Millimeter Accuracy from Centimeter Targets

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SLR Station Graz / Austria

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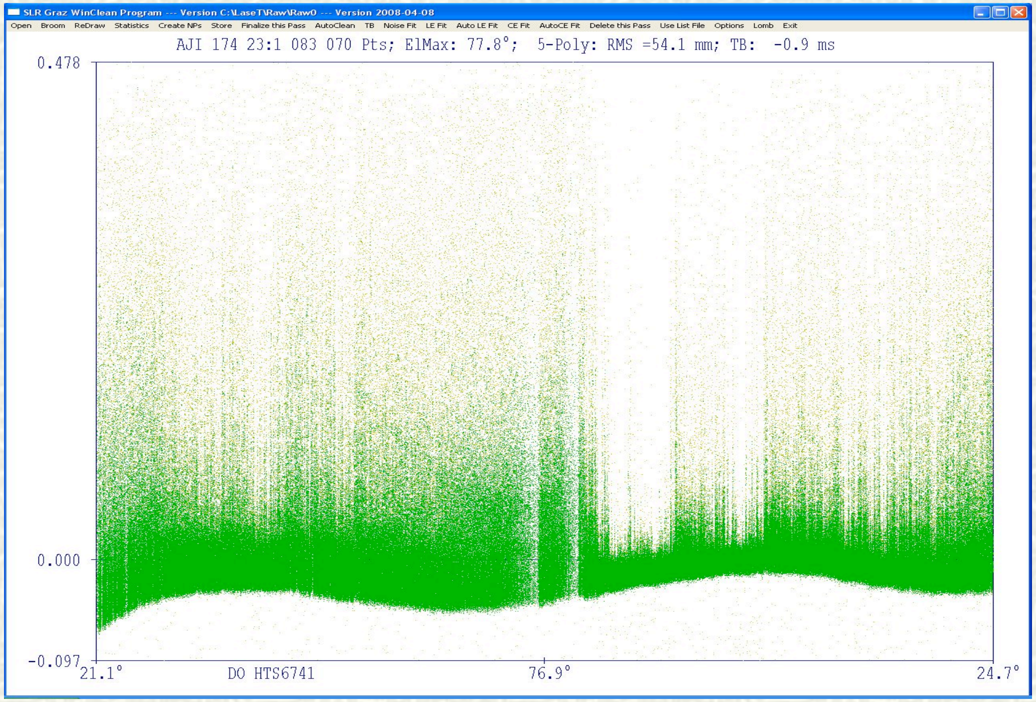
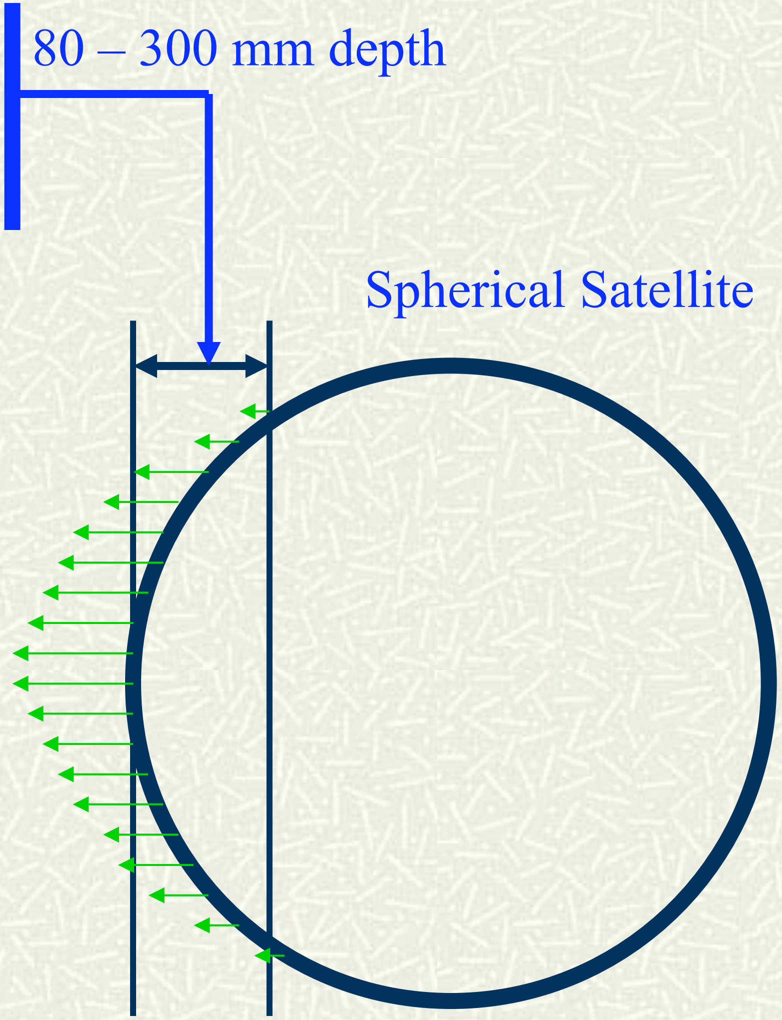
What we **HAVE**: *Centimeter Targets*

