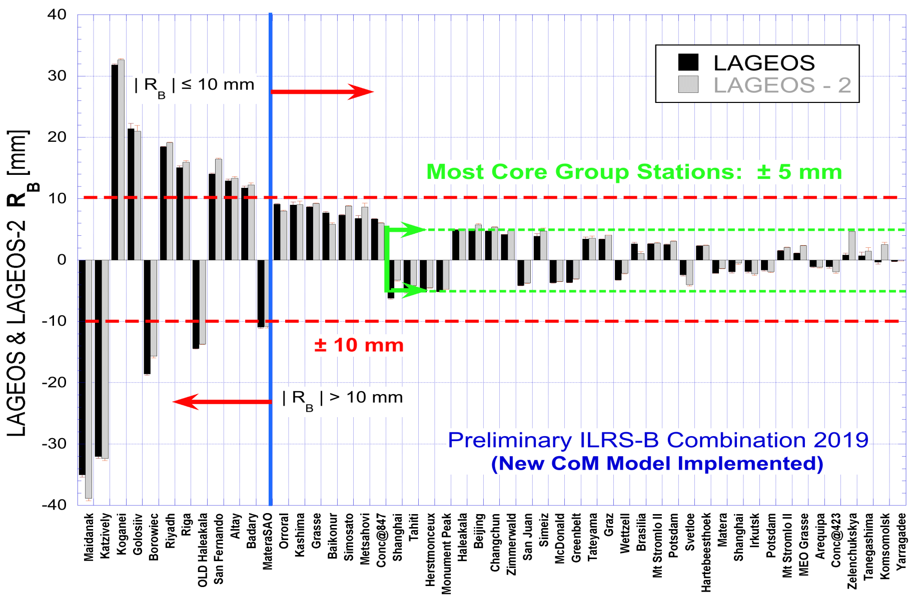
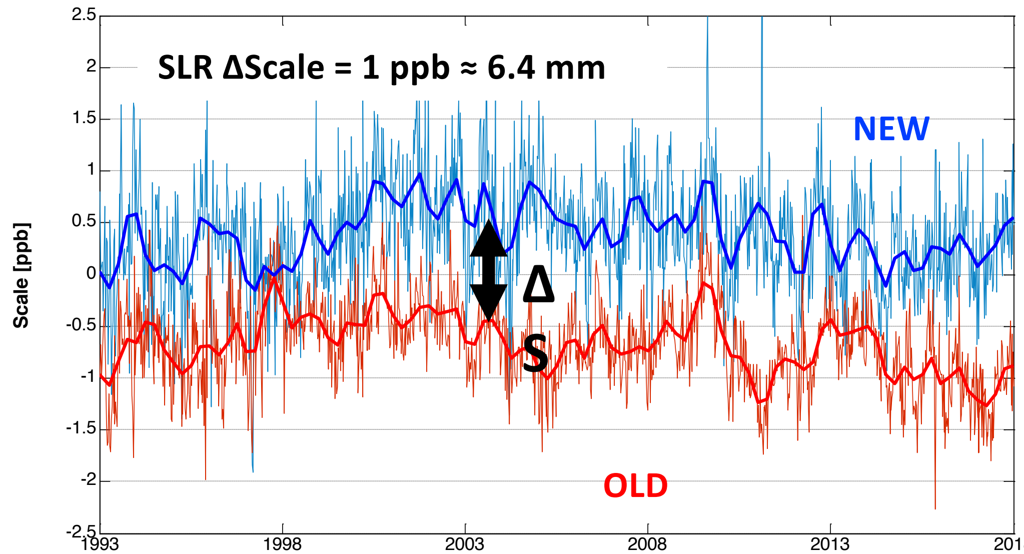
Improved ILRS Modeling: VLBI-SLR Scale Difference ~0.23 ppb





- The systematic re-analysis of LAGEOS-1 & 2 and Etalon 1 & 2 data (1993-2019) produced a preliminary set of persistent long-term biases at the most active SLR stations.
- When these biases are implemented in the reprocessing for the development of the SLR contribution to ITRF2020, they reduce the VLBI-SLR scale discrepancy to ~0.23 ± 0.10 ppb.

Statistical Evaluation of simulated Normal Points calculated with a Wiener Filter

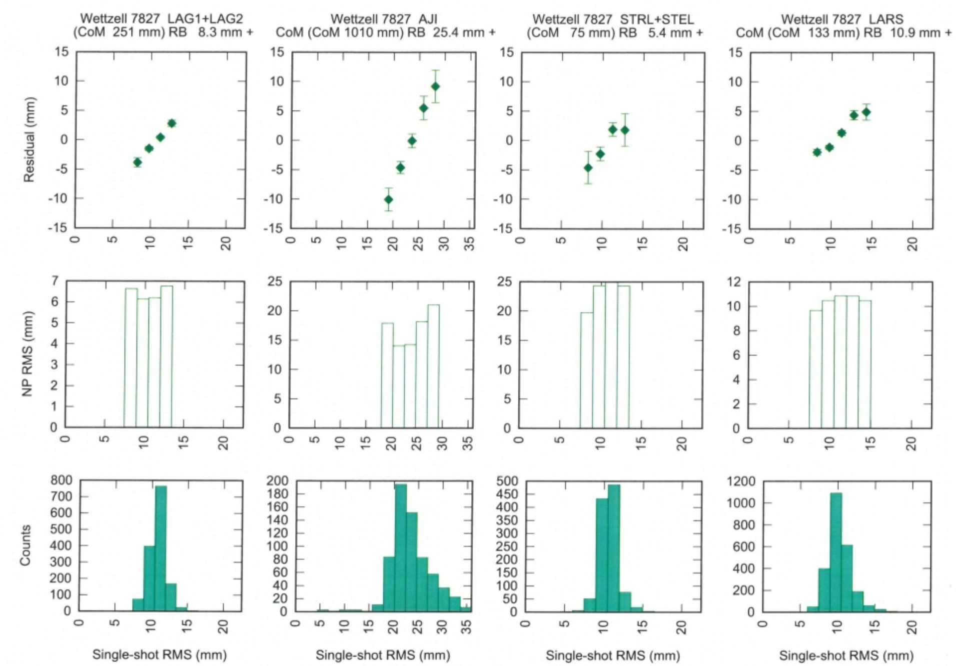
S.Riepl[1], J.Rodriguez[2],T.Schüler[1]

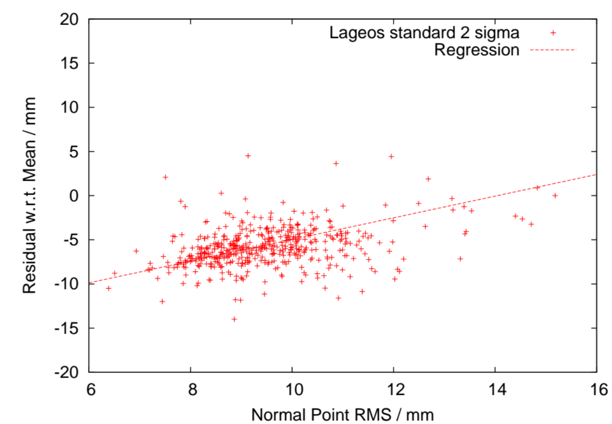
[1] Federal Agency for Cartography and Geodesy
Geodetic Observatory Wettzell
Germany

[2]NERC Space Geodesy Facility
United Kingdom

Motivation

- HIT-U analysis reveals systematic trend in Normal Point Residuals
- Effect is caused by partial sampling of Retroreflector Array, which is not accounted for in standard reduction method (see J. Rodriguez, Variability of LAGEOS normal point sampling, Riga (2017))
- Trend of HIT-U analysis is reproduced by on site normal point algorithm
- Is there a better way to calculate Normal Points than using iterative data clipping techniques ?



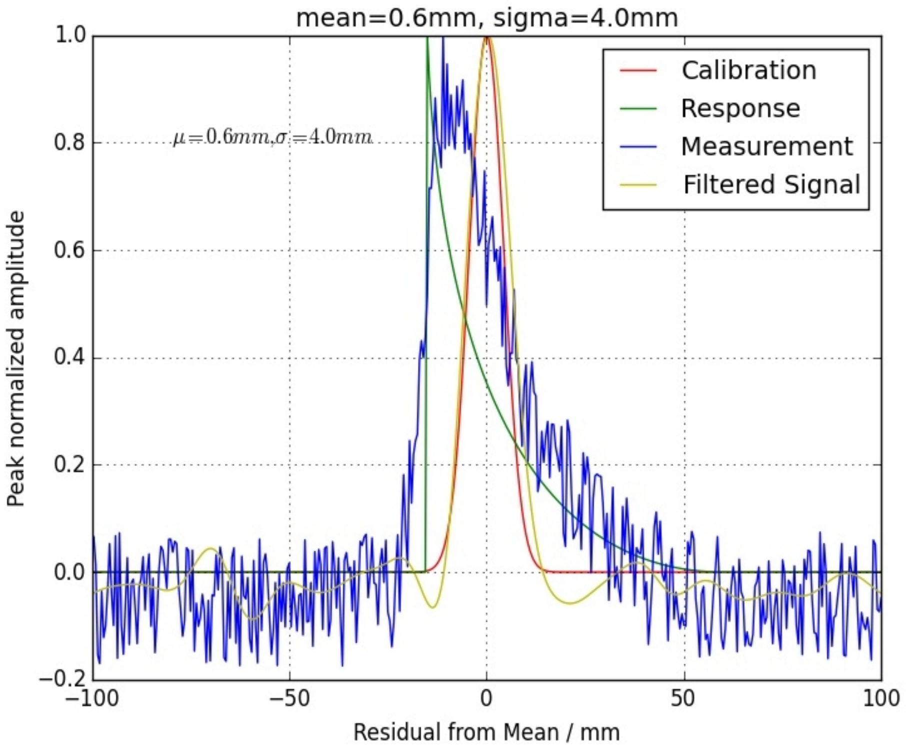


Optimal Wiener (deconvolution) Filter

- Proposed by N.Wiener (1949)
- Statistical Filter based on least squares method
- Application to SPE-SLR straightforward
- Eliminates skewness of data distribution
- Data clipping systematics don't exist
- Removes noise
- Procedure:

  → Calculate histogram for every normal point window

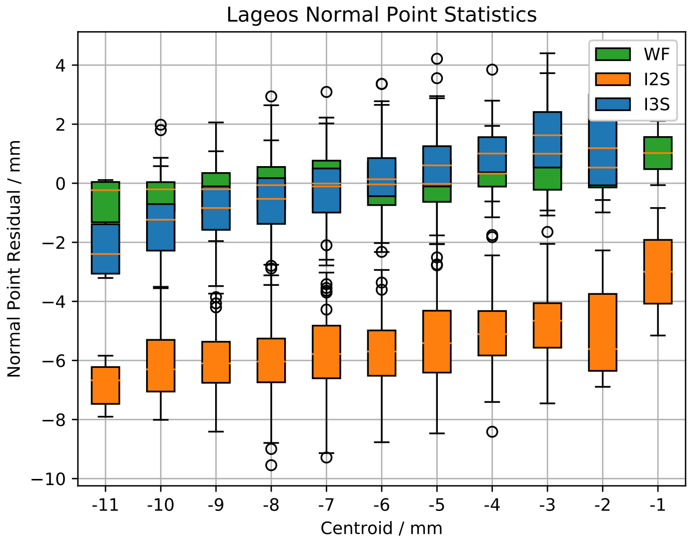
  → Deconvolve Transfer function and do statistics on filtered signal

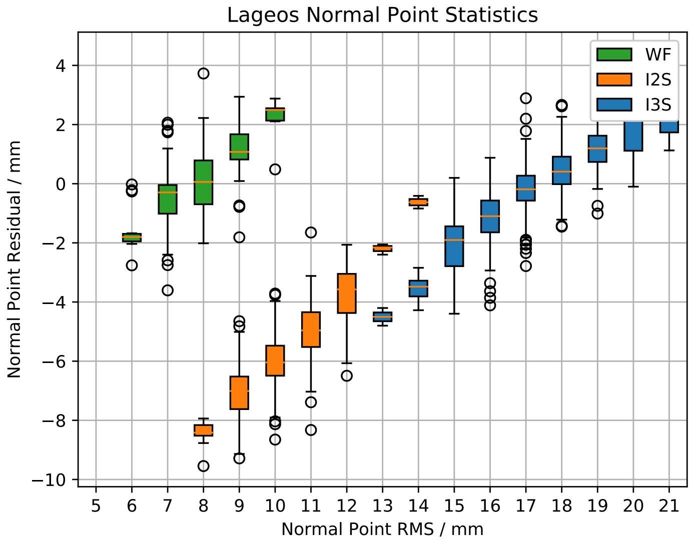


Evaluation Approach

- Evaluation for LAGEOS, Etalon, Ajisai, Lares, Starlette/Stella
- Array specific Transfer Function (850nm) averaged over all orientations
- Residual Simulation for known mean value (see see J. Rodriguez, Variability of LAGEOS normal point sampling, Riga (2017)) calculated for 5% return rate and SOS-W Instrument Function (Calibration Data)
- Calculate Standard Normal Points for 2 and 3 Sigma iterative Clipping as well as with Wiener Filter algorithm
- Compare Results in terms of Normal Point RMS, Centroid and Normal Point Residual

