Implementing Consistent Clipping in the Reduction of SLR Data from SGF, Herstmonceux

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Abstract
Orbital analysis shows a correlation between SLR normal point (NP) residuals with RMS that is mainly present for stations operating at low energy levels of detection and made visible by averaging over sufficiently long periods. It was shown that for LAGEOS 1/2 a significant underlying cause is the orientation-dependent variability of the laser retro-reflector array. To address this correlation and for greater consistency between passes, the Space Geodesy Facility in Herstmonceux, UK is moving towards altering the way it forms normal points from SLR residuals.

Currently at the SGF, SLR observations, recorded at single-photon energy levels, are flattened by applying time and range bias corrections to a reference orbit. The residuals are then clipped at 3xRMS from the centre location of a Gaussian fit and used to form NPs. However, iterative NP processing algorithms such as this one, employed by most stations, show limited robustness to cope with the inherent data variability and this led us to explore more satisfactory data reduction strategies.

A new processing method fits a Gaussian profile to the front-only of the residual distribution and reliably locates the leading edge half-maximum. From this point, fixed, satellite dependent clipping is applied to capture the retro-reflector array. Beginning with the LAGEOS satellites and following the lead of the Graz SLR station, more consistent normal point observations are achieved with tight clipping to sample the very front of the satellite. The impact of adopting this new method on the Herstmonceux coordinate time-series is assessed

Introduction
A satellite laser ranging (SLR) station can upgrade its hardware to boost performance and achieve greater measurement precision. To improve measurement accuracy, a station must aim to eliminate systematic range errors, which can be done in collaboration with the International Laser Ranging Service (ILRS) quality control services (Otsubo, 2018). Finally, to be consistent from pass to pass and over the long-term, a station should continually monitor for reoccurring systematic errors. In addition, it should make subsequent observations in a consistent manner. For example, the SGF, Herstmonceux keeps strictly to single-photon return signals levels. The focus of this study is the post processing of the range measurements, which also must be done in a consistent way. The methods for SLR operations and post-processing should be clearly defined so that an accurate centre-of-mass correction can be estimated for each satellite.

The SGF, Herstmonceux SLR station routinely tracks the full ILRS target list with a kHz system. Once a satellite pass is complete, a calibration is applied to correct for system delay and the SLR returns are extracted from the noise in the raw data file. This is achieved by generating flattened range residuals obtained by adjusting the orbit prediction. These residuals are clipped so that non-SLR data is removed and binned normal point averages are then formed. An alternative method for clipping these residuals is presented here, which is intended to be a more robust method. The aim is to be more consistent from pass to pass and hopefully improve the quality of the SLR output from the SGF, Herstmonceux.

Effect of Normal Point Clipping
It was shown for LAGEOS and other geodetic sphere satellites that the normal point range residuals of the Herstmonceux station appear correlated with the single shot NP RMS, (Otsubo, 2014). Figure 1 shows in the upper plots the range residual trend with normal point RMS for the LAGEOS, Ajisai, Starlette and Stella and LARES satellites. This was also seen directly in the SLR data by plotting