- LAGEOS-1, LAGEOS-2, AJISAI, ...
- **Reflective Depth: Satellite Signature**
- **For AJISAI: > 300 mm**
- **For LAGEOS: > 80 mm**
- TRUE „CM“ Targets ☺

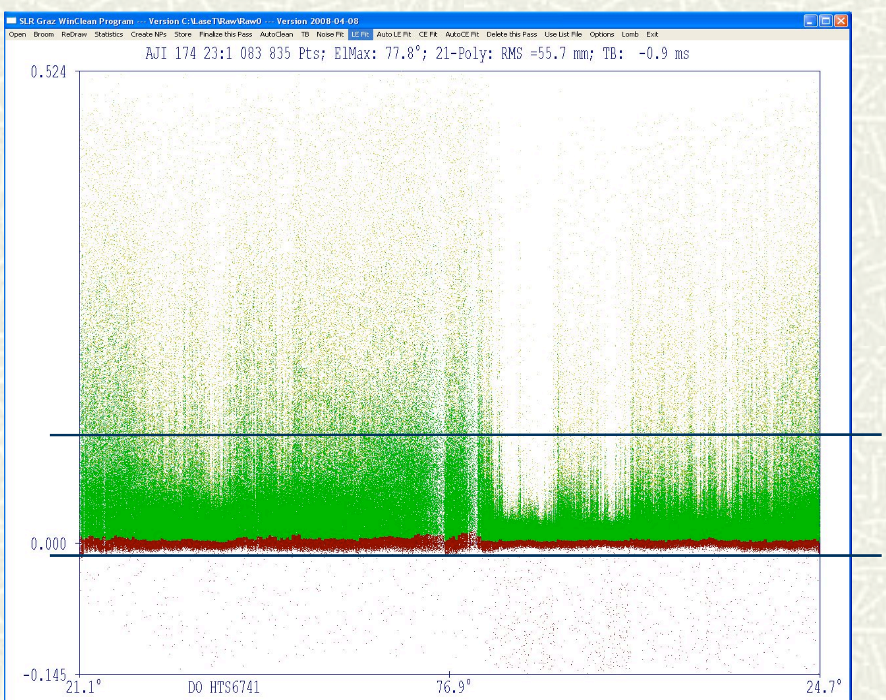




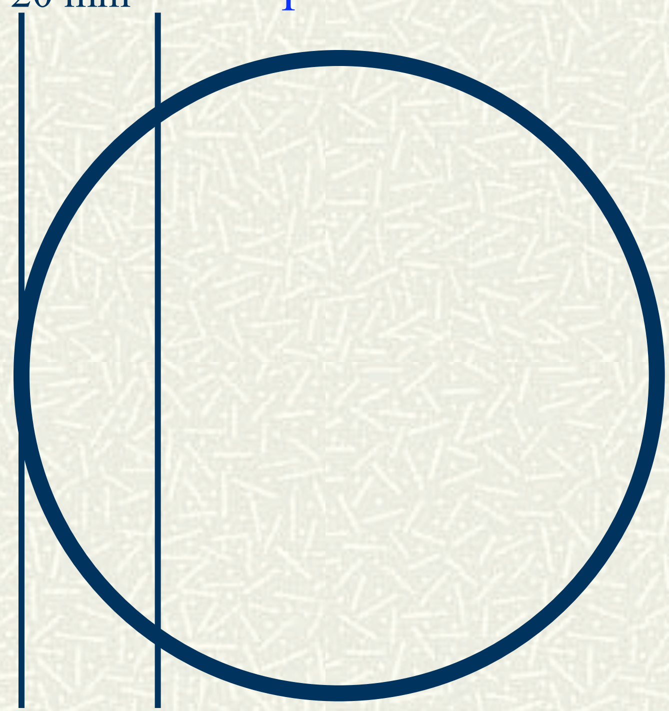
What we **NEED**: Millimeter Results

A possible solution, used in Graz / kHz SLR:

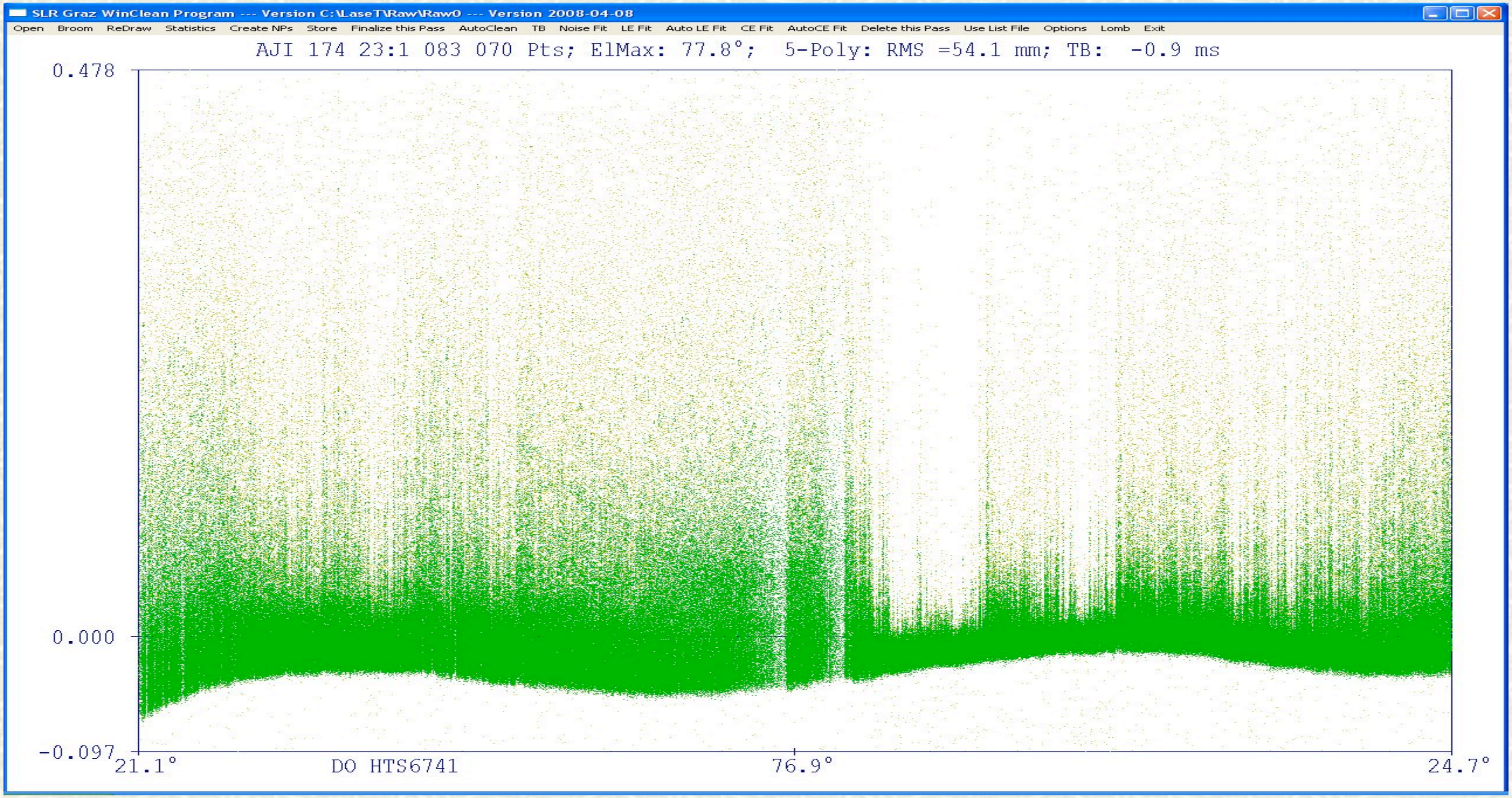
- We accept **ONLY** returns from **NEAREST** Retros
- Reflective Depth is reduced to **20 mm only**
- All returns behind that are rejected (~ 30%)