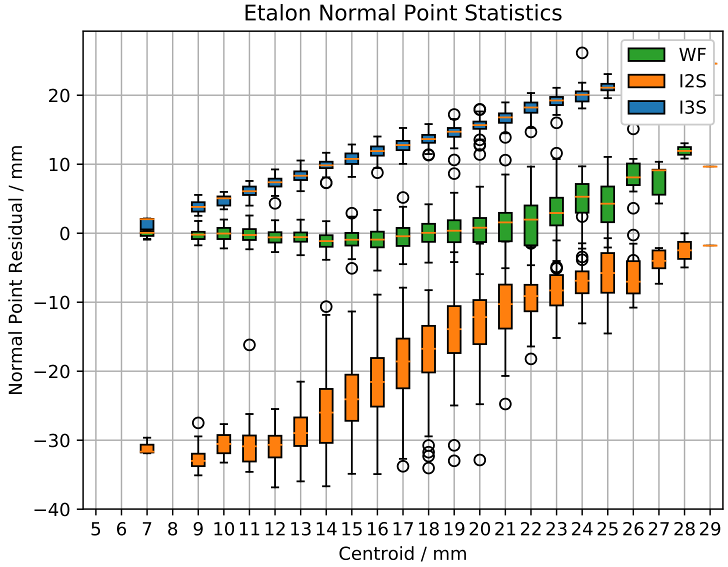
LAGEOS Results



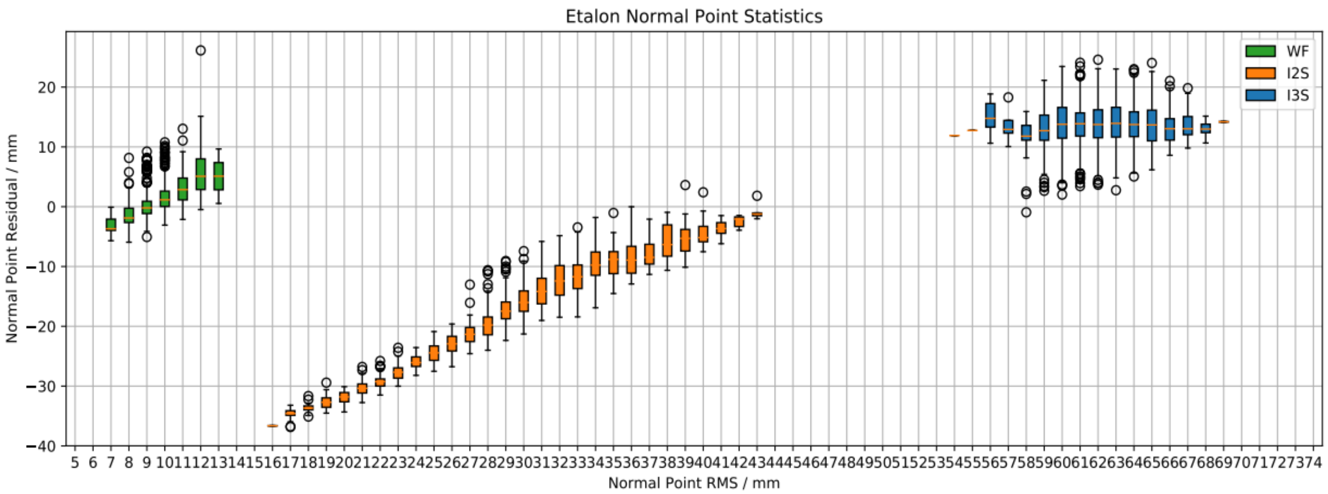


- Wiener Filter (WF) NP Residuals show almost no correlation with Centroid
- Iterative 2 Sigma (I2S) NP Residuals show slope in terms of Centroid
- WF NP RMS in same range as calibration, NP Residual spread is tighter than I2S
- WF NP Residuals located around mean
- I2S slope in terms of NP RMS reproduces HIT-U analysis
- I3S NP RMS unacceptable high

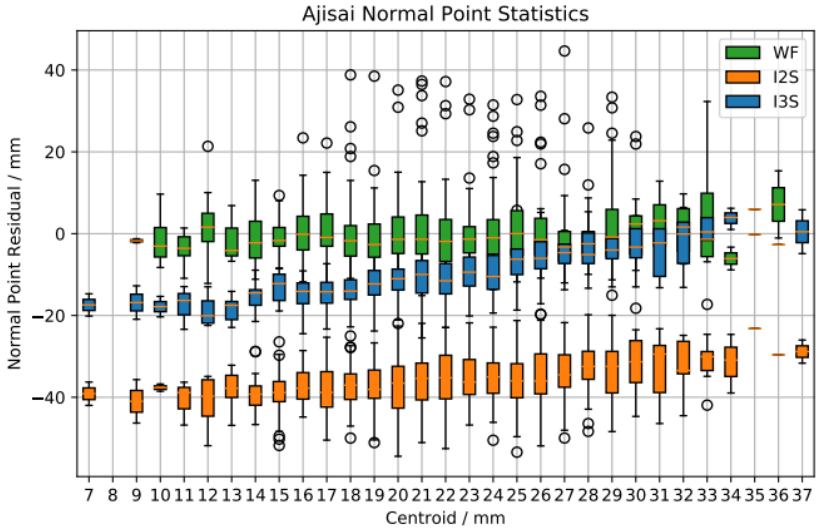
Etalon Results



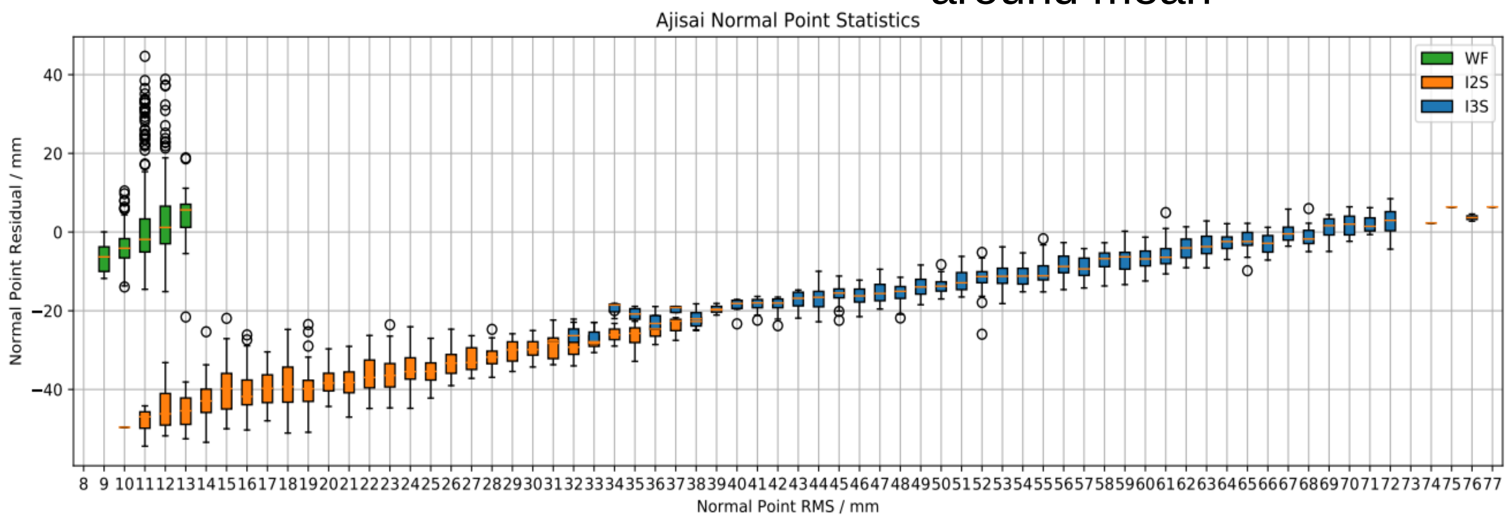
- I2S,I3S NP Residuals show vast dependence on centroid, WF NP Residual variation with Centroid is subcentimeter
- I3S NP RMS unacceptable high
- WF NP RMS in same range as calibration, NP Residual spread is much tighter than I2S
- WF NP Residuals located around mean



Ajisai Results

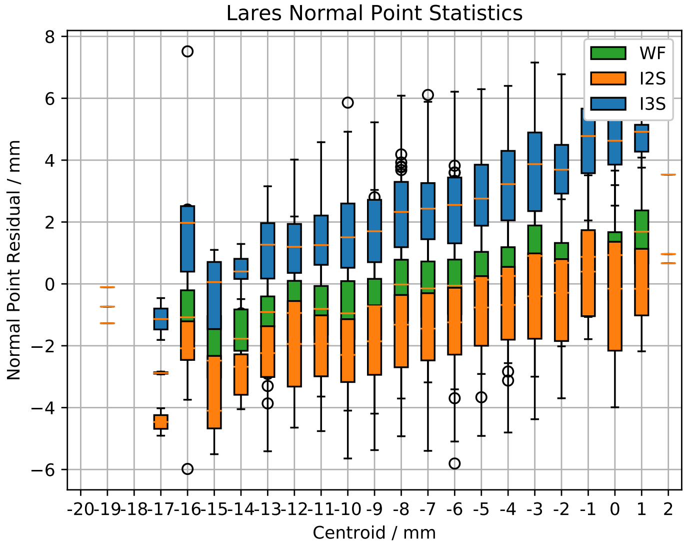


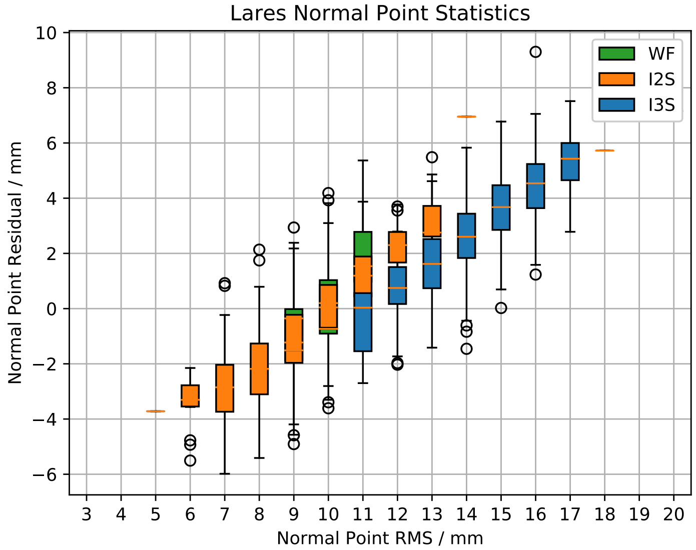
- WF NP Residual variation with Centroid is subcentimeter
- I3S NP RMS unacceptable high
- I2S NP Residual vs. NP RMS slope deviates by factor 2 from HIT-U Analysis
- WF NP RMS in same range as calibration, NP Residual spread is much tighter than I2S
- WF NP Residuals located around mean



Bundesamt für
Kartographie und Geodäsie

Lares Results

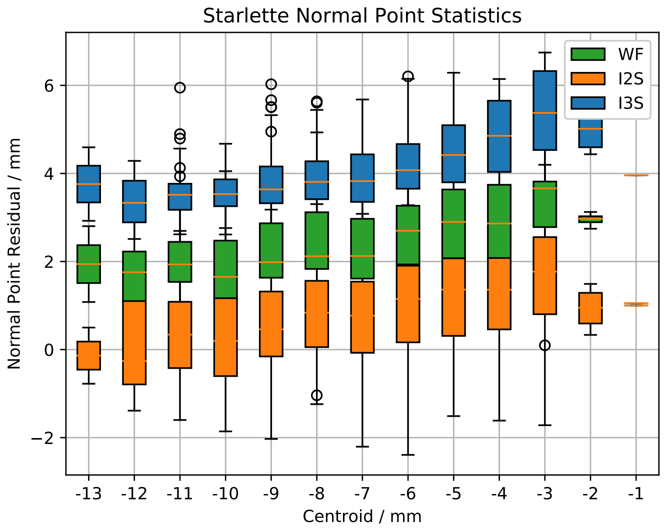


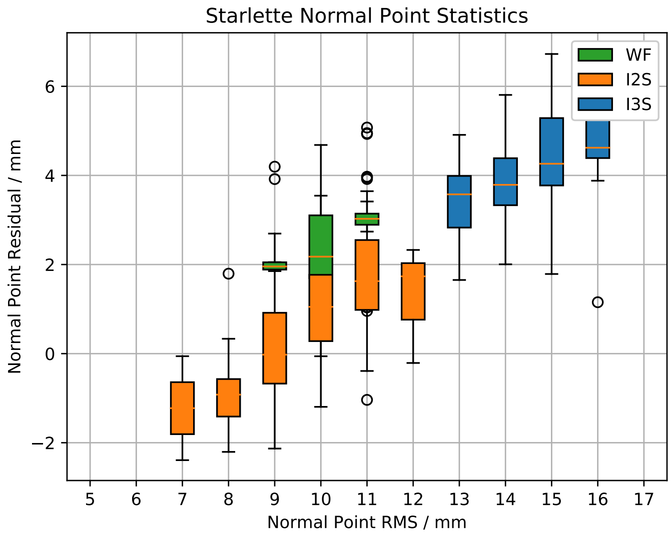


- WF NP Residual show the least variation with Centroid (-2 to +1mm)
- I3S NP RMS unacceptable high
- I2S NP Residuals vs. NP RMS show same slope as HIT-U Analysis
- WF NP RMS in same range as calibration, NP Residual spread is much smaller than I2S
- WF NP Residuals located around mean

Bundesamt für
Kartographie und Geodäsie

Starlette/Stella Results





- WF NP Residual show the least variation with Centroid (+2 to +3mm)
- I3S NP RMS unacceptable high
- I2S NP Residual vs. NP RMS shows similar slope and signature as HIT-U Analysis
- WF NP RMS in same range as calibration, NP Residual spread is much tighter than I2S
- WF NP Residuals located around mean+2mm due to high bandwidth of Starlette response
- Special Tuning of WF causes results to converge against I2S results

Conclusion

- Iterative 3 sigma (I3S) editing is not an option due to high RMS values – it underestimates data quality
- NP-Residual systematics in HIT-U Analysis can be explained to a large extent by the convergence properties of iterative 2 sigma editing
- Wiener Filter NP-Algorithm is able to mitigate these systematics
- Wiener Filter NPs located around mean of Transfer Function for all Satellites under consideration except Starlette(+2mm). With special tuning WF results converge against I2S results
- Wiener Filter NPs show the least correlation with Centroid
- Wiener Filter NPs RMS in the same range as calibration, since satellite signature is removed
- For large diameter Satellites Wiener Filter NPs are of superior quality compared to iterative 2 sigma editing
- Wiener Filter NP procedure is consistent for LAGEOS, Etalon, Ajisai and LARES

From these and tests on numerous other passes we conclude that:

- for a single-photon station there is often a significant difference of the peak from the $3 \times$ rms-rejection mean
- the $1 \times$ rms-rejection mean usually agrees with one or other of the smoothing peak and Pearson peak, and often with both.

6. Recommendations

In conclusion we recommend the following:

a) the ranges to a calibration target or the trend-removed data from a whole satellite pass should be screened at an iterated $3 \times$ rms level, and in the process determine rms and $mean$ of the retained data

b) the skewness and kurtosis of the retained data should be determined

c) using this fixed value of rms a second determination of the mean should be made using an iterated $1 \times rms$ rejection. This provides an estimate of $peak$. Then the bias of the calibration or pass is $bias = peak - mean$

d) for a calibration run, use the value of $peak$ as the calibration value

e) for a satellite pass, form normal points from the screened data within each bin in the usual way, but add the correction $bias$ to the normal point.

A review of where we stand in evaluating the quality of our NP's

Matthew Wilkinson
NERC Space Geodesy Facility

NERC
SCIENCE OF THE ENVIRONMENT

BGS
1835

Introduction

- The method to define normal points is **fixed** by the ILRS as the mean residual applied to a range at a central epoch within a fixed time window.

