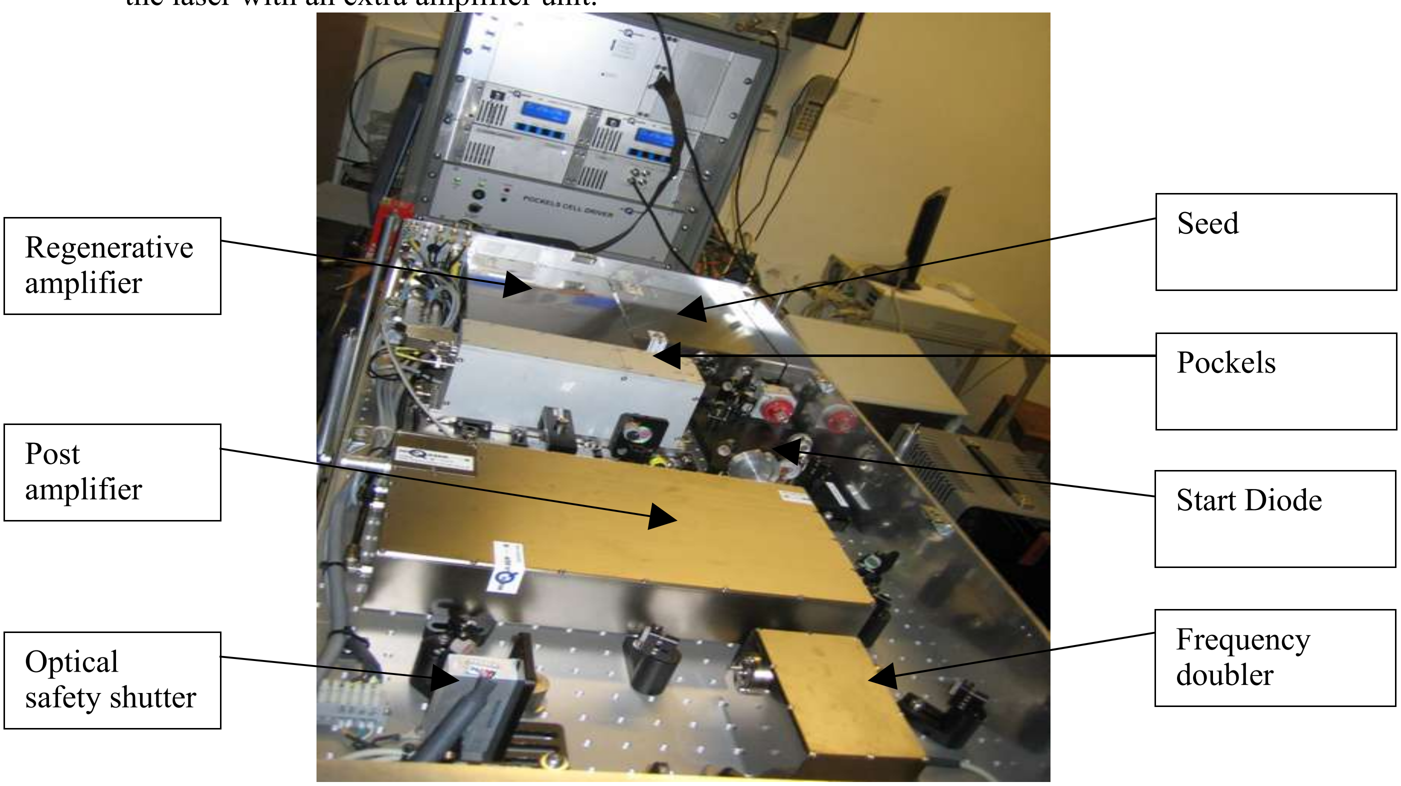
kHz Laser

Preparation for a kHz laser system began in 2003 with a visit to the SLR station in Graz, Austria. Graz had at that time recently purchased a kHz laser and was in the process of validating. This visit proved to be exceedingly useful in providing background knowledge necessary for the specification of a laser for the SGF. In 2004 final specifications for the kHz laser system were agreed and suppliers sought. The specification included a final output wavelength of 532nm with a pulse width of 10 – 15 ps at 1 – 2 kHz and a beam quality (M^2) better than 1.5. The ability of the laser to fire at ~10Hz to enable a smooth validation/transition from the old system to the 2 kHz system was also considered important. Other factors needed were the ability of the laser to fire on a shot by shot, variable rate basis under computer control, the ability of all the safety systems (lid locks, door interlocks and radar system) to be able to communicate with and inhibit firing, and the ability of the laser system to recover well after one of the frequent power cuts experienced at the SGF.