300 mm
20 mm

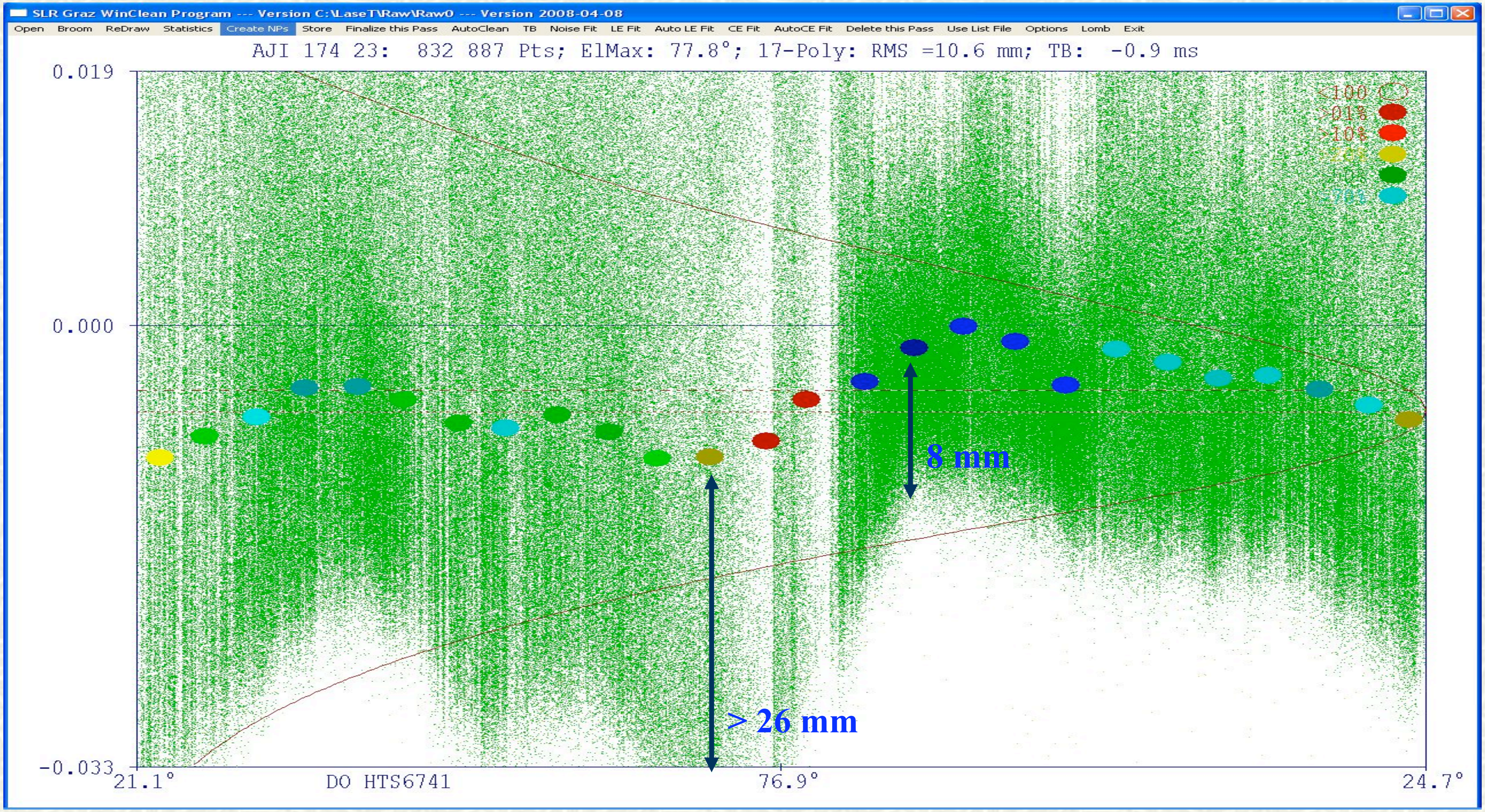


Example: AJISAI



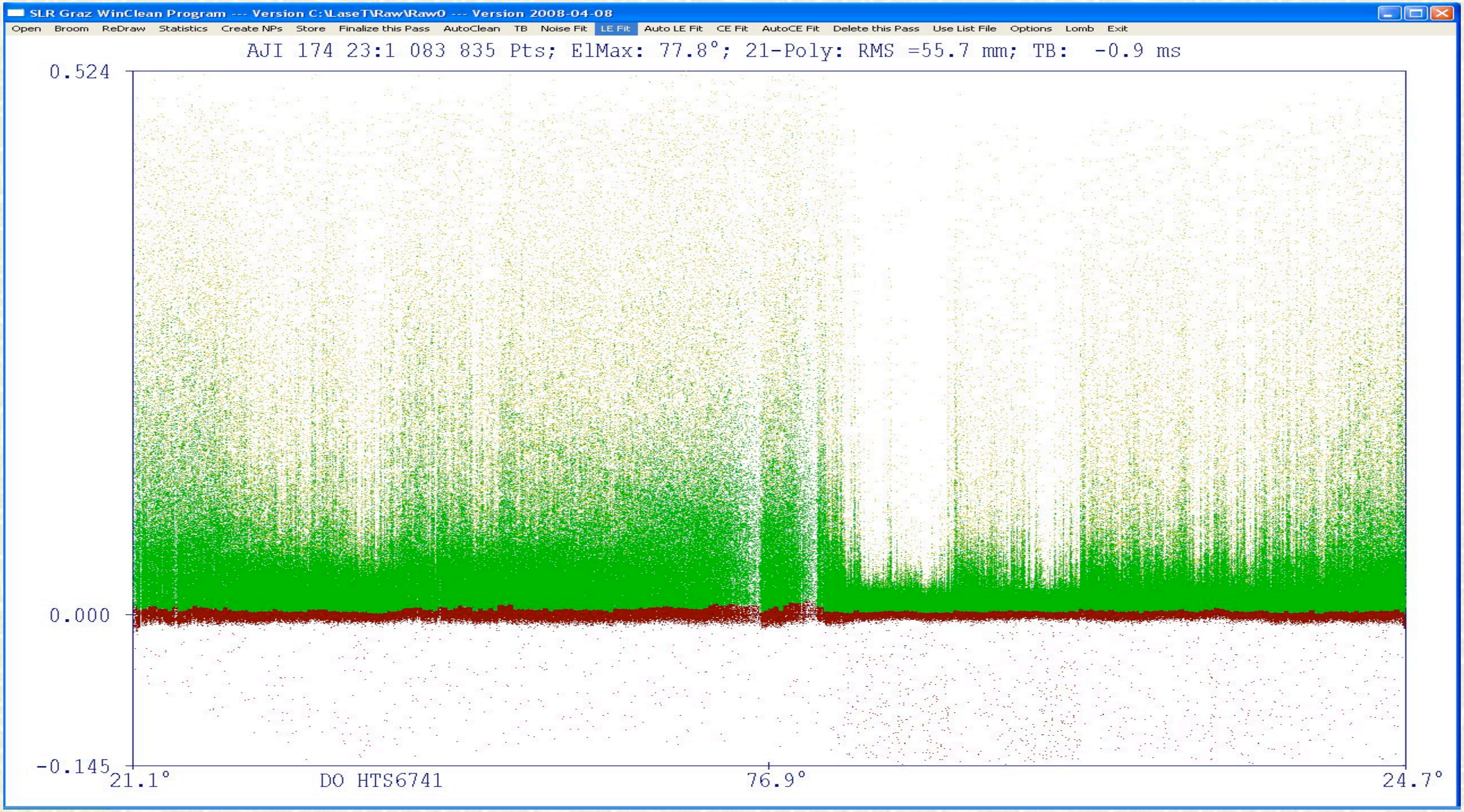
- Raw Data: > 1 Million points, with big variations of return energy;
- Reflection Depth: > 300 mm (Single Photons);
- Strong Returns from Nearest Retros