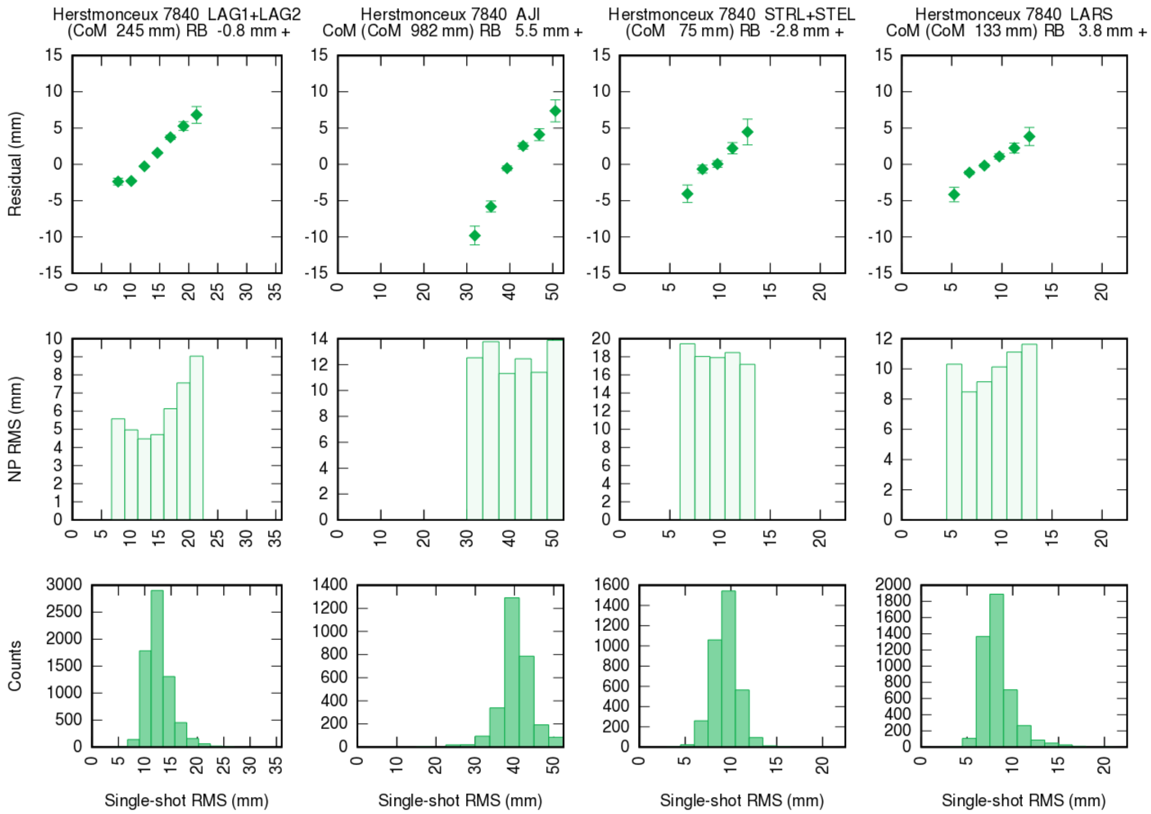
- Stations are responsible for forming their own normal points. Some flatten their laser range measurements by adjusting an orbit prediction. Others do so by fitting a high order polynomial. Clipping of the range residuals is also set by the station.

- The methods used to form normal points by the station must be described in the ILRS Site Log so that a **centre-of-mass** correction can be calculated.

Range vs RMS

For a number of SLR stations, a variation was shown in the orbit fit range residuals of normal points that depends on the RMS.

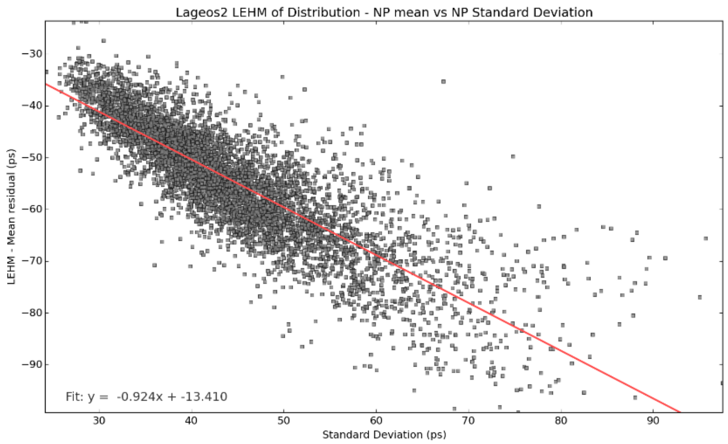
This is due to the shape of the returning pulse and an inconsistency in the clipping applied on a pass by pass basis.



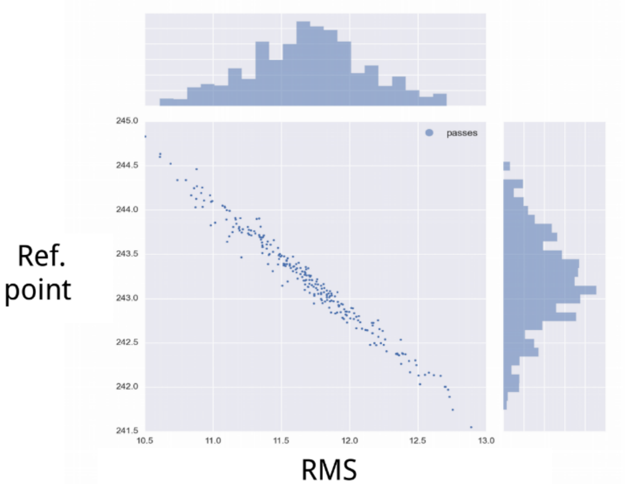
Otsubo, Systematic Range Error, IWLR, Annapolis 2014. *https://cddis.nasa.gov/lw19/Program/index.html*

Range vs RMS

This was also seen directly in the range data by plotting the distribution leading-edge-half-maximum (LEHM) and the NP mean difference against RMS.



And this trend was shown to be partly caused by the variable orientation of LAGEOS from simulations of the satellite response.



Wilkinson, Systematics at the SGF, Herstmonceux, IWLR Potsdam, 2016. *https://cddis.nasa.gov/lw20/docs/2016/papers/41-Wilkinson_paper.pdf*

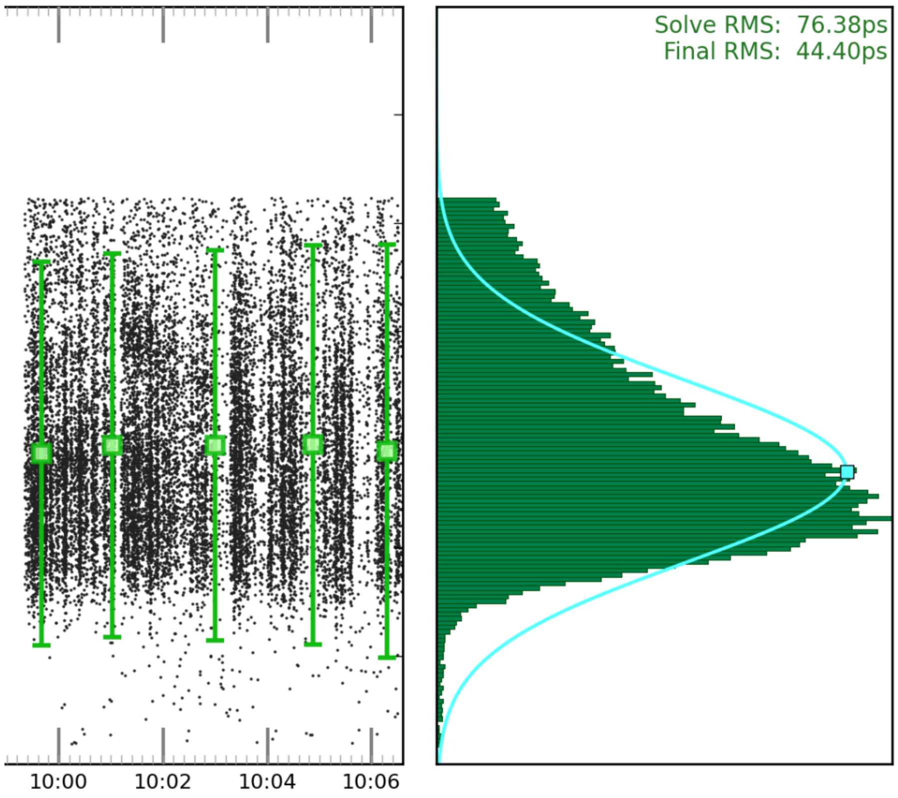
Rodríguez, Variability of LAGEOS normal point sampling: causes and mitigation. Riga ILRS Technical Workshop, 2017. *https://cddis.nasa.gov/2017_Technical_Workshop/docs/presentations/session2/ilrsTW2017_s2_Rodriguez.pdf*

Forming Normal Points

At Herstmonceux, currently the clipping is applied at ± 3σ from the centre of a Gaussian fit.

The σ value depends on the level of signal to noise and the 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.

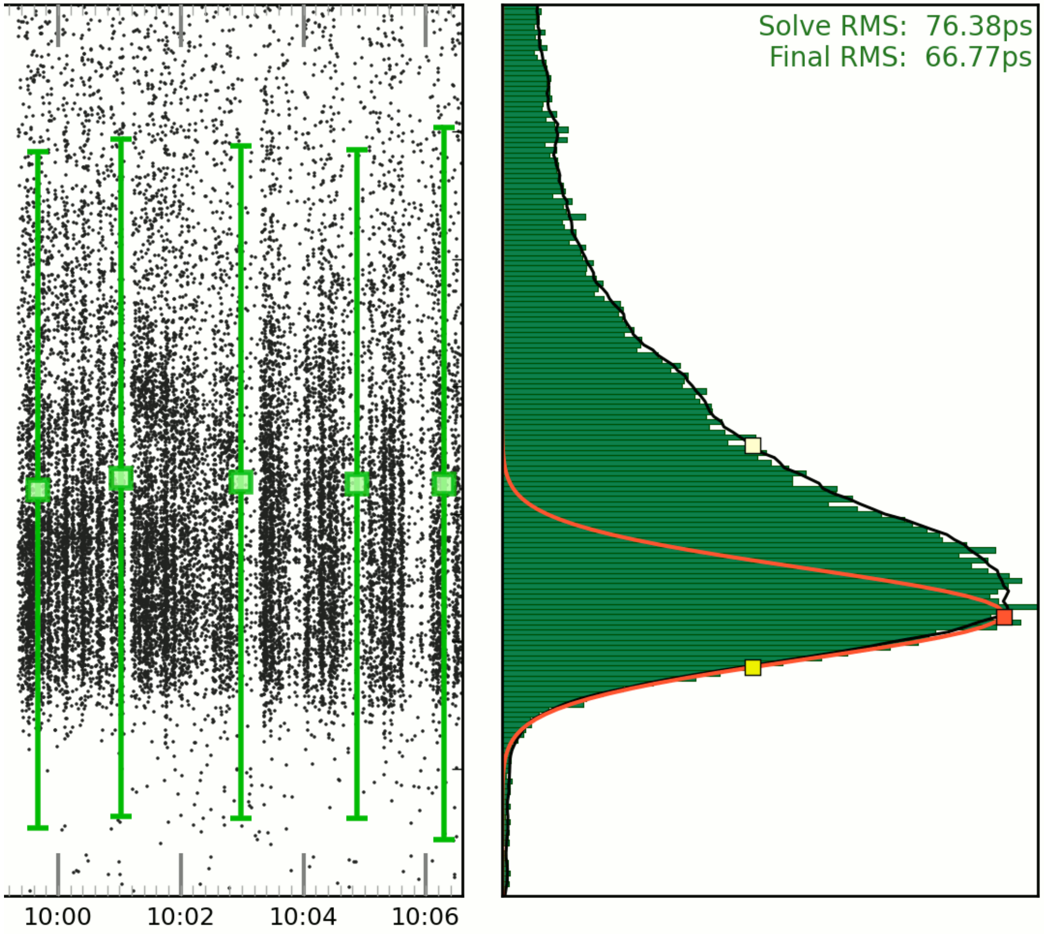


Clipping for Normal Points

To apply consistent clipping a stable point on the distribution is required, such as the leading-edge-half maximum (LEHM).

From the LEHM, fixed clipping can be applied that is set for all passes.

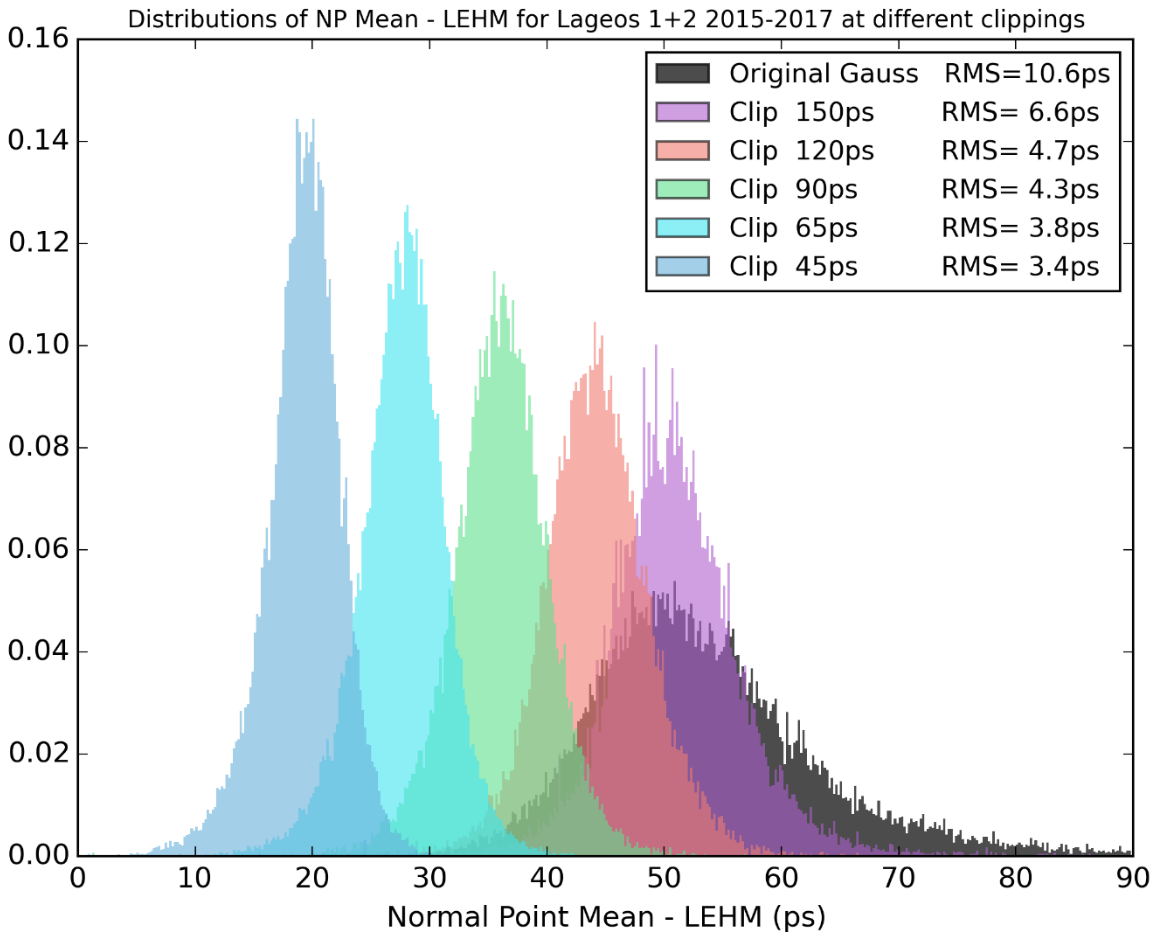
But, what level of clipping is best?