Given these specifications, a tender exercise identified two potential systems from High Q Lasers of Austria; one generating a power output of 0.4 mJ at 532nm and the second being capable of 1mJ at 532nm. With these power outputs the link budget calculations, to estimate return rates using a given laser system, were favourable. The following table shows our estimates for the link to the Lageos satellites in daytime, assuming an average amount of cirrus and a horizontal visibility of a poor 8km. The percentage value is the return rate of photons detected by the C-SPAD and the number in brackets is the resultant number of returns per 2-minute normal point:

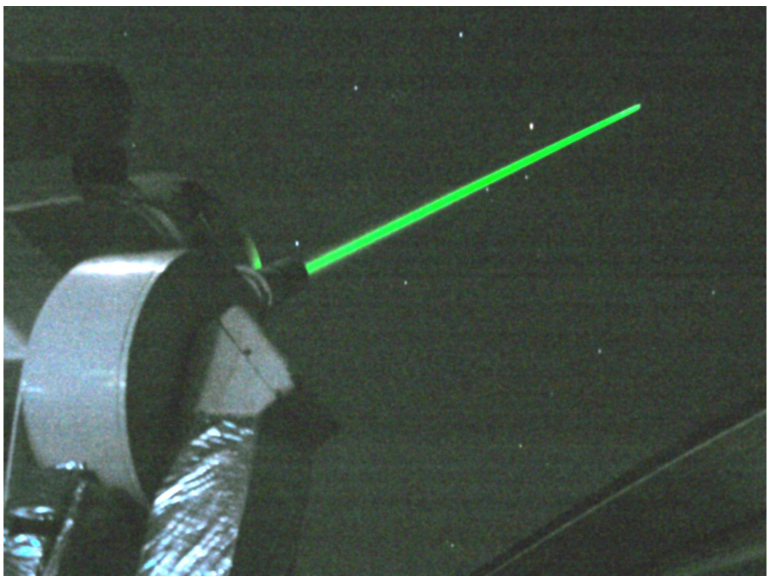
Elevation		90 °		50 °		30 °		25 °	
0.4mJ,	2kHz:	20%	(12000);	8%	(4000);	1%	(500);	0.3%	(150)
1.0mJ,	1kHz:	50%	(15000);	19%	(6000);	2%	(700);	0.7%	(150)

Following these calculations and financial considerations the 0.4mJ system was deemed sufficient but an extra long housing was ordered to enable possible future modification of the laser with an extra amplifier unit.



In summary, the specifications for the kHz laser are as follows:

- Nd: Vanadate picoREGEN laser from High-Q Lasers
- Pulse energy   0.5mJ at 532nm at 1kHz
  0.4mJ at 532nm at 2kHz
- Repetition rates of between 10 and 2000 (although large changes may require realignment). To date rates between 100 and 2000 Hz have been used without re-alignment.
- Pulse width is 10ps FWHM at 532nm.
- Upgradeable to >1mJ at 532.
- Firing predictability to 6ns.
- Typical lifetime of pump diode in excess of 10000 hours
- Beam quality – TEM_{00} $M^2<1.5$



Shown here is a picture of the kHz laser at night

Event timer

A decision was made in 2004 to replace our SR620 timers with a timing system which would be linear across the range of times being measured and also be usable for a Kilohertz system. After investigating various options it was decided to build in-house an event timer with 3 Thales modules (1 clock module and 2 timing modules).
The design of HxET included providing power supplies for each module plus some fifteen other power supplies, building an interface between the modules and the ranging computer, the ability to have start and stop signals as either NIM or TTL, and 1pps signal. It also had to include an onboard 1 kHz signal to monitor the difference between the two timing modules.

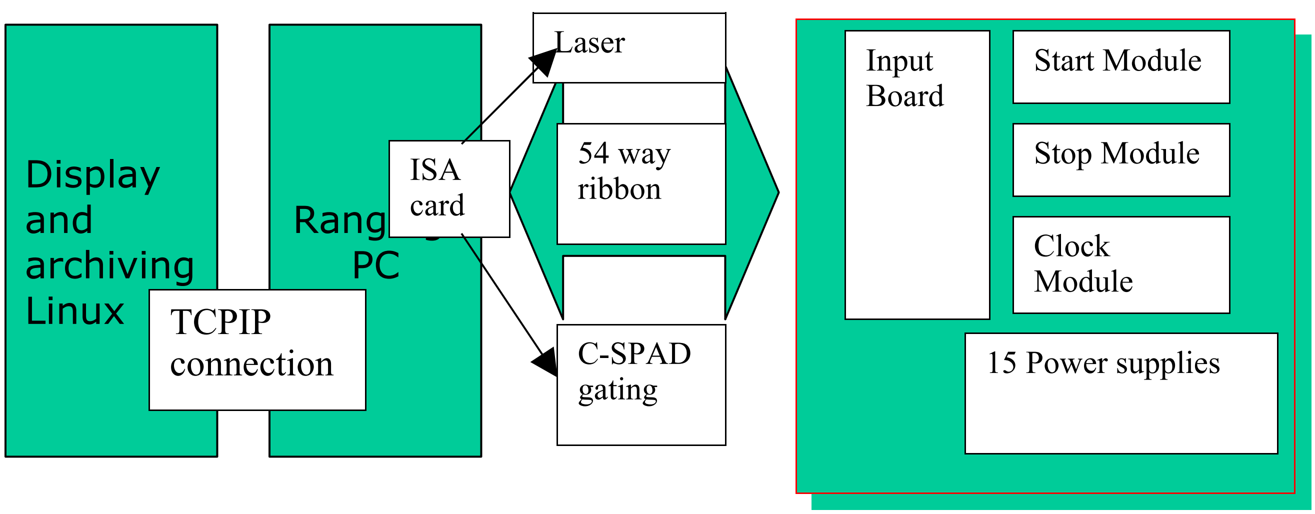
The timer was completed in late July 2006 and ready for use soon after.