Not a good post-processing ....



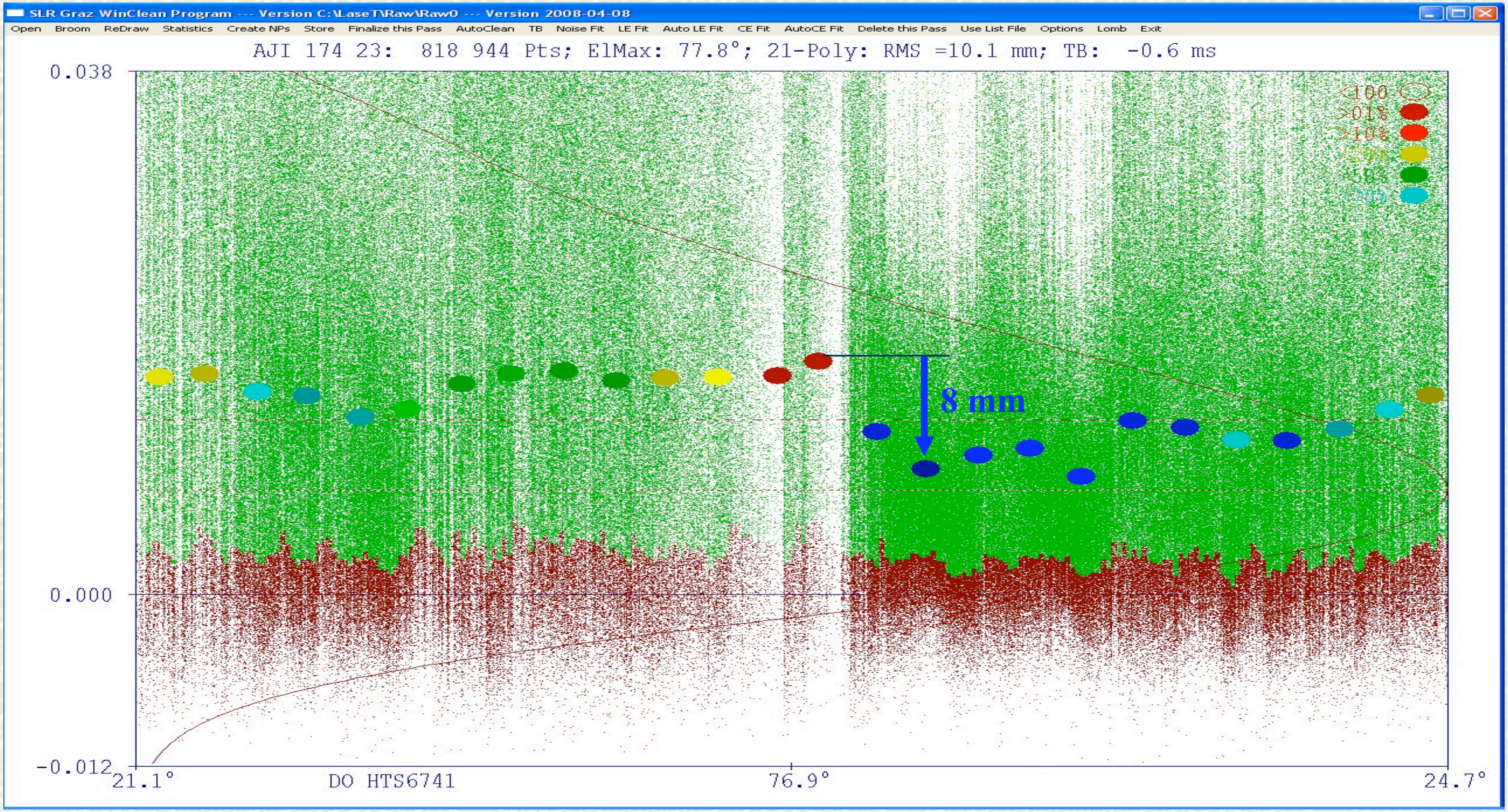
- Big variations of reflection points / NP distances to Leading Edge
- 2.5 Sigma: > 10 mm RMS; 0.282 Skew; NPs: big variations...