the residual distribution leading-edge-half-maximum (LEHM) and the NP mean difference against RMS, (Wilkinson, 2016). This trend was shown to be partly caused by the variable orientation of LAGEOS as seen from stations, from simulations of the satellite response, (Rodríguez, 2017).
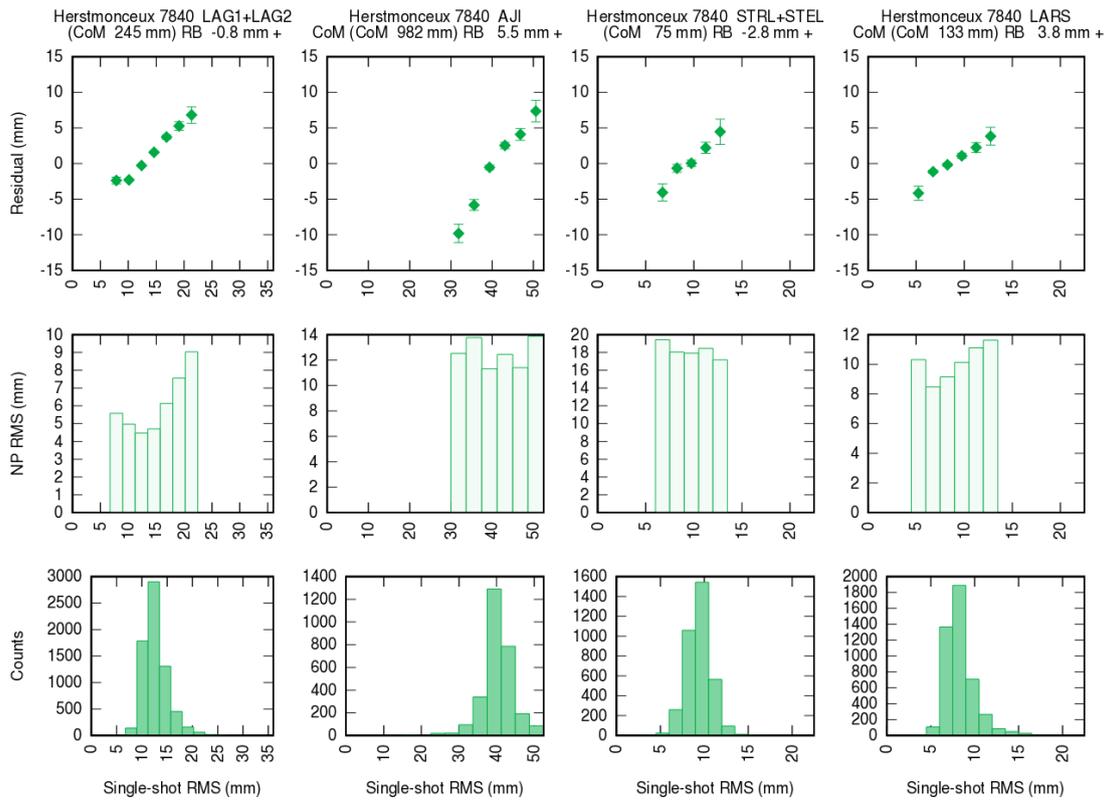

Figure 1. Range residual, RMS of the normal points and the frequency are plotted against normal point single-shot RMS values. A trend is present in the range residuals for all satellites.

In order to minimise this observed effect, a method to reduce the variability in the clipping of the SLR residuals was developed.

Fixed Clipping from the LEHM
An advantage of kHz SLR is the large number of observations that can be taken over the duration of a satellite pass. This results in a well defined distribution of residuals, the shape of which depends on the laser pulse width, detector characteristics and the satellite retro-reflector array size and shape.
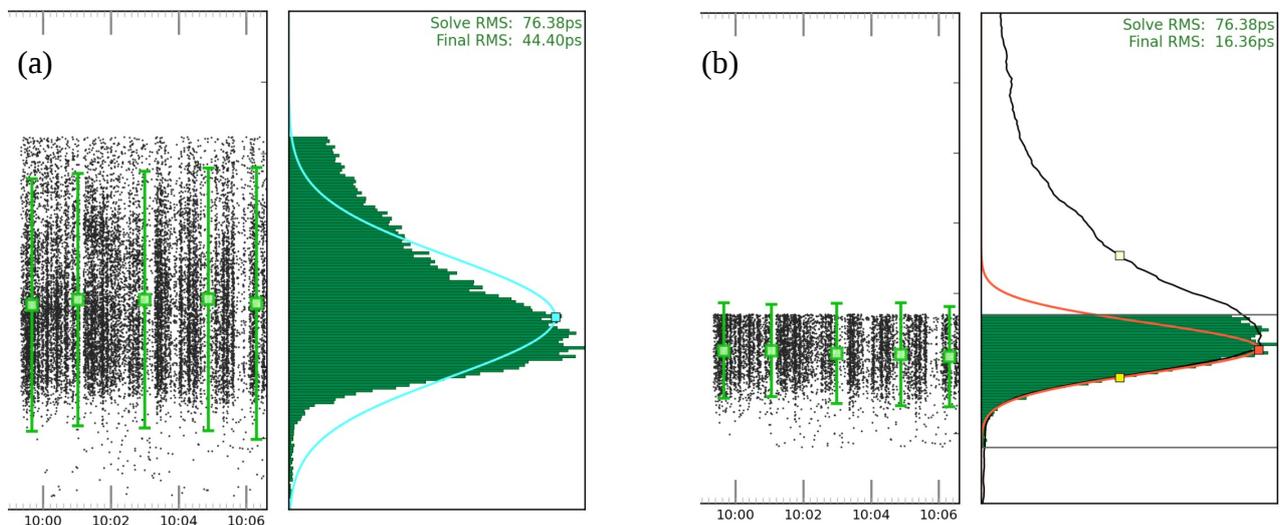