Initial tests of HxET using a split signal to the start and stop channels resulted in a total jitter of 7ps. If we assume an equal contribution from both the start and stop channels, this result gives a jitter of 5ps for each, in agreement with the specifications for the modules.

Tests were also carried out using HxET to determine the behaviour of our SR620s across the whole timing range from local targets to the GNSS satellites; the results agreed with the results of previous identical tests carried out between PPET and the SR620s (Florence 1998). This we believe shows that there is agreement between PPET and HxET and that HxET is linear across the full range of current timing measurements. This calibration work is the subject of a further paper in these proceedings (Gibbs, Appleby and Potter, 2007).

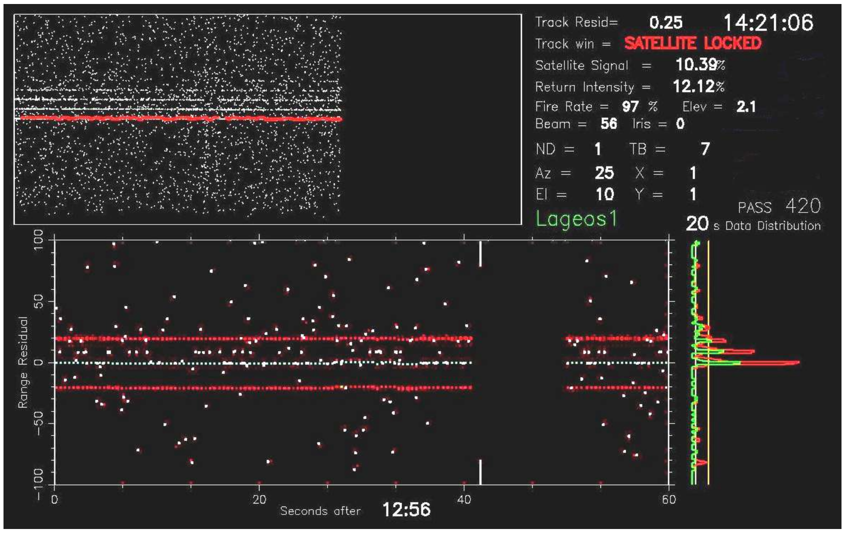
Computer configuration.

The station computer configuration is as shown below. It comprises a Linux machine that is used to display and archive the data and run the reduction processes. This machine receives in real-time the data from the ranging PC (running under DOS) using TCPIP.
The ranging PC communicates with HxET via a Programmable ISA card that was supplied to us by the GRAZ group. The ISA card also controls the Laser and arms the C-SPAD.
The ranging PC also controls the telescope tracking, the safety radar, laser beam divergence and an iris in the receive optical path, as well as determining average return rate in real-time and maintaining a single photon return level via a neutral density wheel.



Real-time display.

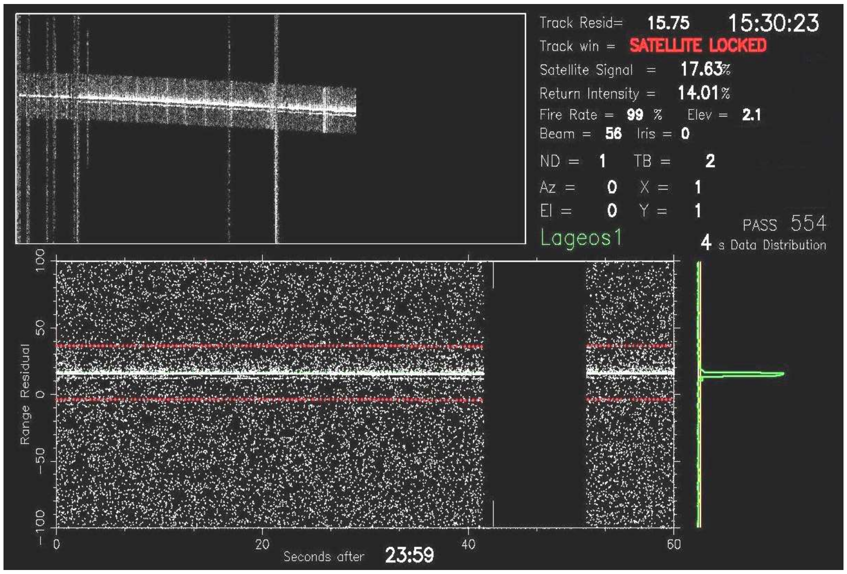
Recognising that moving to kHz ranging will significantly reduce the signal to noise ratio of the recorded data, early preparations were made to upgrade the display software. Previously, detection of track in the O-C real-time data within the range gate was aided by the known profile of the semi-train. The high rate data, lack of a semi-train and reduced satellite return signal associated with the low energy laser would make this procedure far more difficult, both for the observer and for the software.