Clipping Results

NP mean – LEHM distributions from the clipped datasets are tighter.

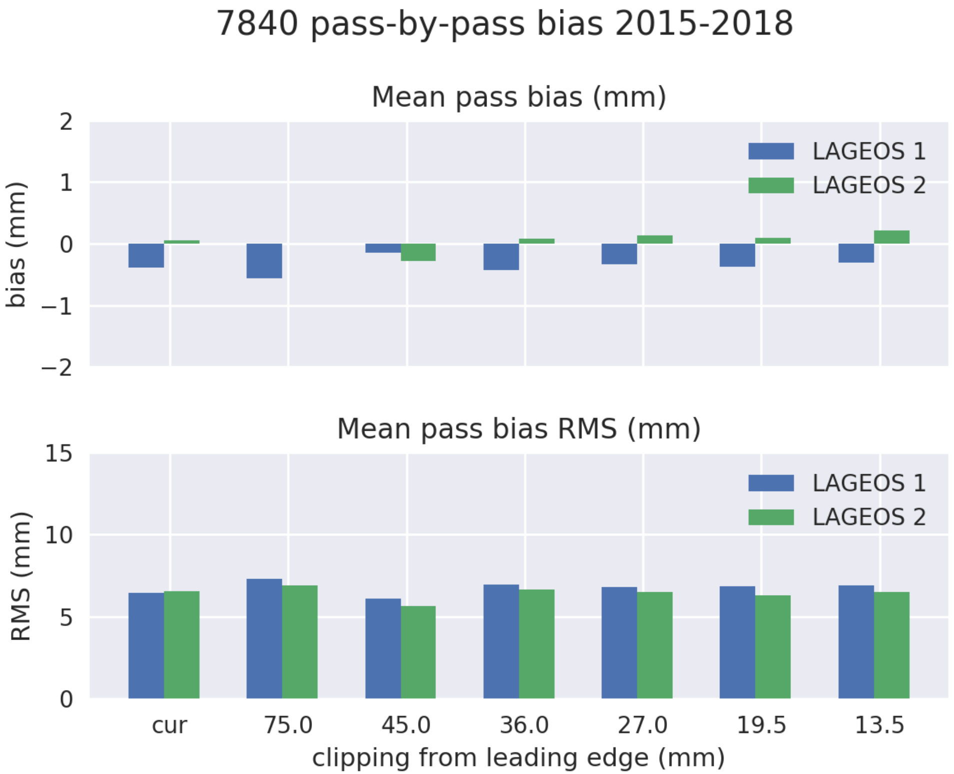
Clearly, as the clipping applied is tighter the distance from the NP mean and the LEHM is reduced and the measurement is made closer to the front of the satellite.



Analysis Results

The clipping does not have much effect on the average pass range bias or the RMS of pass range bias.

An alternative way to look for any improvement is to account for modelling error in the solutions using a polynomial fit to each pass.

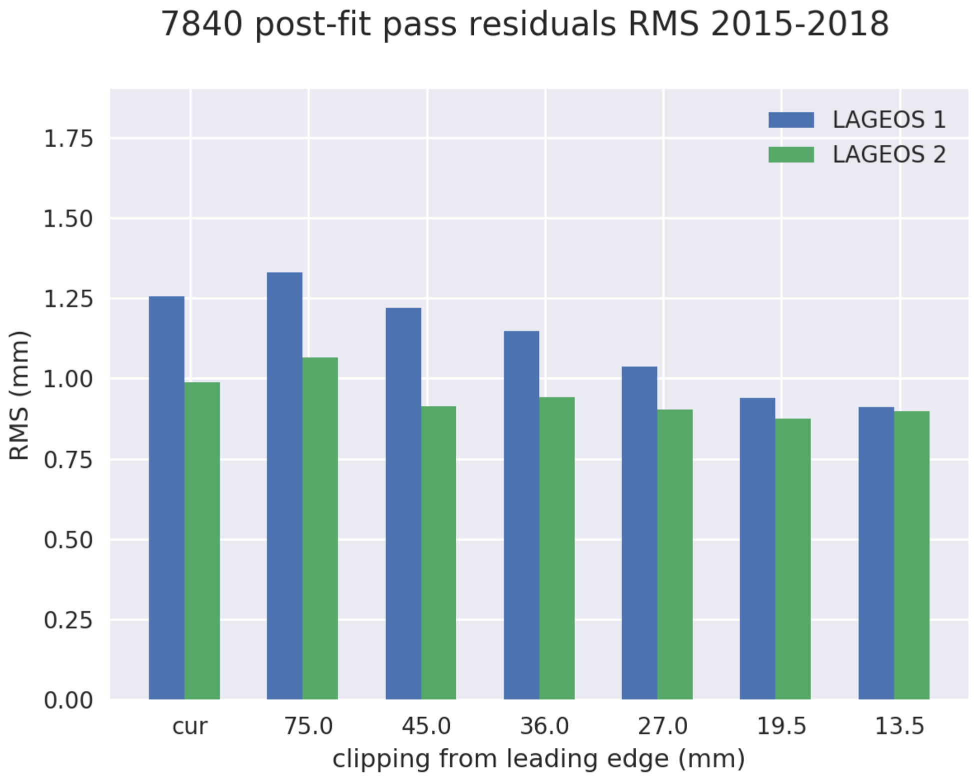


Analysis Results

A quadratic polynomial was removed from every pass to account for modelling errors

The RMS of the remaining residuals was then calculated for each dataset for LAGEOS 1 and 2.

Using this method, it can be seen that the clipping reduces the normal point to normal point variation.

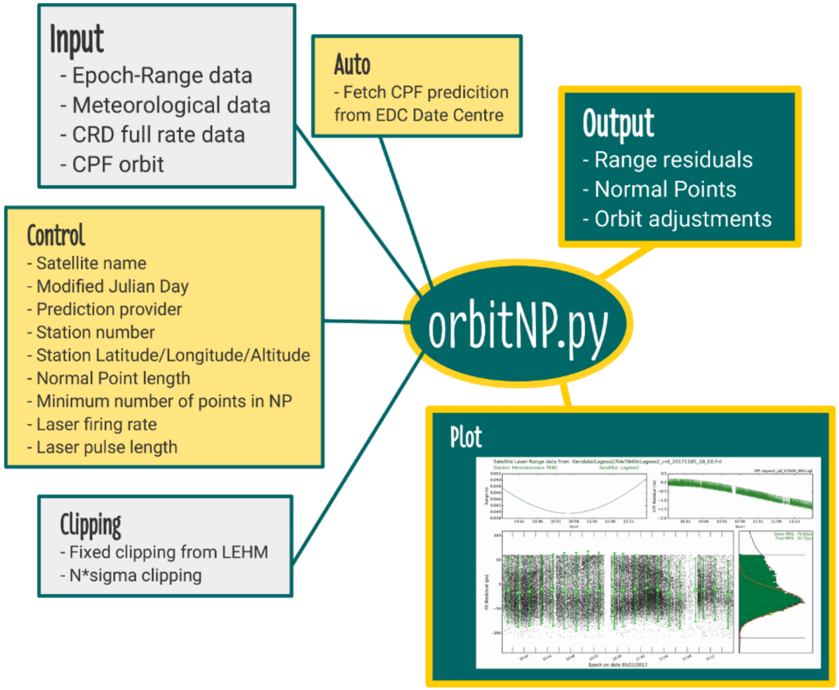


OrbitNP.py

The orbit adjustment PYTHON program from the SGF was released to the SLR community at the start of 2019. This was provided for stations to make comparisons with their methods to produce flattened range residuals and normal points.

It can process full-rate data or raw epoch-range data.

It could be used to process normal points from full-rate data to make assessments of the quality of our NPs.



Conclusions

- The normal point range residual dependency on single shot RMS can be minimised with controlled clipping about a well defined point on the satellite distribution.
- Alternatively, allowing stations to calculate normal points using other methods could avoid this bias.
- We did not find any evidence of this having an impact on the analysis products.
- However, tighter clipping does improve the quality of the SLR measurements from Herstmonceux by decreasing the normal point variability.
- Alternative methods to calculate normal points could be compared if the corresponding centre-of-mass values were defined.

NASA SLR Issues impacting Data Quality

Author: Van S Husson
Peraton/NASA SLR Network
ILRS Central Bureau
vhusson@peraton.com

Agenda

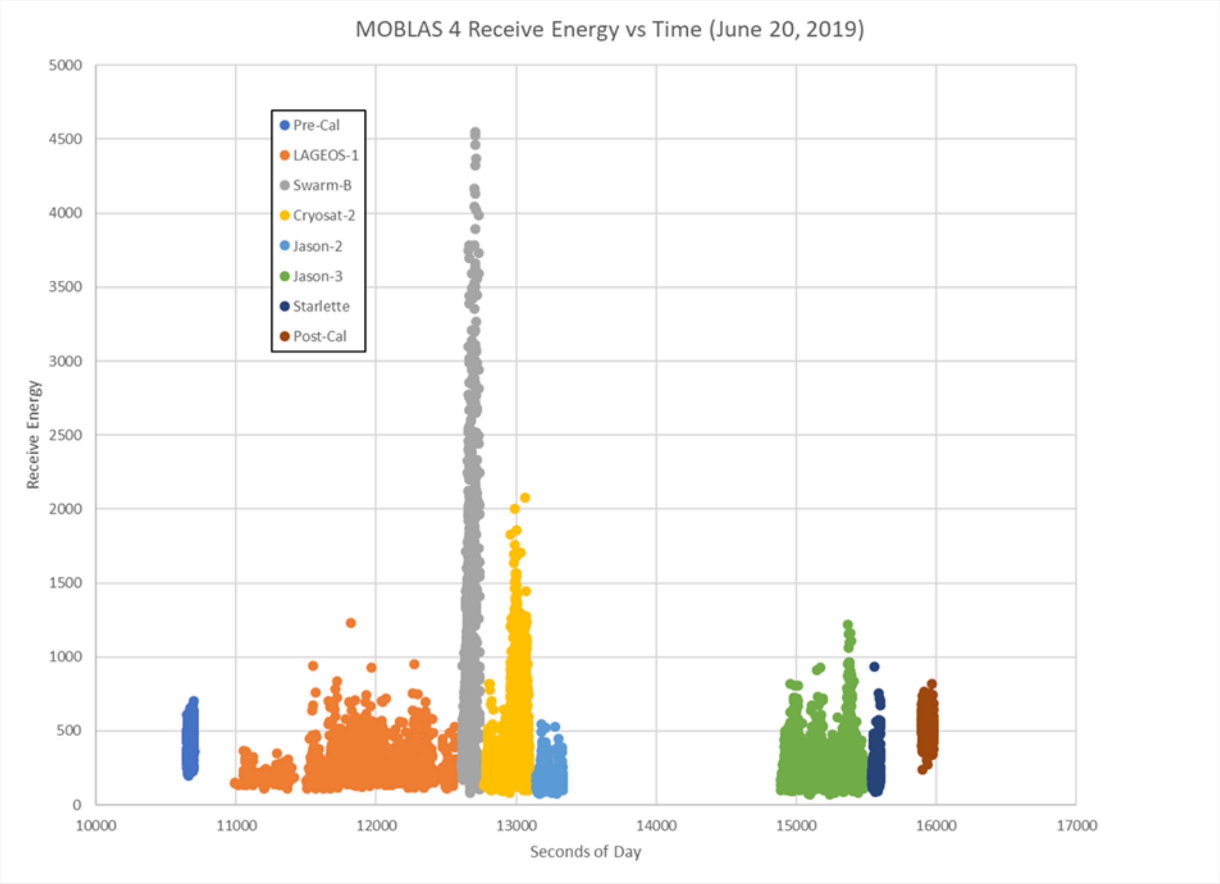
- NASA SLR Site Survey Related Issues
- Three Potential NASA SLR Calibration Issues

NASA SLR Site Survey Related Issues

- NASA SLR survey accuracies:
  - The accuracy in determining the NASA SLR system eccentricities in each component (North, East and Up) is at the 1-2 mm level, because direct measurements are not possible
  - The accuracy is determining NASA SLR calibration distances is at the 2-4 mm level, because it depends in part upon the accuracy of the system eccentricities
  - There is a potential 2 mm up discrepancy in the MOBLAS eccentricities based on IGN independent measurements of the self centering plate (ref: 2007 Tahiti survey)
  - Axes of rotation are offset at the 1-2 mm level. Note: VLBI antennas may have the same issue
- NASA SLR resource constraints have led to:
  - Reduction in frequency of NASA SLR site surveys
  - The contracting of surveying services to outside agencies who don't necessarily fully understand our SLR needs
- Survey Management:
  - The ILRS system eccentricity files and station site log do not always reflect the eccentricity data contained in the survey reports and vice versa

NASA SLR Satellite Interleaving Calibration Philosophy

- Pre satellite interleaving, each satellite (LEO, LAGEOS and HEO) were calibrated separately with a pre and post calibration taken immediately before and after the pass. Maximum time between a pre and post calibration was 50 to 55 minutes.
- Post satellite interleaving, one pre and post calibration are taken after a session of satellite tracking. The combined calibration is applied to all satellites (i.e. LEO, LAGEOS and HEO) in the session. Pre and Post calibrations are within 2 hours of each other. (See pass interleaving example on the right, 6 satellites with a common calibration. A timer series or receive energies.)