Figure 2. Flattened range residuals from a LAGEOS 1 pass taken at Herstmonceux, UK. The current Gaussian fit method with 3*σ clipping is shown in (a) and tight clipping from the LEHM as determined by a Gaussian fit to the front of the distribution is shown in (b).

A normal point is the residual mean applied to a range at a central epoch for a fixed timespan. For the LAGEOS satellites, this timespan is 120 seconds. The normal point result will change according to the level of the range residuals included and therefore clipping is important and needs to be consistent. At Herstmonceux, currently the clipping is applied at ± 3σ from the centre of a Gaussian fit, see figure 2(a). However, the σ value depends on the level of signal to noise and the system/satellite response profile. Because the profile is not Gaussian, if tighter clipping is applied, due to a lower σ, then the normal point range will be shorter than if looser clipping were applied.

Clipping from the front of the distribution for certain satellites was first proposed by and now in use at the Graz SLR station in Austria (Kirchner, 2008). In order to apply consistent clipping from pass to pass, a stable point needs to be located on the residual distribution. This was chosen to be the LEHM. To determine this point, a Gaussian profile was fitted to the front-only of the distribution, as shown in the figure 2(b). From the LEHM, fixed clipping can be applied.

Regenerating Normal Points
In order to assess the impact of this new method, normal points are required for processing. To produce these, unclipped full-rate data files were first generated using the raw SLR data files and the original full-rate data files for LAGEOS 1 and 2 for 2015 to 2017 inclusive. These files were reduced, forming normal points, with fixed one-way range clipping values of 50ps below the LEHM and 150, 120, 90, 65 and 45 ps above.
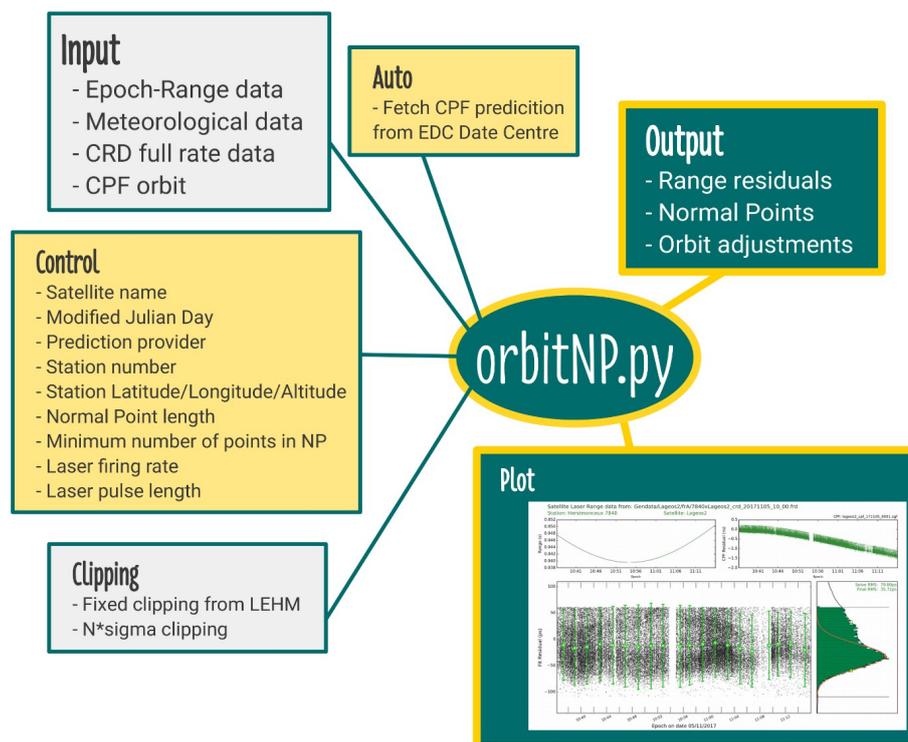