The display process runs on a Linux platform using a TCP-IP connection to the dedicated ranging PC. The display shows long term and short term range gate O-C values as well as a histogram of user defined time span to plot the intensity profile of the data.

The histogram technique is a very good indicator of the presence and the strength and stability of a satellite return signal and is used for automatic real-time track detection. The technique was developed and implemented for the 13Hz system with the eventual goal of preparing for kHz ranging. The 13Hz laser profile is an initial pulse followed by a significant semi-train, so to avoid tracking the wrong pulse within the semi-train a second histogram was designed in which later pulses are folded in to enhance the initial pulses. This technique exaggerates the first pulse and allows it to be continually tracked. The original (green) and altered (red) histogram profiles can be seen at the bottom right corner of the image above.

A confirmed satellite track is defined by a histogram bin reaching a level of 3-sigma above the background noise in the range gate. Two 3-sigma uncertainties for this track detection are calculated from the instantaneous histogram peaks and from peaks in short blocks of data over the histogram time period. If the satellite signal is strong and stable the software 'locks' onto the track. Once the satellite is locked, the track uncertainties are reduced to 2-sigma and only peaks falling within the newly-defined track window are considered as possible track.



The long-term range gate displays the entire pass, as seen in the image at left. At high repetition rate this window becomes filled with noise points that mask any true track. However, by introducing a grayscale contrast for intensity of points, the track is revealed. This is a very powerful addition to the kHz tracking display, complementing the new histogram-based track determination.

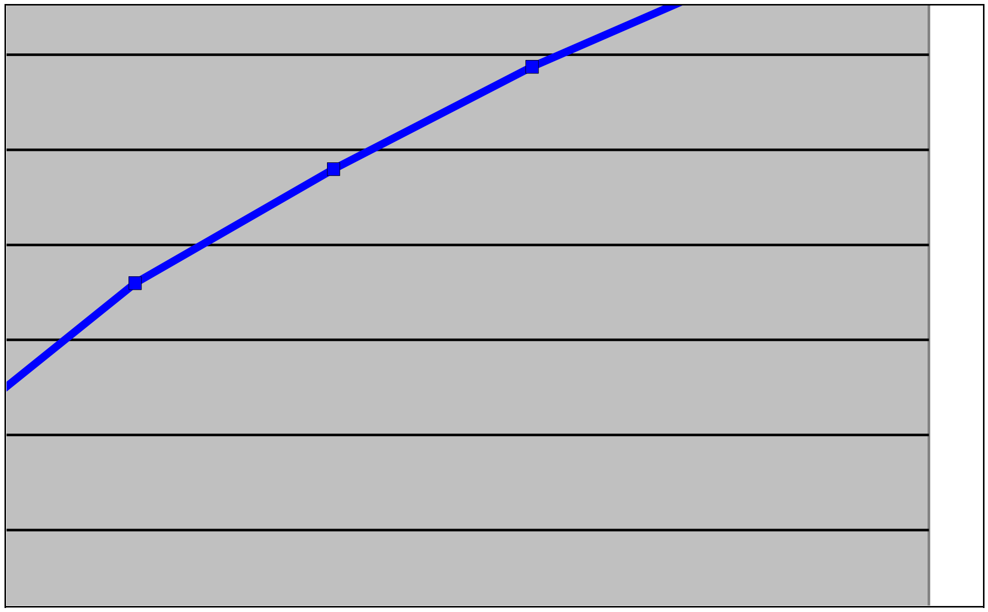
The kHz laser has one dominant pulse and can be tracked with a single histogram. The high firing rate also means that a shorter histogram time span is sufficient, but additionally the histogram can pick out a weak intermittent track if it is given a longer time span. From experimentation the software can lock on to a 1% satellite return signal with a 3 second time span and lock onto a 2% signal with a 2 second time span.

First Results.

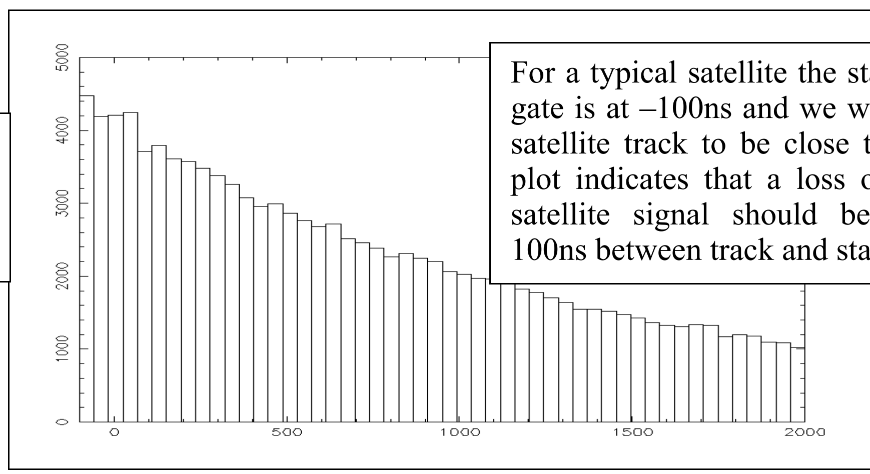
Testing of HxET and a full range of comparison tests between HxET and the SR620s were completed in late September 2006. Once completed, we designed the simplest possible software/hardware package that would enable us to obtain some high-rate satellite data as quickly as possible. To this end we simply used a pulse generator to fire the laser at approximately 2kHz. This simple system meant that we had no 'collision' control and as a result periods of high noise can be seen clearly in the data displayed below. We also did not attempt automatic control of return level (although manual control was still available) – in truth we were just happy to see that we were getting data. After just one week we had a software package that could collect data at kHz rates without any losses and then tried observing both in daylight and at night.