Better Post-Processing ....



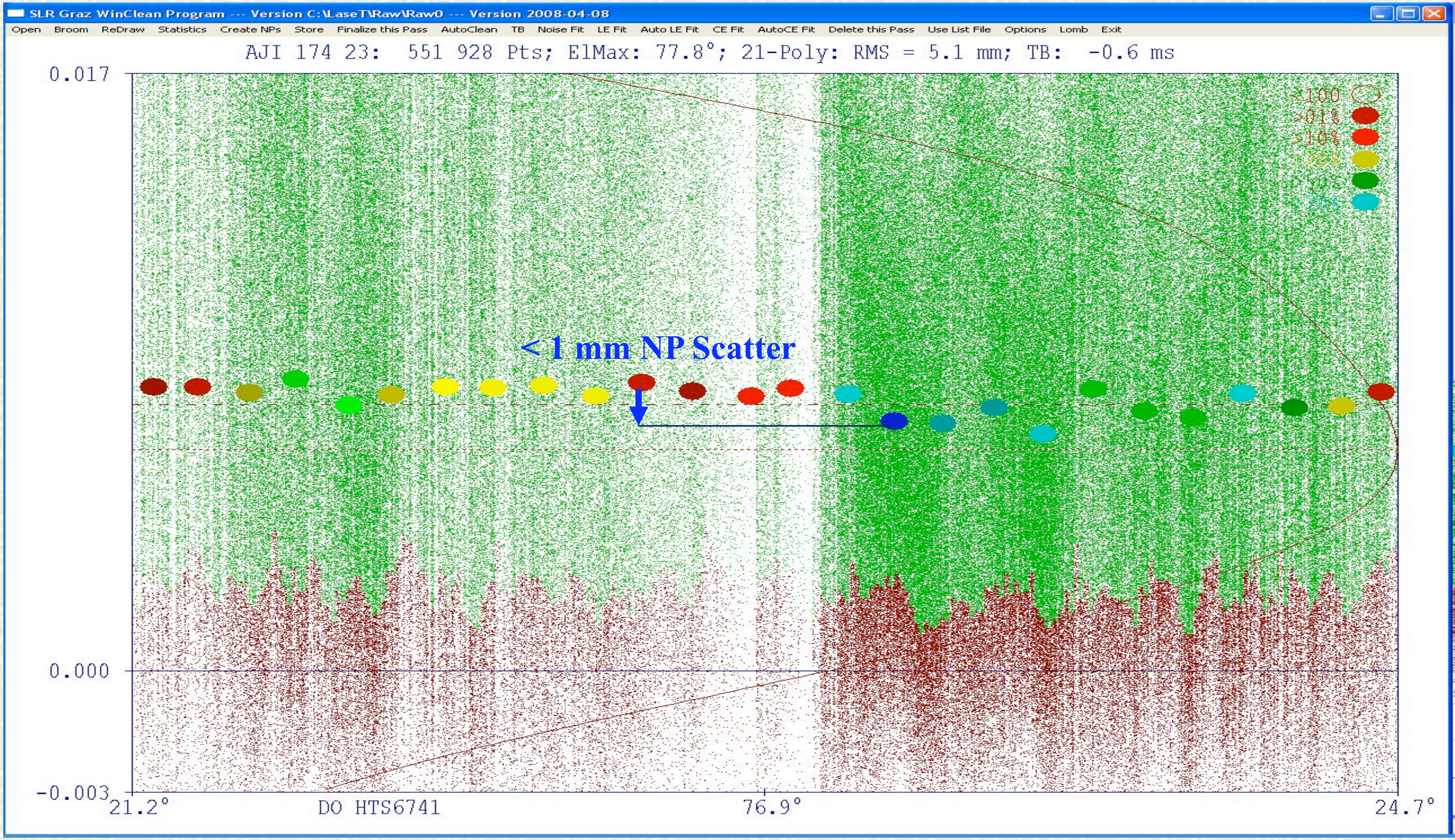
- Poly-Fit to „Leading Edge“ (Returns marked ‘RED‘)

Leading Edge Fit, 2.5σ : Better...