Figure 3. The orbit correction and normal point software orbitNP.py.

OrbitNP.py
The residuals and normal points were generated using the orbitNP.py program, written in Python3 to process Satellite Laser Ranging (SLR) observations. It originates from FORTRAN code and was developed at the Space Geodesy Facility, Herstmonceux, UK. An observation is comprised of an accurate time-stamp epoch in Coordinated Universal Time (UTC) and a highly precise time interval representing the 2-way time-of-flight to a satellite and back. Flattened observed-computed (O-C) range residuals are produced by solving for along track and range bias corrections to a reference

orbit prediction and then used to form normal points. It is now available for download on the ILRS Software webpage https://ilrs.cddis.eosdis.nasa.gov/technology/software/index.html.

Clipping Results

The variability of the normal point results from each clipped dataset is shown as histograms in figure 4. The distances of all of the normal point values from the LEHM were binned and plotted. The distribution of this distance for our current Gauss fit method for the 3 years of LAGEOS 1 and 2 data has a standard deviation of 10.6ps. The NP mean – LEHM distributions from the clipped datasets have lower RMS values, with the tightest clipping RMS being 3.4ps. Clearly, as tighter clipping is applied the distance from the NP mean and the LEHM is reduced and the measurement is made closer to the front of the satellite.
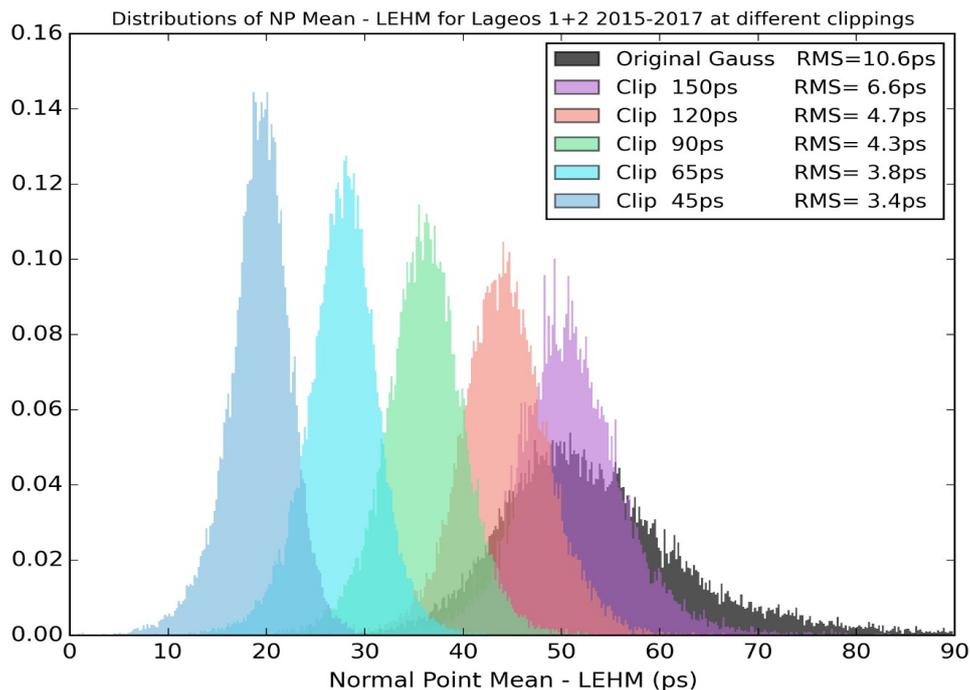

Figure 4. Histograms showing the variation in normal point average values from the LEHM. The current Gaussian method has the greatest variation at 10.6ps. This value reduces with tighter fixed clipping.