During the daytime we were able to track successfully all satellites from Lageos' heights and lower except for Champ and Grace. At night we were able to range to all the ILRS satellites, again except Champ and Grace. These exceptions were caused by a software problem which has subsequently been solved.

One of the first things that was noticed was that many more noise events were detected than had been expected; initial tests indicated a noise increase of about a factor of 7 between tracking at 10Hz and at 2kHz. This appears to be due to an increase of dark noise in the C-SPAD as a function of arming rate. This effect had been discovered and quantified by the Graz group, and below is a plot provided by Graz of their results for C-SPAD noise vs. repetition rate.



To estimate the effect this increase of noise would have on our system we examined a histogram of noise collected at 2kHz.

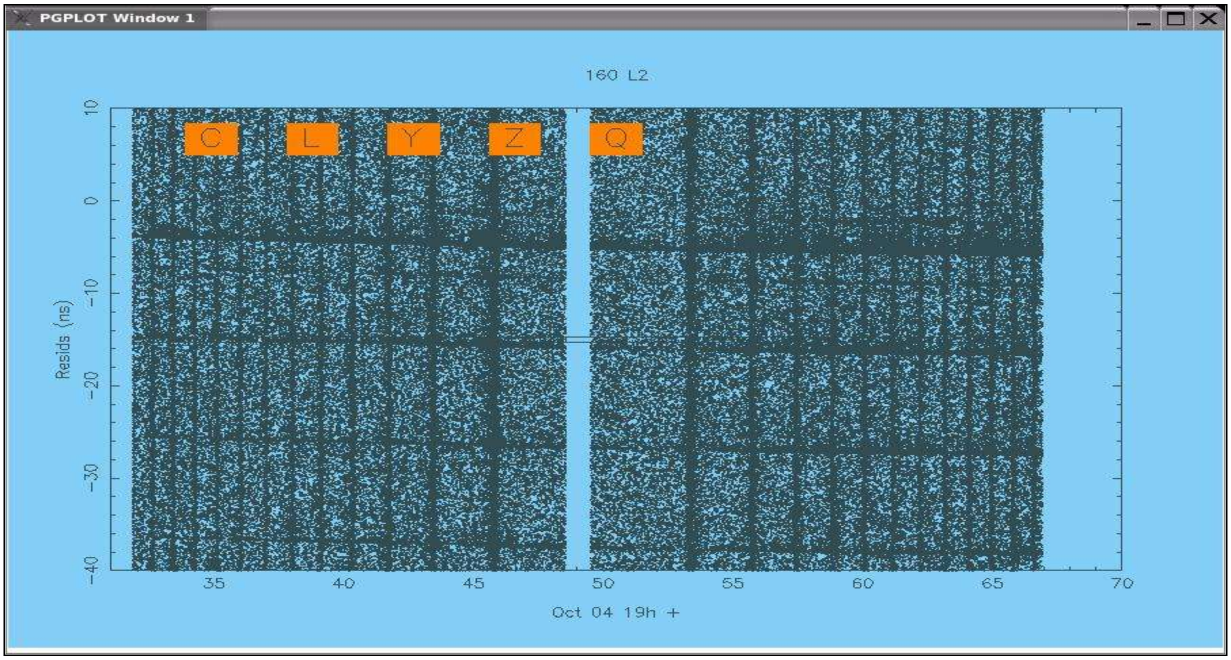


Counts Vs. Range gate time (ns)

For a typical satellite the start of the range gate is at –100ns and we would expect the satellite track to be close to zero ns. The plot indicates that a loss of about 4% in satellite signal should be expected per 100ns between track and start of gate.

Results from LAGEOS

Shown below is a plot of range O-C for Lageos-2 from October 4th 2006. Present is a number of interesting features. Clearly seen are the ‘collision’ periods when there are overlaps between incoming return pulses (C-SPAD gated on) and spurious detections of backscatter from outgoing laser light. Also apparent are pre-pulses and spurious other pulses because at the time of the observation the laser pockels cell was not optimally tuned. The uppermost O-C track represents the primary return signal.