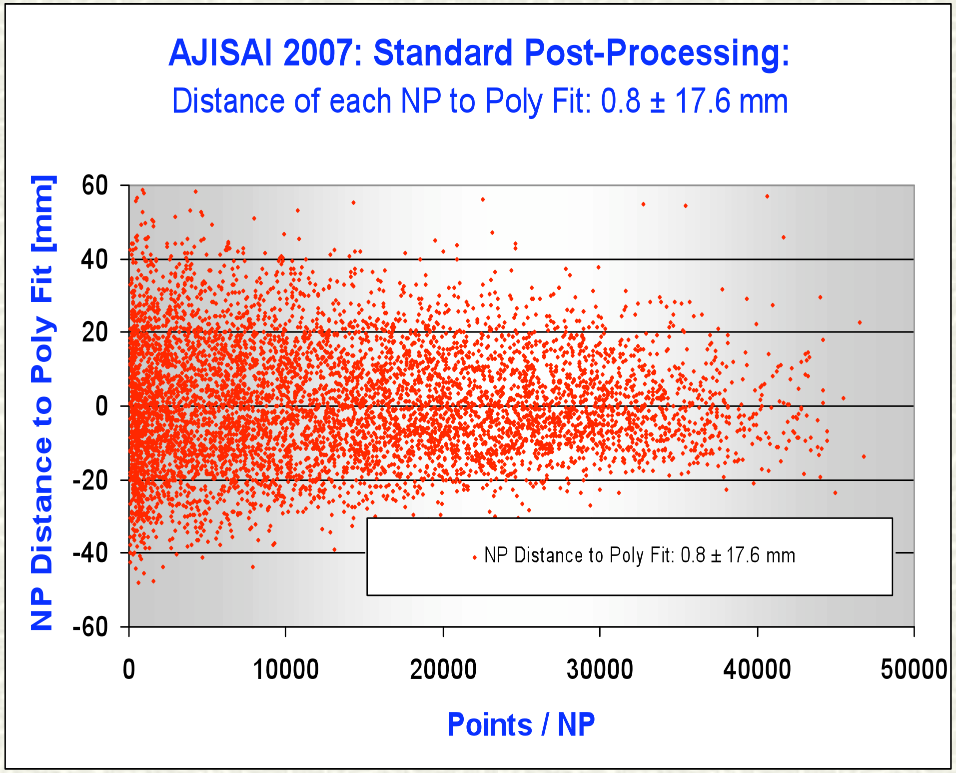
- LE, 2.5 σ, 10 mm RMS, NPs: Still 8 mm diff ...