Orbital Analysis Results

These new normal point datasets were submitted for orbital analysis using the SGF SATAN software. Weekly solutions were made for 2015 to 2018 using LAGEOS 1 and 2 data from the whole ILRS network and substituting the data from Herstmonceux for the new data at different clipping levels. The solutions computed 7-day arcs, solving for initial conditions, station coordinates, EOPs and range bias parameters for each station.

The correlations between the normal point range residuals and RMS were calculated for each dataset and are shown in figure 5. The values reduce as the clipping is applied closer to the LEHM, to a low Pearson r value of < 0.1 with the tightest value. Comparing the correlation coefficients (LAGEOS-1/2) for the current data reduction method employed at Herstmonceux, shown as squares in the figure, we note that even for an equivalent level of clipping, the fixed LEHM method reduces the correlation.

Three-year averages of the weekly station range bias are plotted in figure 6. Using a fixed centre-of-mass value of 245 mm, the range bias for the Herstmonceux station increases (in absolute value) with tighter clipping. This is to be expected as the normal point range is being measured closer to the front of the satellite.
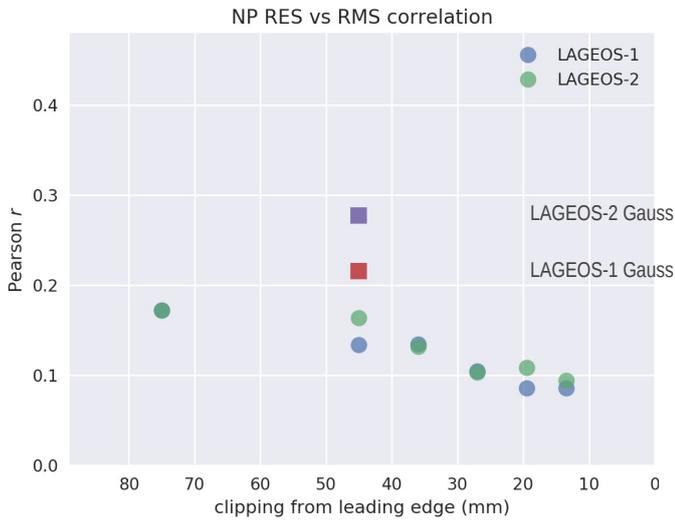
Figure 5. The correlations between normal point range residual and RMS decreases with tighter applied clipping.
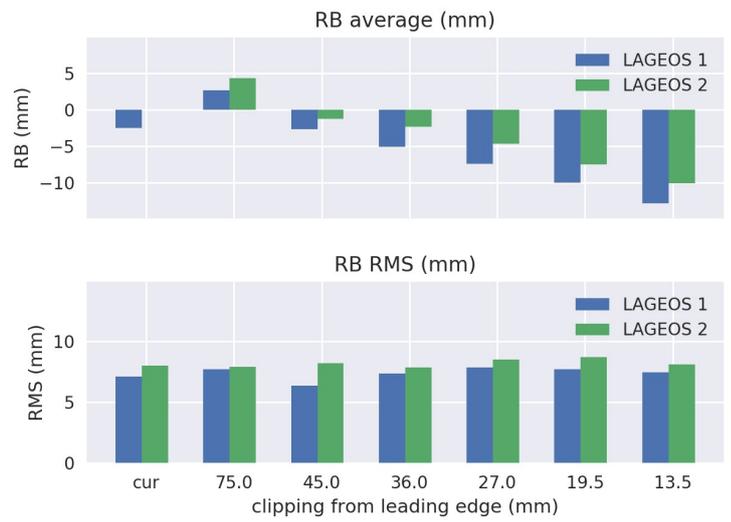

Figure 6. The average range bias for Herstmonceux increases with tighter clipping, but this is due to a fixed centre-of-mass value. The RMS of the weekly range biases does not change much with the applied clipping.