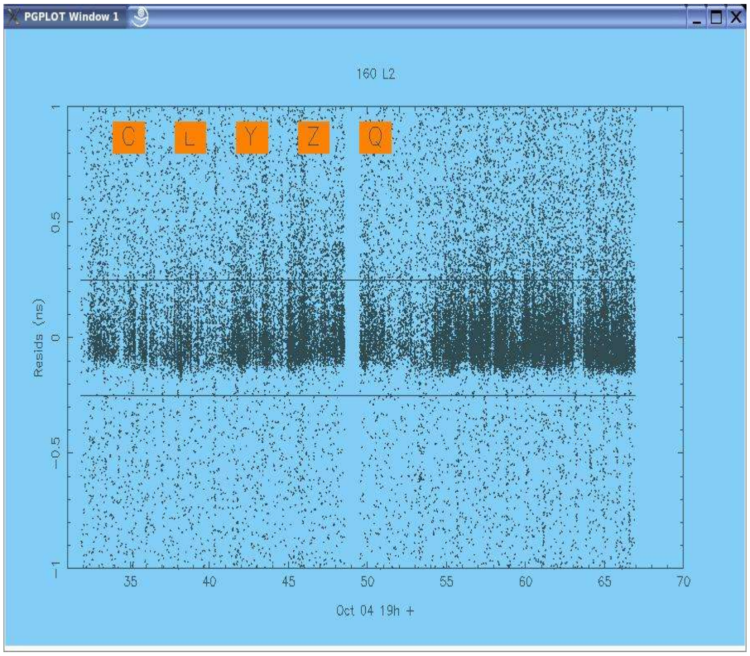


Having collected kHz data the next step was to use our current 10Hz reduction system to check whether there are any significant differences in the data, primarily in systematic effects that may compromise its quality.
The current reduction system comprises the following steps:

- Extract a data set by a combination of linear and polynomial fitting to the raw O-C data. A minimum limit to the data set of ±0.75ns about the zero mean is imposed by the software to prevent the reduction being biased by the observer.
- Fit an orbit to the extracted data, iteratively rejecting residuals at a 3-sigma level;
- Remove this orbit from the entire raw data set and reject at 5-sigma level (yes 5);
- Fit a smoothing function to this data set, rejecting at 2.5-sigma, using the routine DISTRIB that was produced and made widely available by A. Sinclair (SLRmail 0008).

Extraction of data.

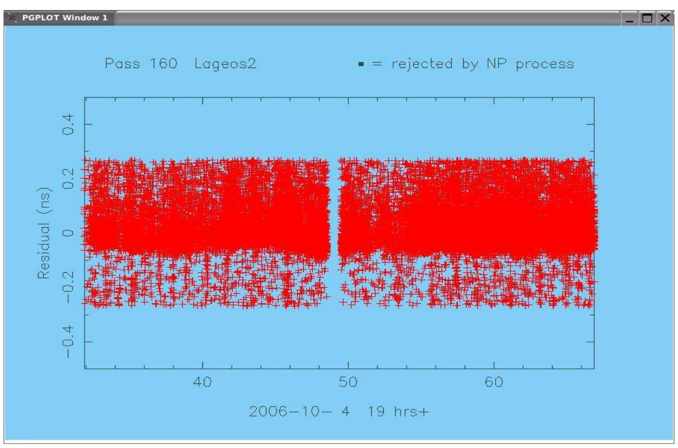
Below is a plot of the initial data set from which the observer will select the data to be passed to the orbital solution.



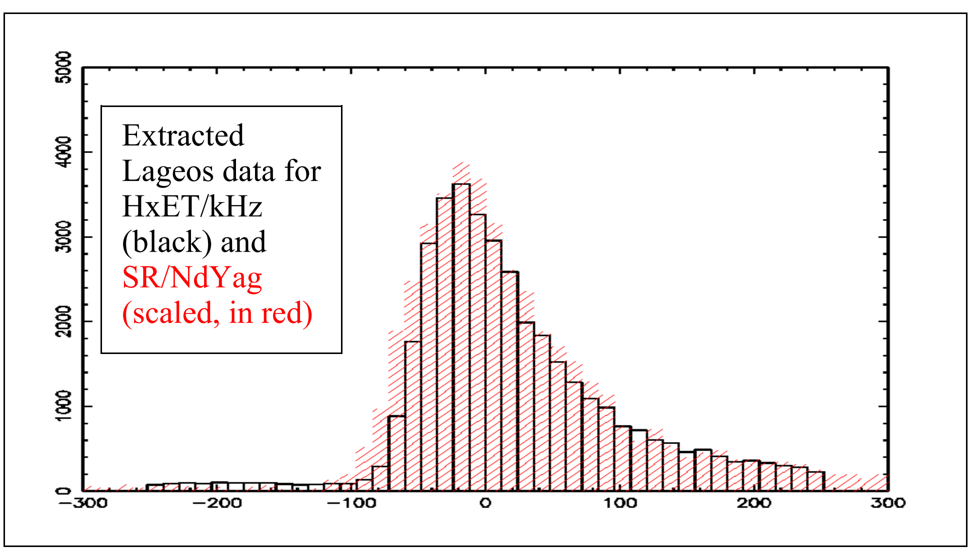
With the increase in background noise apparent at kHz rates it was felt that keeping at least ± 0.75ns of data would introduce too much noise in the preliminary signal extraction. We are currently experimenting with a reduced restriction of ± 0.25ns as shown in the plot, although the observer has the option of overriding these limits. In fact, better predictions, better software and higher-precision data means there is much less scatter in the residuals.