Differences between Calibration and Satellite

Station	Marker	Calibration Firerate	Calibration PMT (v)	LAGEOS Firerate	LAGEOS PMT (v)	LARES Firerate	LARES PMT (v)	Etalon Firerate	Etalon PMT (v)
MOBLAS 4	7110	10 Hz	3200	5 to 10 Hz	3300	10 Hz	3200-3300	4 Hz	3200-3300
MOBLAS 5	7090	10 Hz	3000	5 Hz	3100-3400	10 Hz	3300-3400	4 to 5 Hz	3300-3400
MOBLAS 6	7501	10 Hz	2700	5 Hz	2800-3000	10 Hz	2700-3000	4 Hz	2900-3000
MOBLAS 7	7105	10 Hz	2700	5 to 10 Hz	2900-3100	10 Hz	2800-3300	5 Hz	3300-3400
MOBLAS 8	7124	10 Hz	3100	5 Hz	3100	10 Hz	3100	4 Hz	3100-3400
TLRS 3	7403	5 Hz	3000	5 Hz	3000-3200	5 Hz	3000	N/A	N/A
TLRS 4	7119	5 Hz	2800	5 Hz	2900-3000	5 Hz	2800-3000	N/A	N/A

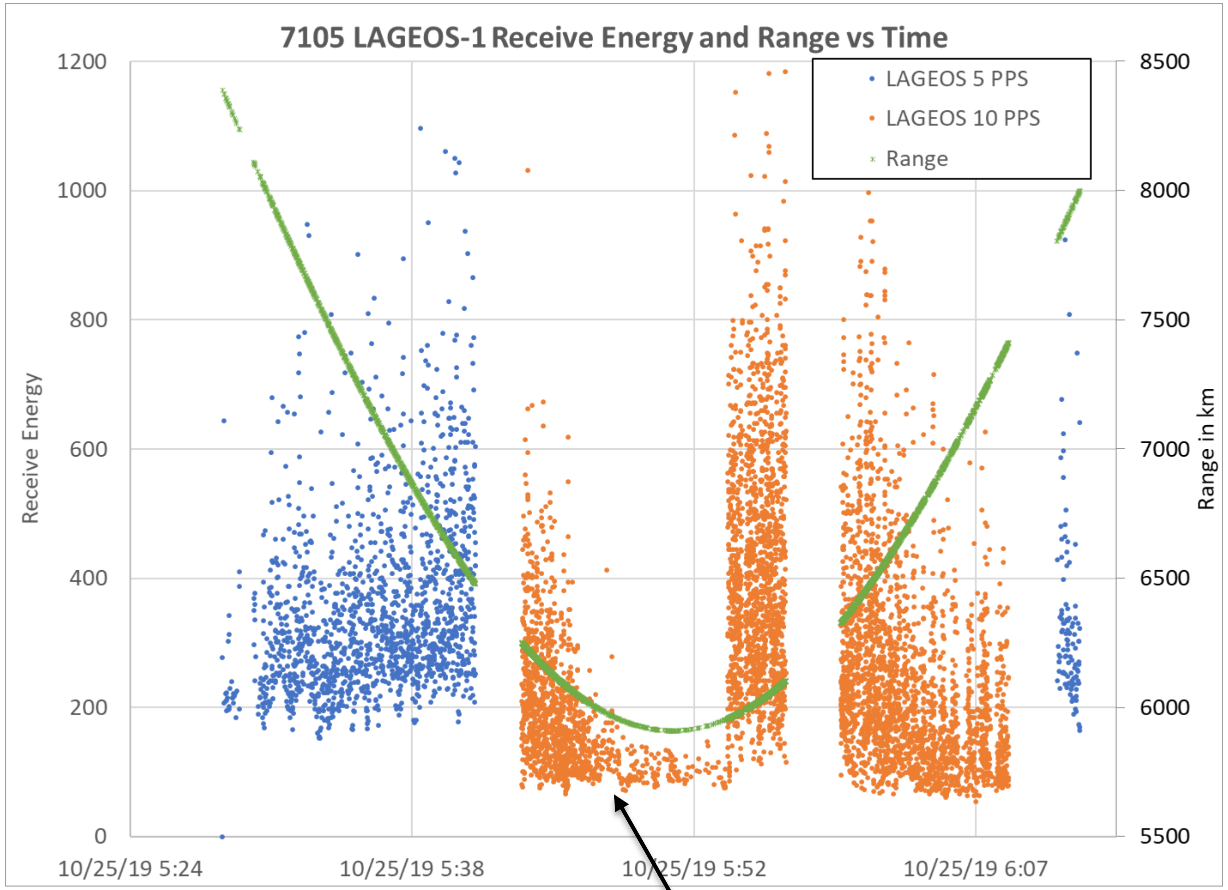
Are these differences of the laser fire rates and PMT voltages between calibration and satellites inducing a range bias? If yes,

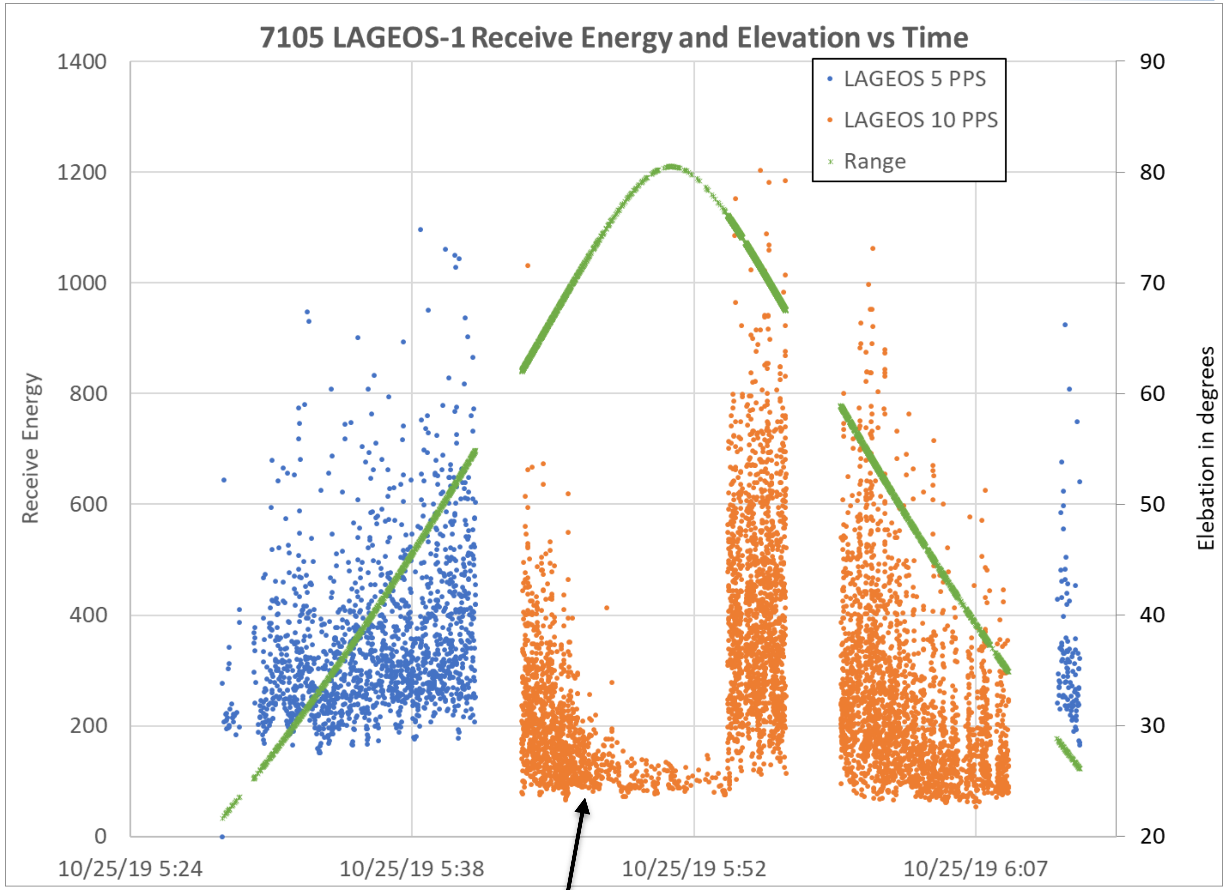
1. What is the magnitude of these biases?
2. Are they recoverable?
3. When did these changes take place since in the pre satellite interleaving, these differences did not exist?

Potential Calibration Issue #1 (Laser Fire Rate)

- Our laser maximum repetition rate is 10 Hz, but there were other constraints which kept the NASA SLR network at 5 Hz
  - Prior to the 2009 MOBLAS laser ranging controller (LRC) upgrade which enabled the laser to fire at 10 Hz, all ranging was done at 5 Hz
  - Post LRC upgrade, calibrations and LEO tracking was performed at 10 Hz, but LAGEOS and HEO were still constrained to 5 and 4 Hz; respectively, due to HP5370 TIU constraints
  - The laser can only be optimized at one rate and 5 Hz was chosen to maximize LAGEOS and HEO data yield
  - The last few years, Event Timers have replaced the HP5370s, enabling 10 Hz and 5 Hz ranging on LAGEOS and HEOs; respectively; some of the time dependent upon the satellite range
- Question #1: Since the characteristics (e.g. beam divergence) of the laser change when the fire rate is altered, does that impact system delay and how much if it does?

7105 MOBLAS-7 LAGEOS-1 Pass on Oct 25, 2019



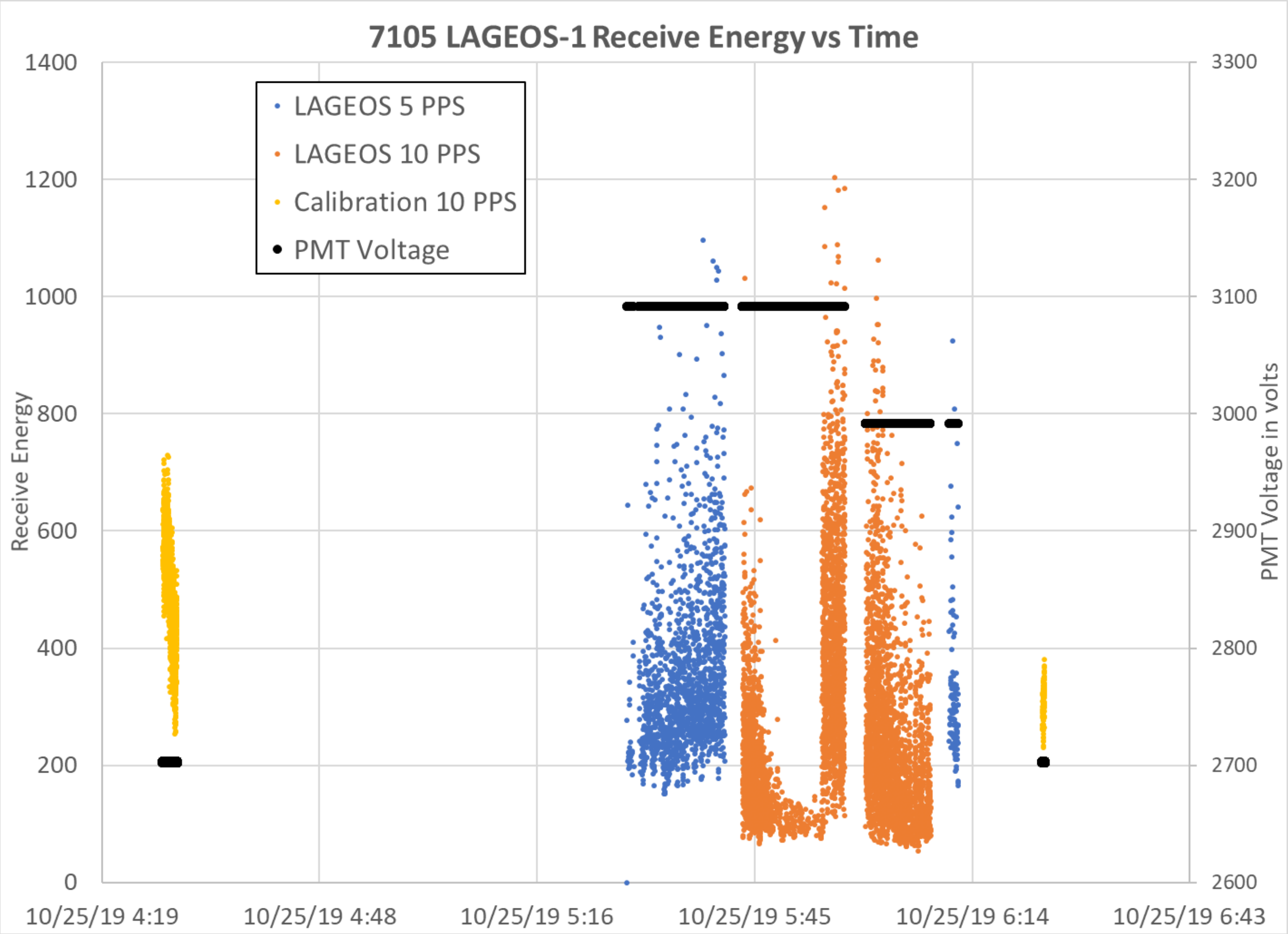


These graphs are a time series of receive energies of a high elevation 7105 LAGEOS pass (i.e. > 80 degrees) where the laser fire rate was toggled between 5 and 10 Hz. The receive energies decrease as the mount has trouble keeping up as the pass approaches the satellite Point of Closest Approach (PCA). The ranges and elevations are plotted on the right axes on the left and right charts; respectively.