The clipping does not have much effect on the average pass range bias or the RMS of pass range bias, as can be seen in figure 7. An alternative method was used to look for possible improvements that accounted for any remaining modelling error in the solutions by using a polynomial fit to the normal points for each pass. The RMS of the remaining residuals was then calculated for each dataset for LAGEOS 1 and 2. Using this method, it can be seen in figure 8 that the clipping reduces the normal point to normal point variation. We note that beyond certain level, there is little motivation to increase the clipping, as no further reductions in RMS are achieved.
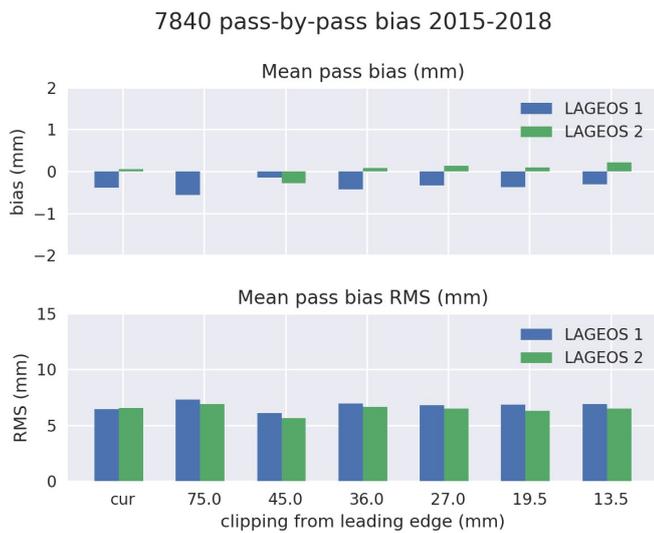

Figure 7. The mean pass bias and mean pass bias RMS does not change significantly with tighter clipping.
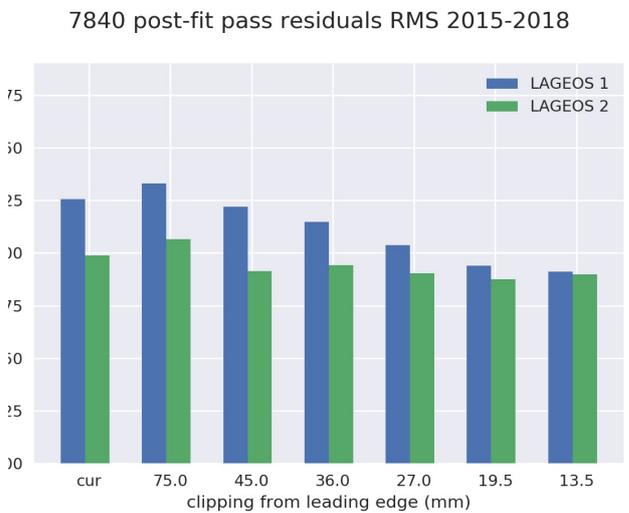

Figure 8. The normal point RMS after a pass by pass polynomial fit is applied decreases with tighter applied clipping.

Conclusions

SLR measurements need to be made with the highest accuracy and to be consistent over time. This includes the post processing of these measurements. The previously observed normal point range residual dependency on single shot RMS can be minimised with controlled clipping about a well defined point on the satellite distribution. We have not found any evidence of this correlation having an impact on the current analysis products (i.e. station coordinates). However, this post-processing method does improve the quality of the SLR measurements from Herstmonceux by decreasing the normal point variability within individual passes.

The orbitNP.py software is available to assist users in using orbit correction to produce flattened range residuals from https://ilrs.cddis.eosdis.nasa.gov/technology/software.

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