Gaussian fit

Having selected the data as shown in the above plot an orbit is fitted to it. The orbit is then removed from the whole data set and residuals rejected at 5-sigma. We then need to know if this data set is different for the 10Hz and kHz systems.

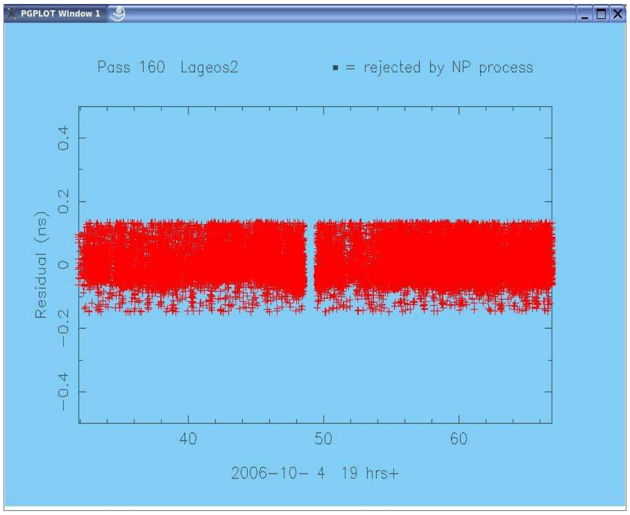


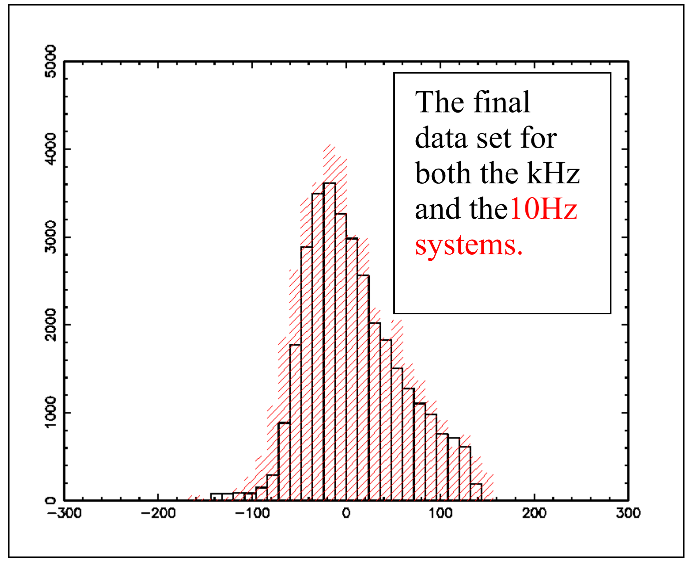
Pictured here is the data set after removing a best-fit orbit and rejecting residuals at a 5-sigma level. Apparent is a "significant" amount of noise below the track and some structure above the track. But is this behaviour significantly different to our current system?



The distribution of the residuals from the two systems is very similar since the Lageos response dominates. As expected, the 10Hz data appears to be slightly broader as the timer and laser contributions are larger:

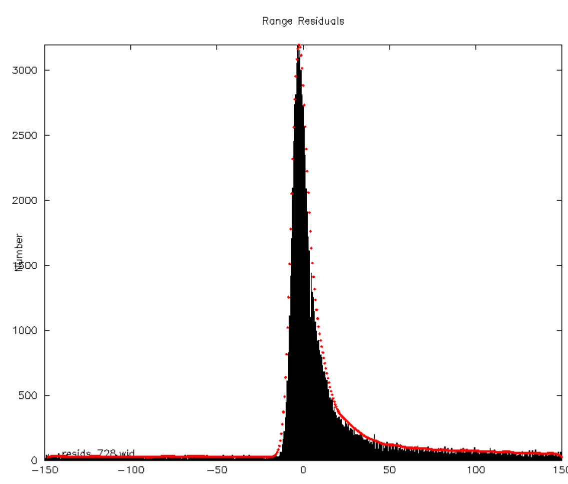
10Hz: 35ps for SR620
100ps for laser
KHz: 7ps for HxET
10ps for laser