Summary of 5 pps vs 10 pps Ground Tests

System	System Delay Diffs (10 pps – 5 pps) in mm	10 pps LRC Upgrade
MOBLAS 4	2.3	22-Sep-2009
MOBLAS 5	1.5	28-Sep-2009
MOBLAS 6	TBD	04-Sep-2009
MOBLAS 7	TBD	11-Jul-2009
MOBLAS 8	-1.0	03-Nov-2009

7105 MOBLAS-7 LAGEOS-1 Pass on Oct 25, 2019

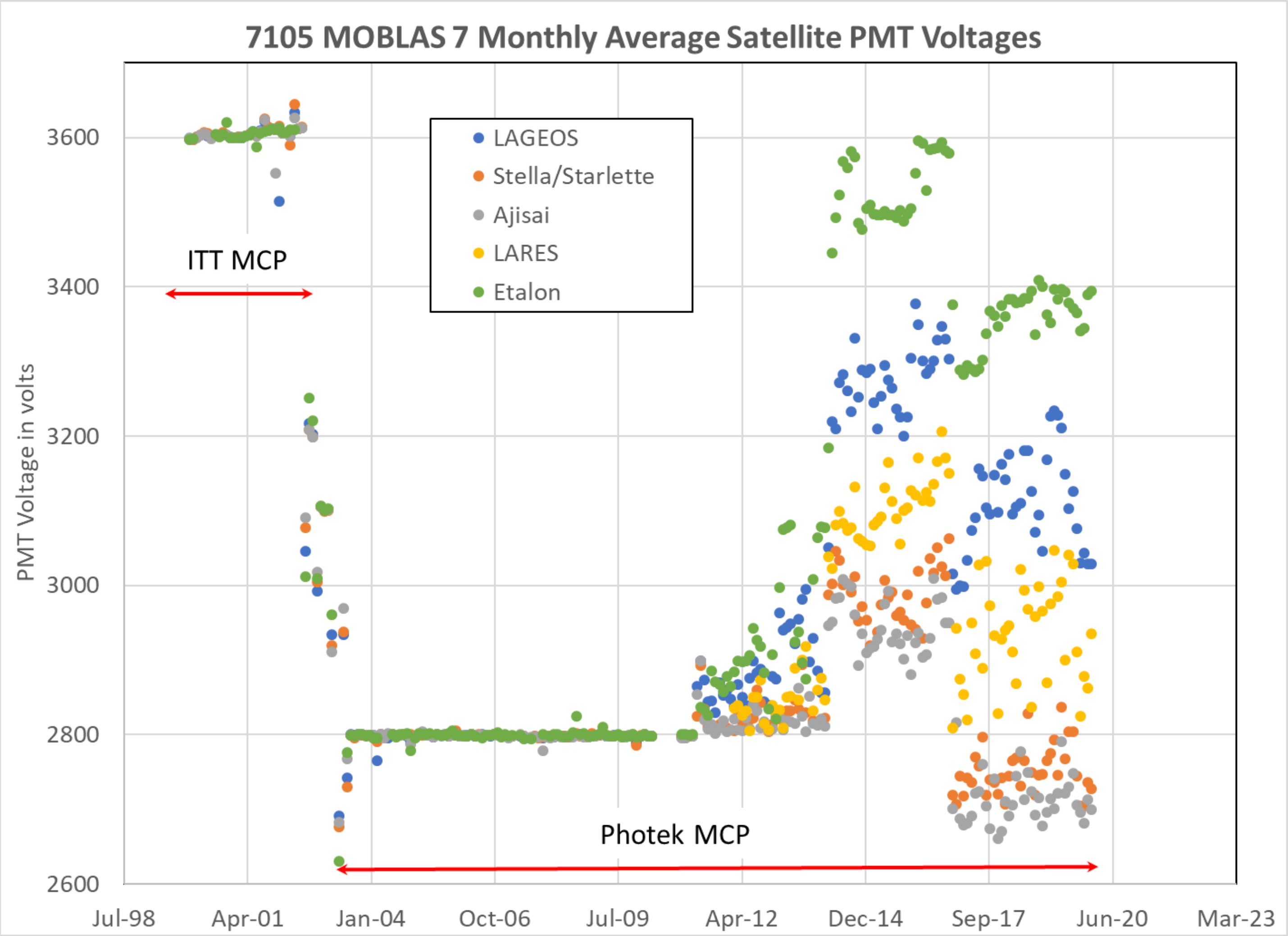


This is the same time series of receive energies from the same 7105 LAGEOS pass including the pre and post calibrations. On the right axes are the PMT voltages.

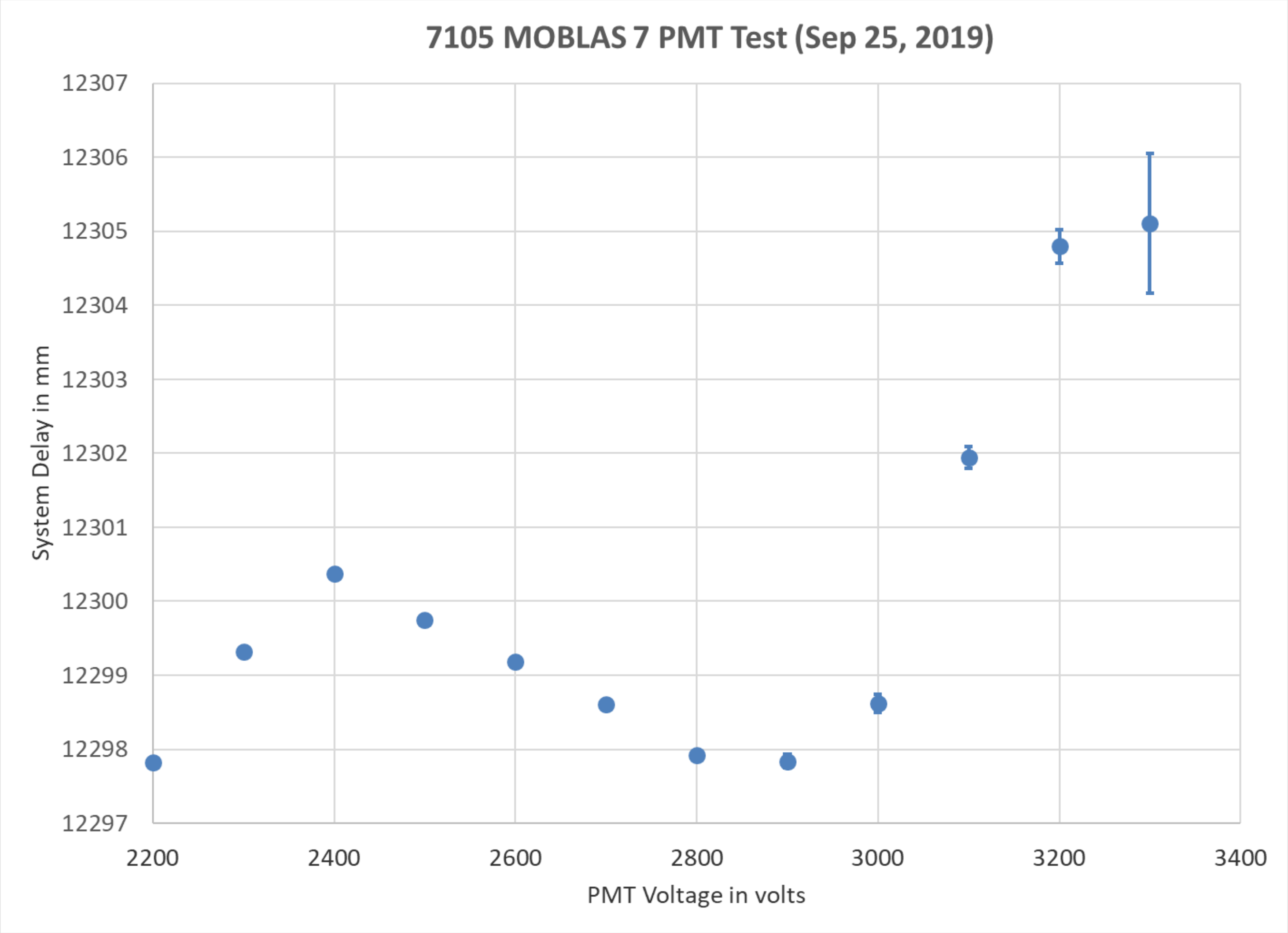
The satellite PMT voltage is in the C2 CRD record. When the NASA SLR software was written to create CRDs, the PMT voltages weren't varied from one satellite to another, so the PMT voltage was placed in static config file. Also, the current CRD V2 format does not have a field for calibration PMT voltage in the 40 or 41 calibration records.

Potential Calibration Issue #2 (altering PMT voltages)

- Starting in 2011, NASA SLR stations were permitted to use higher voltages on satellites with weaker signals (i.e. LARES, LAGEOS, Etalon) to maximize data yield.
- Does changing the PMT voltage change the system delay and if so how much?



MOBLAS 7 PMT Voltage Test

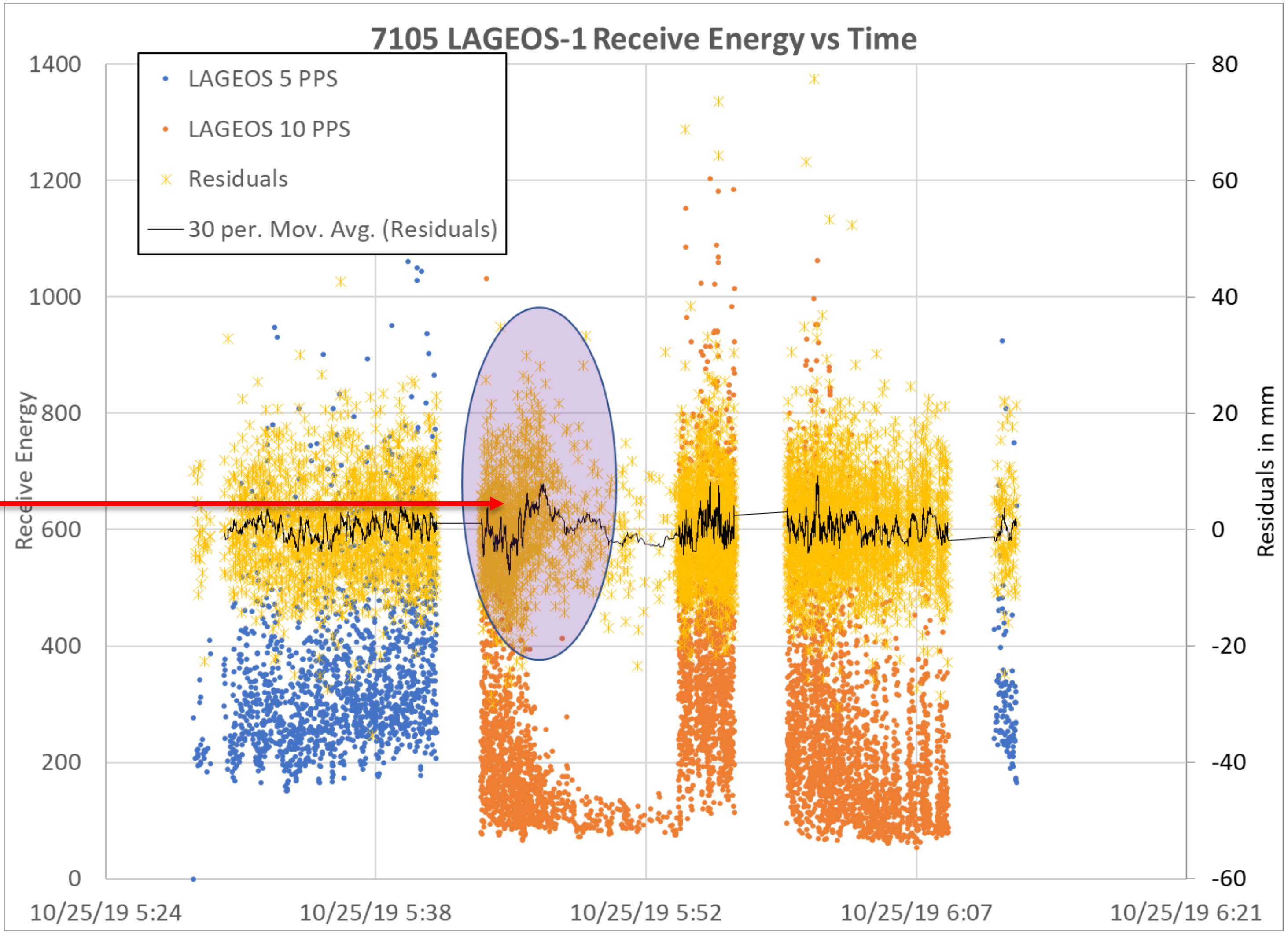


The scatter increases as the PMT voltage increases. Currently MOBLAS 7 calibrates at 2700 volts; LARES data is taken between 2800 to 3300 volts; LAGEOS data is taken between 2900 to 3100 volts; and Etalon data is taken between 3300 to 3400 volts.

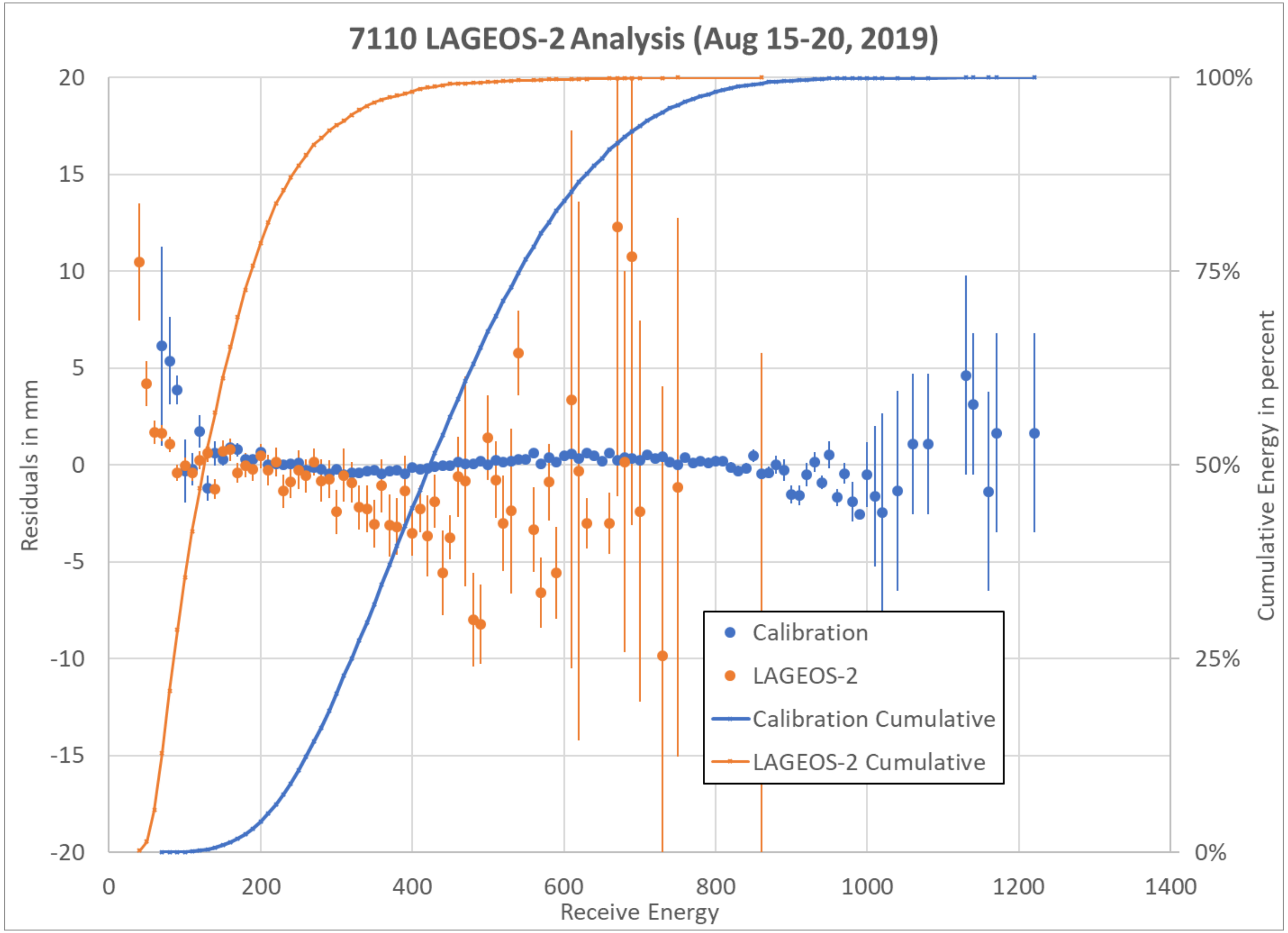
We plan to have the other NASA SLR systems perform this test so we can characterize the impact. We also need to determine if these results are repeatable.