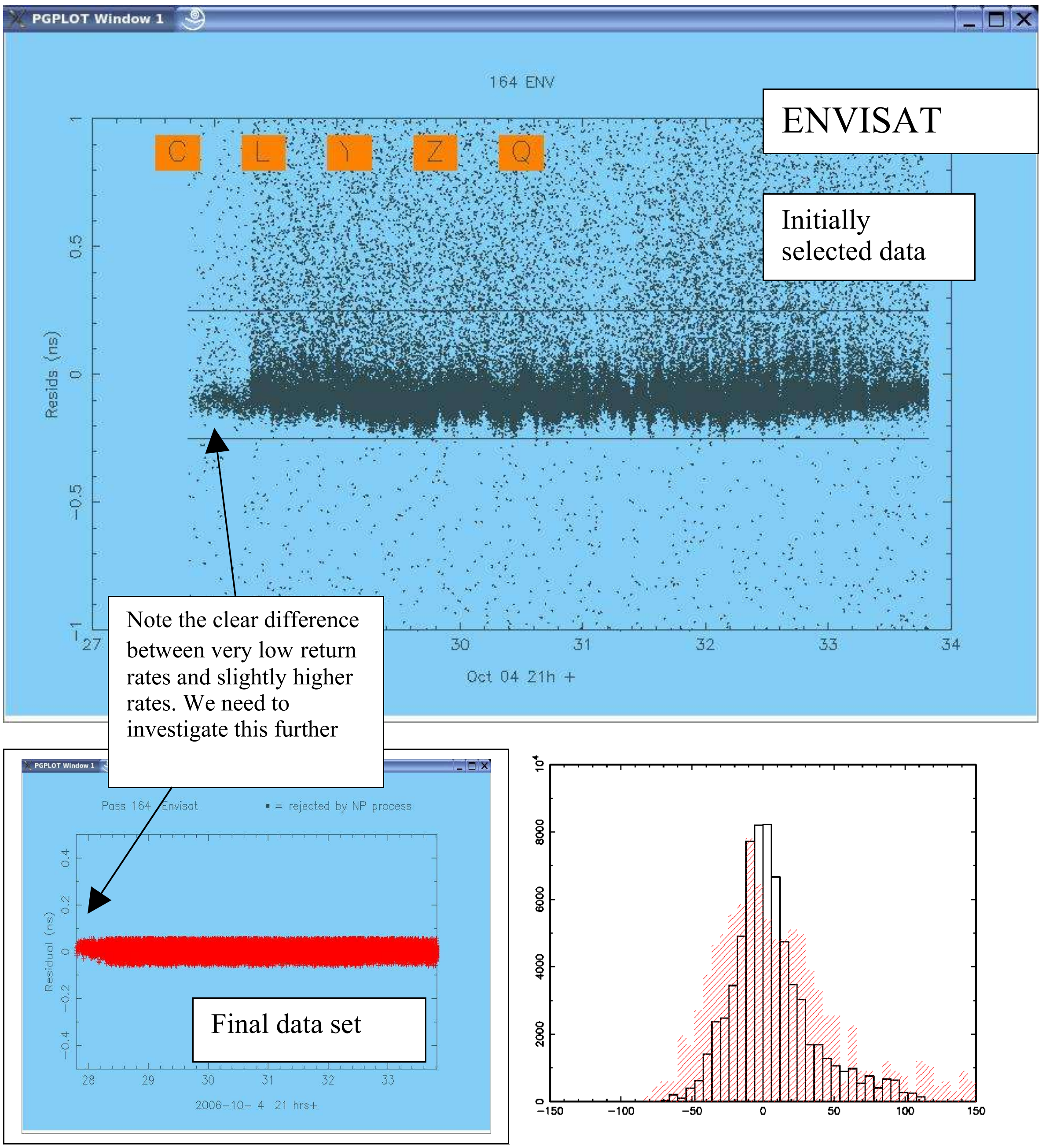
Shown above is the final data set for Lageos. There is clearly some noise below the track and the sharp cut off of dense data above may well have removed real observations.

At first glance it would appear that our reduction process is producing the same results for Lageos from both systems, but we have started a more detailed analysis in order both to define a robust reduction process and also to derive an accurate centre of mass correction. Previous work (Otsubo and Appleby, 2003) found that uniquely for the Herstmonceux single-photon system a Lageos centre of mass correction (CoM) of 245mm should be applied (cf 251mm for high-energy ILRS systems). It is important that once our new kHz data becomes available to the analysis community that we have also determined an accurate CoM correction, which may well be a few mm different from the current 10Hz value. This ongoing work will be reported elsewhere, but the plot below shows the result of an initial investigation of the detailed post-reduction O-C distribution. The rapid rise of the leading edge is as expected and is a result of the short pulse length of the kHz laser, as suggested in the discussions above.



The smoothing function fitted to the distribution is shown in red, and will be used in an asymmetric filtering process to remove primarily leading-edge noise and in a model to determine an accurate CoM value.

Results from a small-array satellite (ENVISAT).



The final data set for kHz and 10Hz (scaled in plot) shows that with small satellite signature there is an overall improvement in the RMS due to lower contributions from timer and laser.

Conclusion

The SLR system at the UK Space Geodesy Facility is at an advanced stage of kHz repetition rates, and incorporates a very accurate event timer. Param upgrade plans is that on-site reduction of the new data should not in discontinuity into the long series of high quality laser data from the site.

Acknowledgement

We would like to thank the staff of the Institut for Space Research, Observatory Lustbuehel at Graz, Austria for their help and encouragement during the development of our kHz system at Herstmonceux.

References

Gibbs, P., Appleby, G.M. and Potter, C.P., 2007. A re-assessment of laser ranging accuracy at SGF, Herstmonceux; *these proceedings*.

Otsubo, T. and Appleby, G.M., 2003. System-dependent centre-of-mass correction for spherical geodetic satellites, JGR, vol. 108, doi:10.1029/2002JB002209.