Potential Calibration Issue #3 (Receive Energy)

- Pre satellite interleaving, the stations would calibrate each pass individually, station operators where trained to try and mimic the dynamic range of the satellite receive energies during calibration.
- On this same LAGEOS pass residuals were added to the right axes and there is a several mm shift in the residuals as the receive energy decreases.
- How much does system delay depend upon receive energy and how well do our systems calibrate?



7110 MOBLAS-4 LAGEOS-2 Analysis



This is an aggregation of 7110 residuals from 6 days in Aug 2019. The calibration and LAGEOS-2 residuals are binned vs receive energy. Both LAGEOS-2 and calibration show similar trends at the weaker signal levels. Unfortunately, the area between the cumulative distributions is quite large and thus there is a potential for a range bias.

Conclusions and Next Steps

- **Conclusions**
  - Surveying techniques are a limiting factor in absolute data accuracy.
  - Millimeter levels biases are being introduced in our current calibration scheme.
- **Next Steps**
  - Investigate the feasibility of having close-in calibration targets.
  - We need to characterize these potential errors sources for each of our systems and determine if the results are repeatable. Then document the finding and if deemed necessary update the data handling files.
  - The ILRS has recommended we reduce systematic biases caused by each component to the sub-mm level [Prochazka 2015]. However, not ever mission needs mm level accuracy. We recommend the ILRS determine the accuracy requirements for each mission and then we need to re-evaluate our calibration procedures to balance maximizing data accuracy on the high value satellites without sacrificing data quantity.

Backup Material

NASA SLR Survey Summary (last two)

Location	Marker	System	Last Survey	Organization	SLR System Reference Point	SLR Calibration Piers
Monument Peak, USA	7110	MOBLAS 4	May-2018	NGS	Yes	Yes
			Nov-2011	NASA	Yes	Yes
Yarragadee, Australia	7090	MOBLAS 5	Mar-2014	Geoscience Australia	Yes	?
			Jul-2010	Geoscience Australia	Yes	?
Hartebeesthoek, South Africa	7501	MOBLAS 6	Feb-2014	IGN	Yes	Yes
			Aug-2003	IGN	Yes	Yes
Greenbelt, USA	7105	MOBLAS 7	Aug-2012	NGS	Yes	Yes
			Mar-2008	NASA	Yes	Yes
Tahiti, French Polynesia	7124	MOBLAS 8	Oct-2007	IGN	Yes	No
			Jan-2002	NASA	Yes	Yes
Arequipa, Peru	7403	TLRS-3	Jan-2013	IGN	No	Yes
			May-2007	NASA	Yes	Yes
Haleakala, USA	7119	TLRS-4	Mar-2019	NGS	No	Yes
			May-2013	NASA	Yes	Yes

To support 1 mm accuracy recommendations, surveys need to be more frequent.

MOBLAS and TLRS Calibration Targets

MOBLAS 4 Target Ranges and Azimuths:
A: 187 m, 104 degrees (PRIME)
C: 107 m, 199 degrees

MOBLAS 5 Target Ranges and Azimuths:
B: 150 m, 115 degrees (PRIME)
G: 150 m, 242 degrees

MOBLAS 6 Target Ranges and Azimuths:
D: 131 m, 230. degrees (PRIME)
E: 199 m, 279 degrees

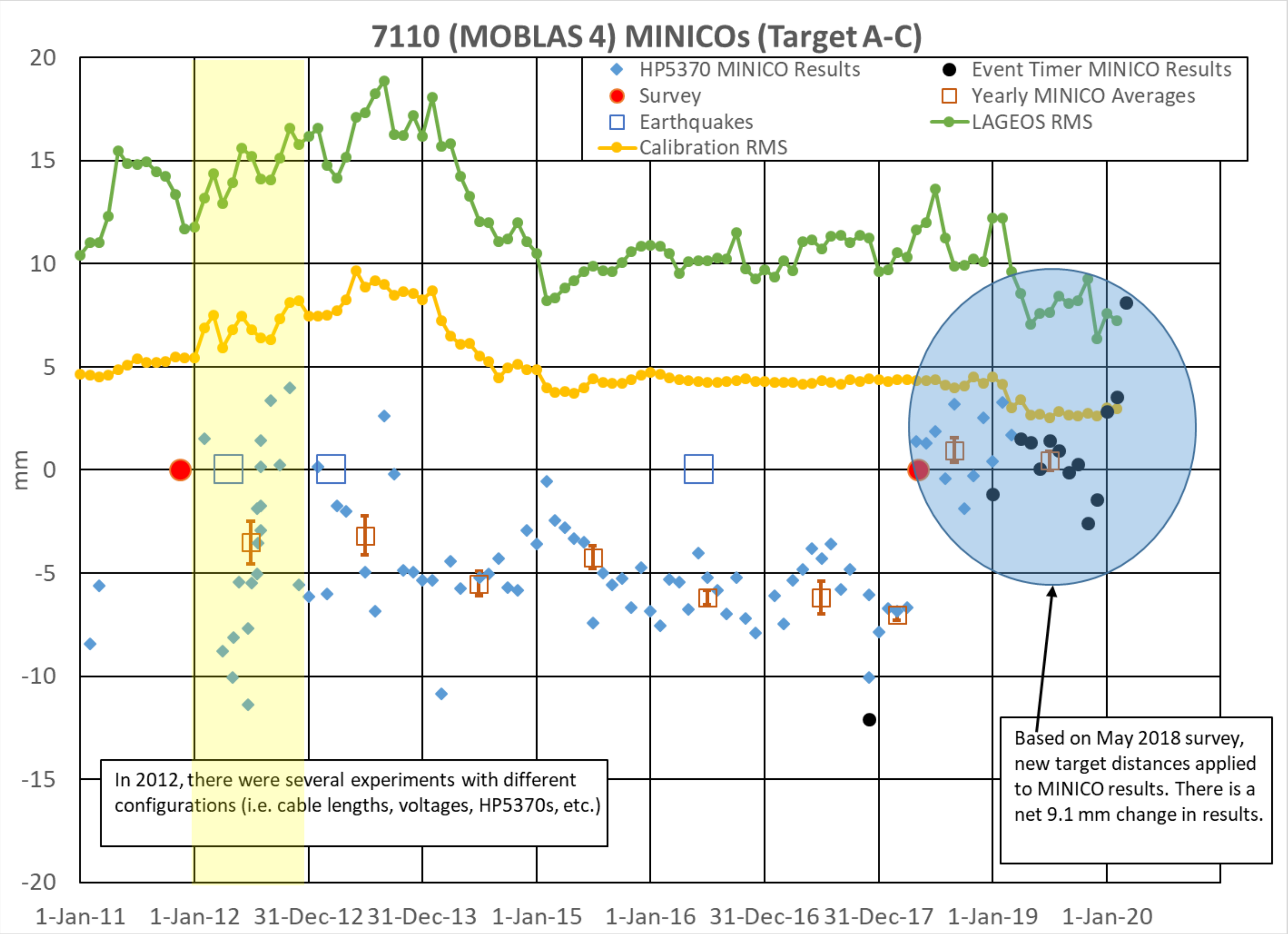
MOBLAS 7 Target Ranges and Azimuths:
A: 107 m, 65 degrees
B: 175 m, 96 degrees
C: 171 m, 105 degrees (PRIME)

MOBLAS 8 Target Ranges and Azimuths:
A: 171 m, 42 degrees
B: 263 m, 138 degrees (PRIME)
C: 122 m, 332 degrees

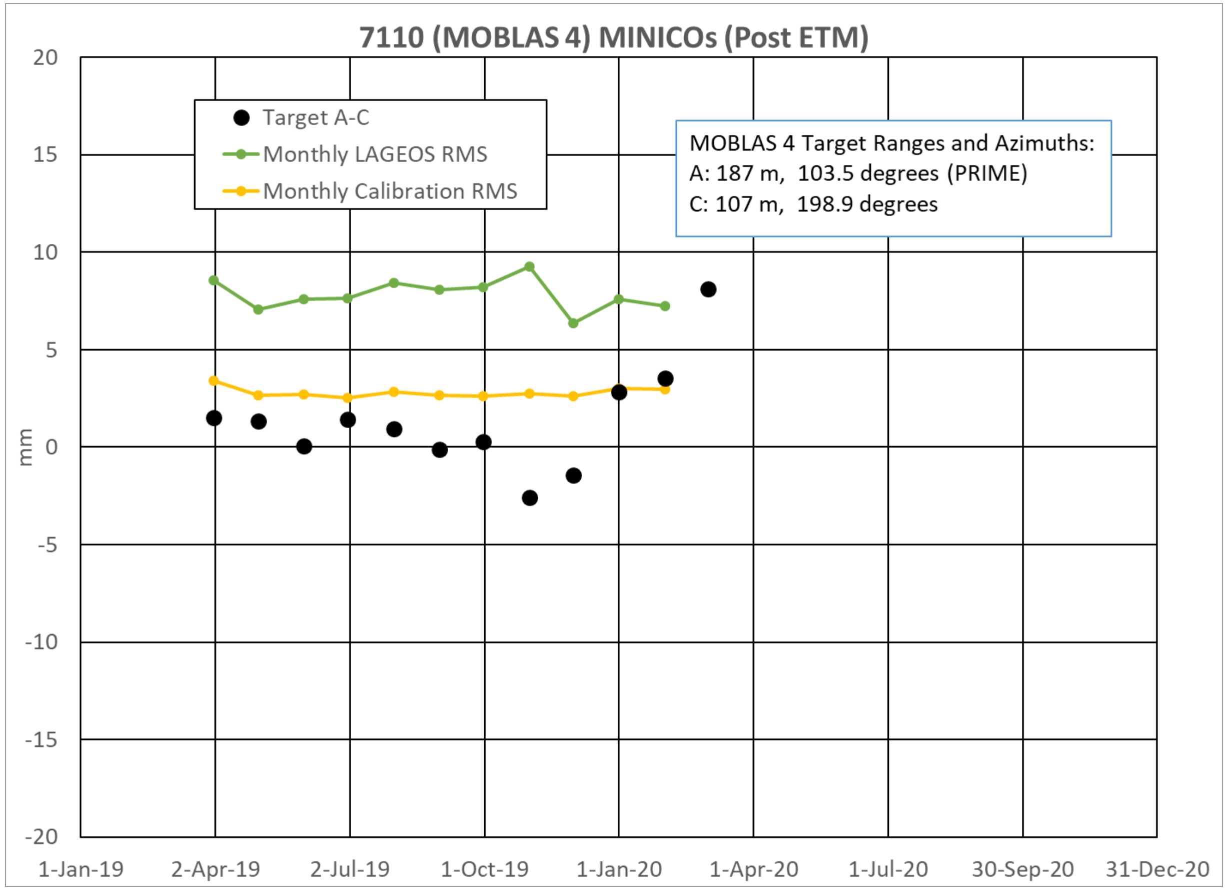
TLRS-3 Target Ranges and Azimuths:
A: 105 m, 10 degrees
B: 105 m, 48. degrees (PRIME)
D: 51 m, 205 degrees

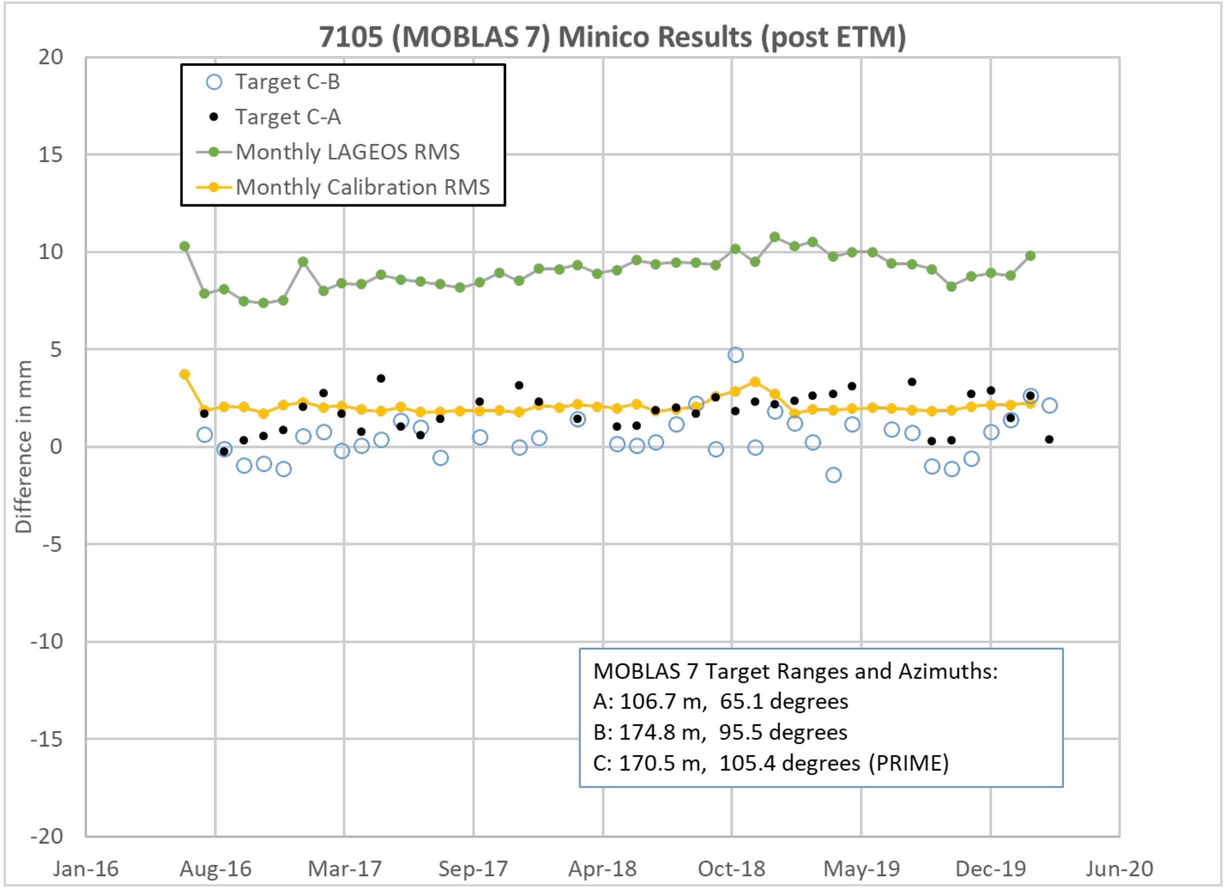
TLRS-4 Target Ranges and Azimuths:
A: 89 m, 14. degrees (PRIME)

7110 MOBLAS 4 MINICO Results



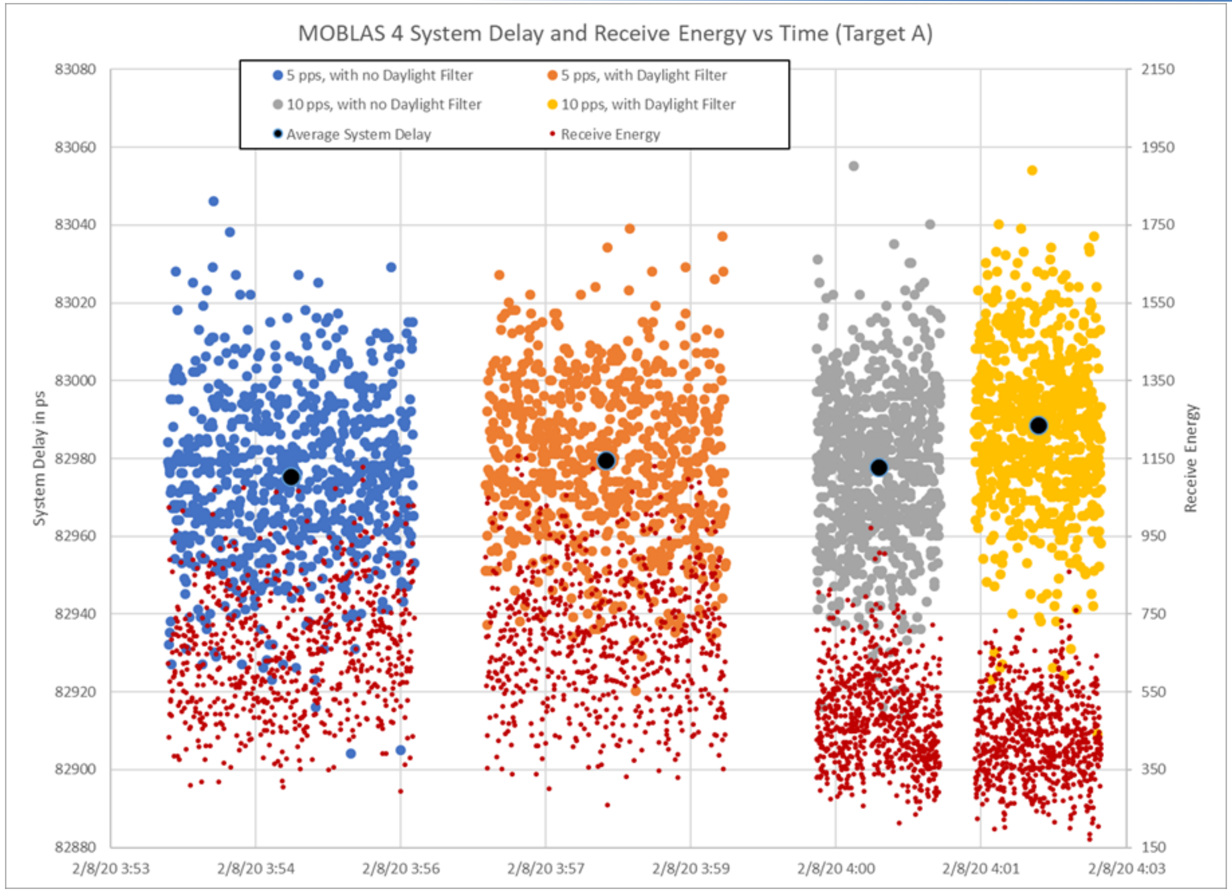
MOBLAS 4 and 7 MINICO Results

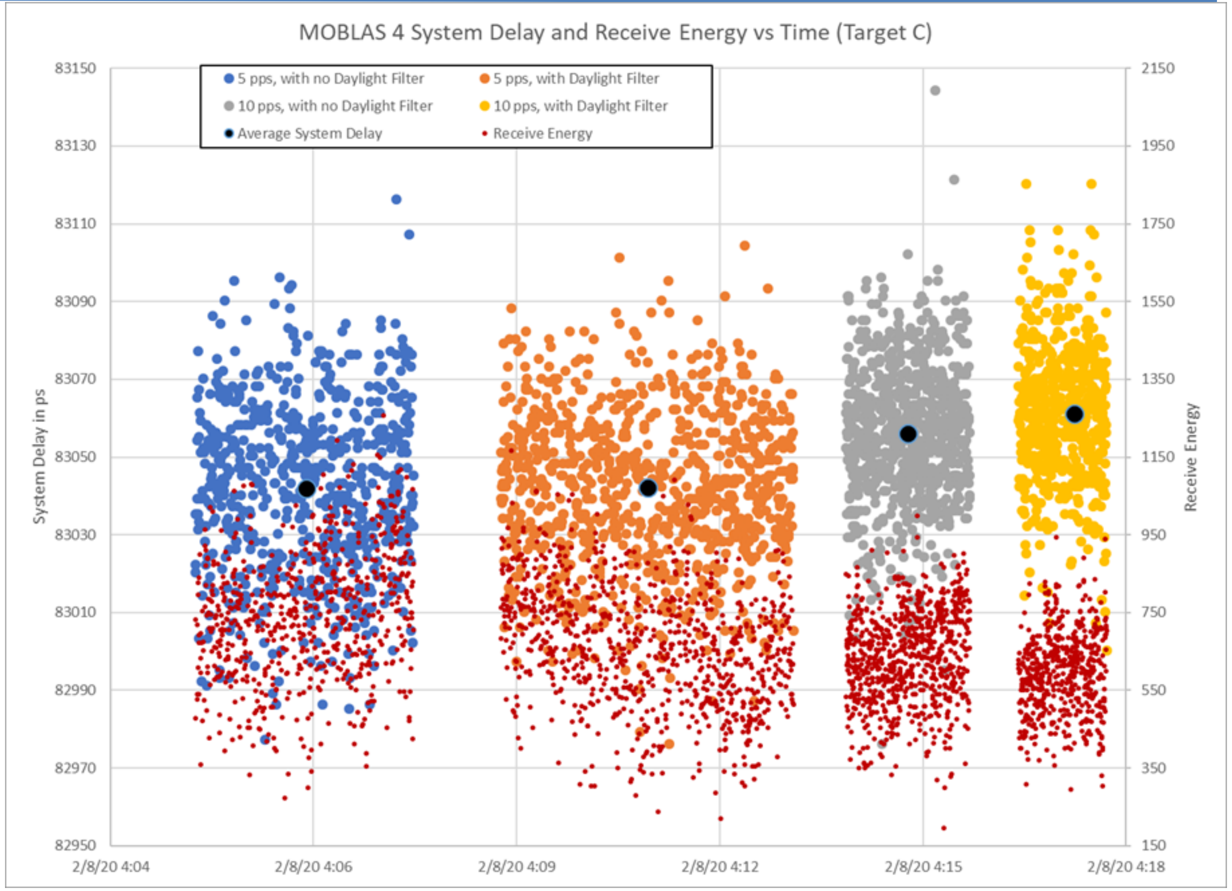




Post ETM, MOBLAS 7 results are more stable than MOBLAS 4

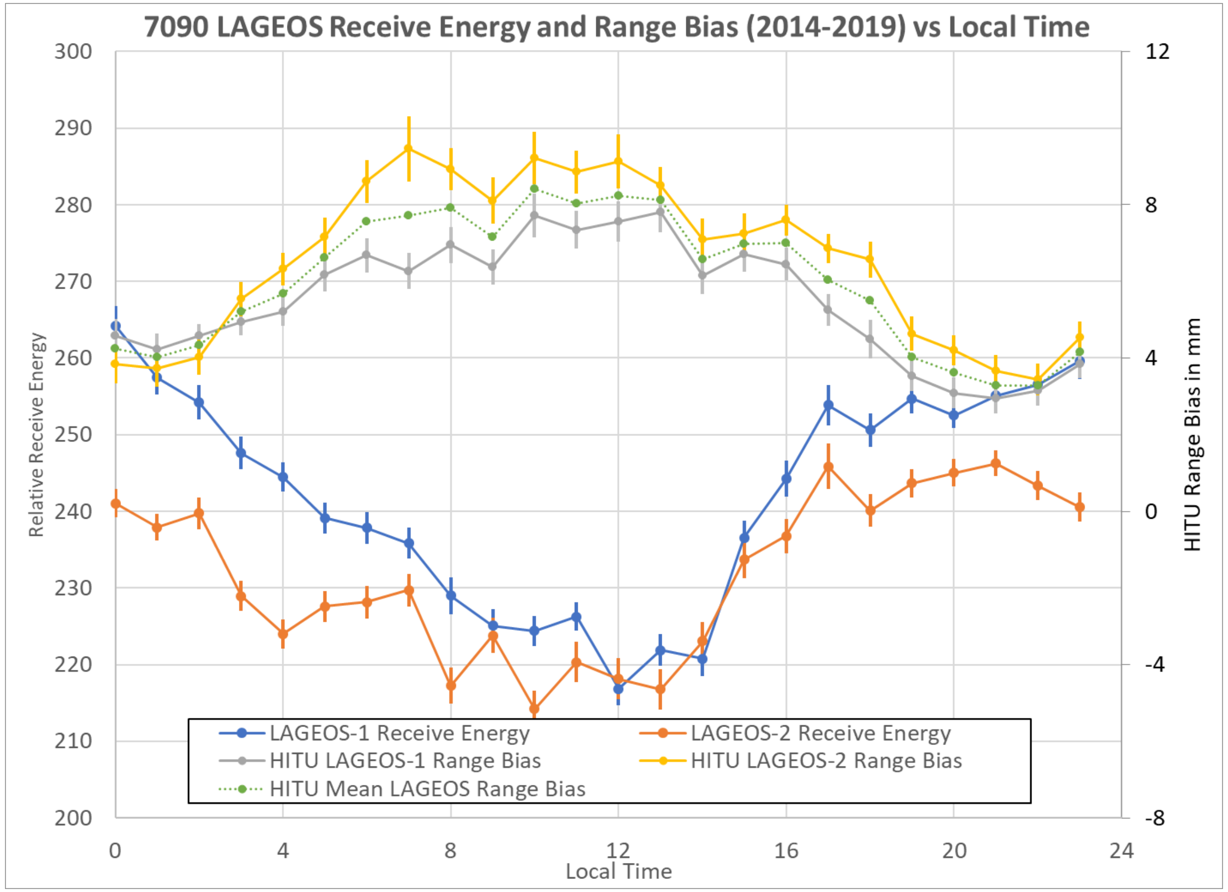
MOBLAS-4 Laser Fire Rate Ground Test (5 vs 10 pps)

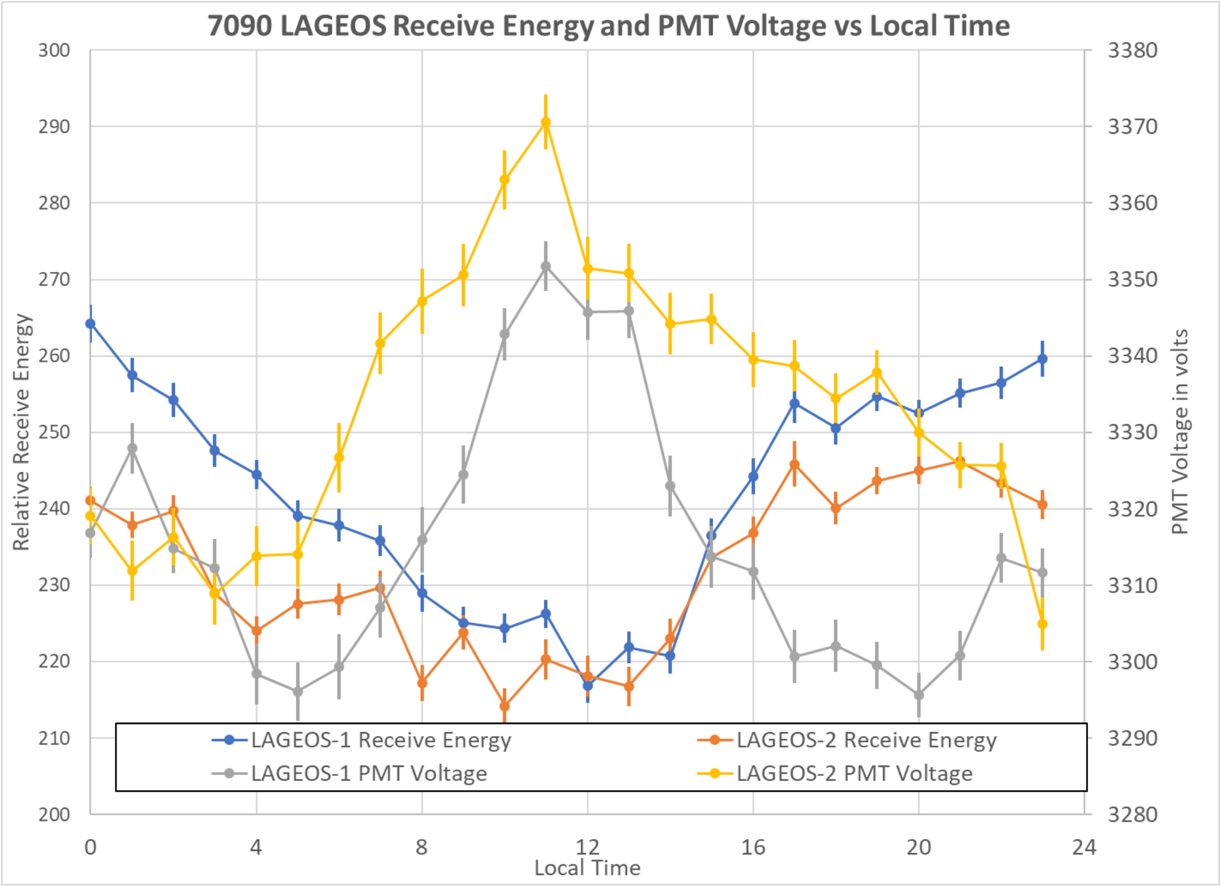




MOBLAS 4 did a laser fire test from both of their two targets A&C (Target A is prime). Since we are looking for millimeters the results on C are more accurate since the mean and dynamic range of receive energies were better maintained.

7090 MOBLAS-5 Diurnal Range Bias Analysis





Toshi's yearly aggregate analysis starting in 2015 has shown mm level diurnal effects in some of the NASA systems
Are these effects real? If so, are PMT voltage changes and/or receive energies differences the root cause?