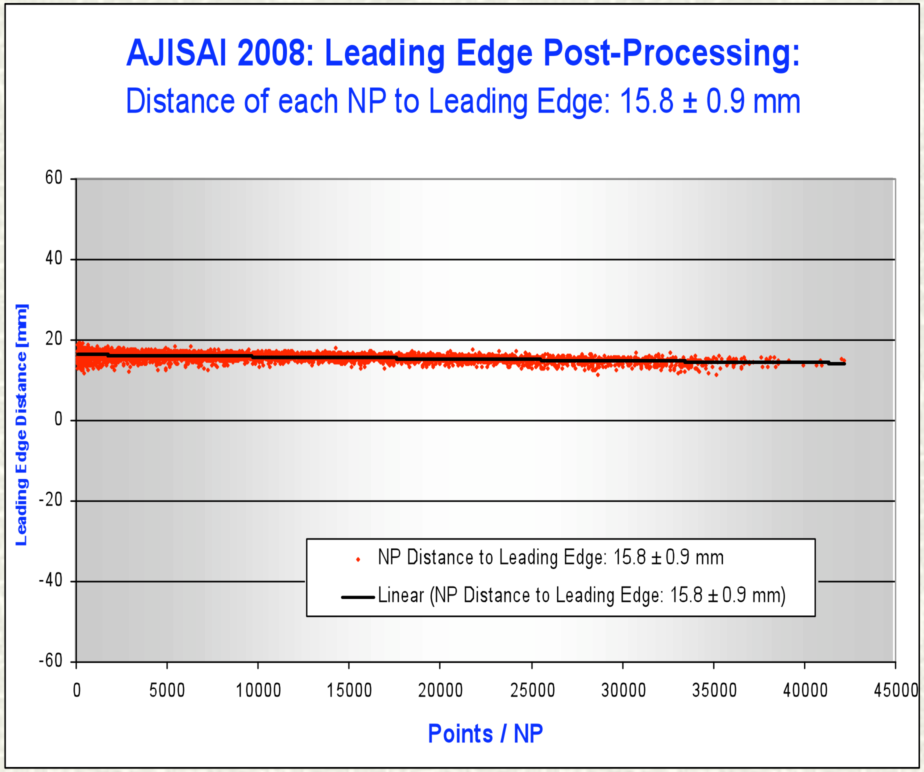
LE Fit, 2.2σ, 20 mm Max Depth …



- Only first 20 mm of Reflective Depth accepted: **NP Scatter: < 1 mm**

AJISAI: Big improvement …

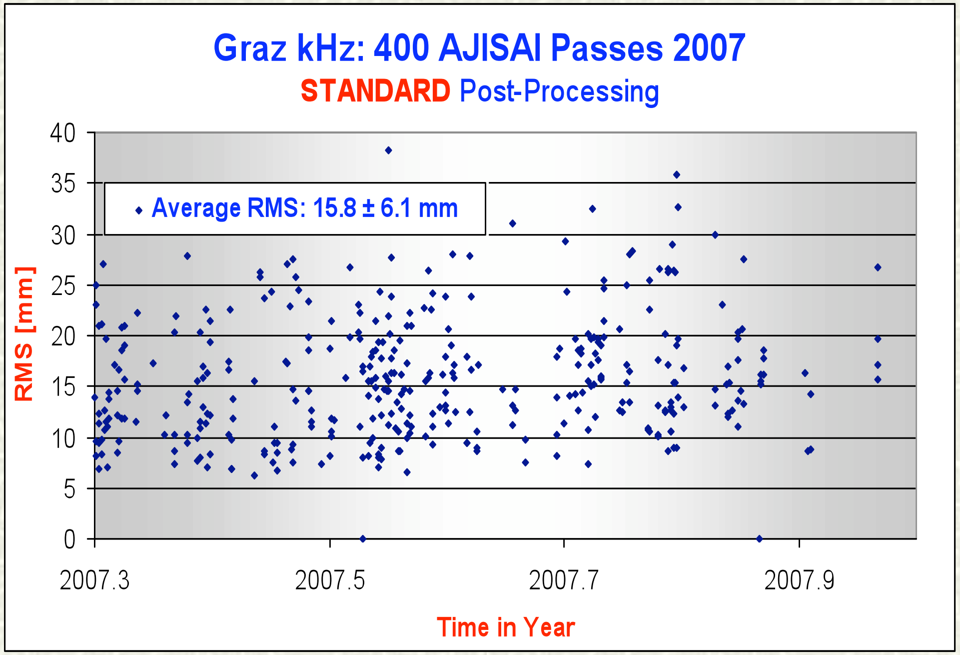


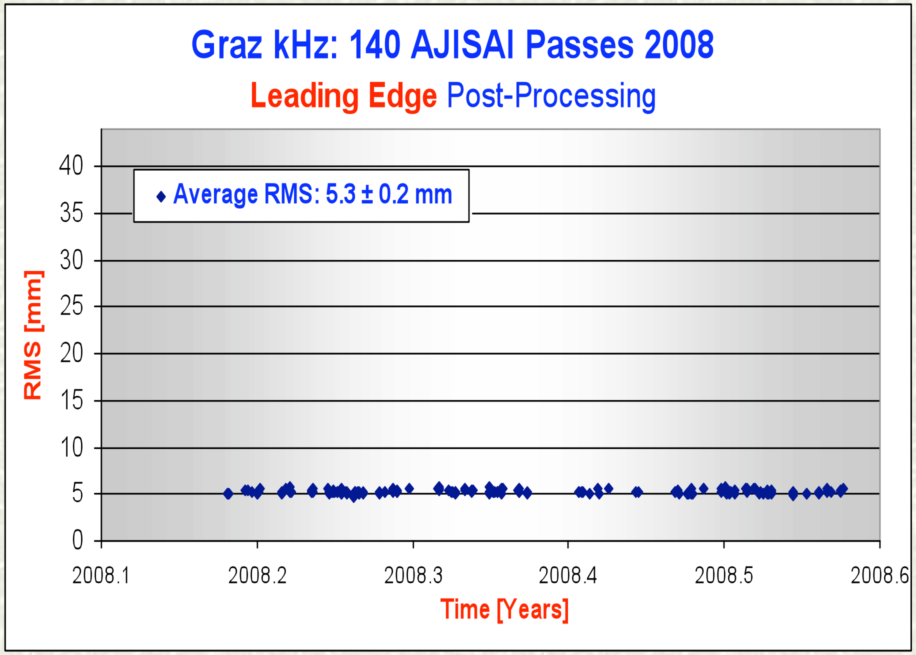


- AJISAI Standard Post-Processing
- NP Distance to Poly Fits: 0.8 ± 17.6 mm
- BIG NP Scattering referred to LE

- AJISAI LE Post-Processing:
- NP Distance to Poly Fits: 15.8 ± 0.9 mm
- STABLE NP Distance to LE

LE Post-Processing: AJISAI passes

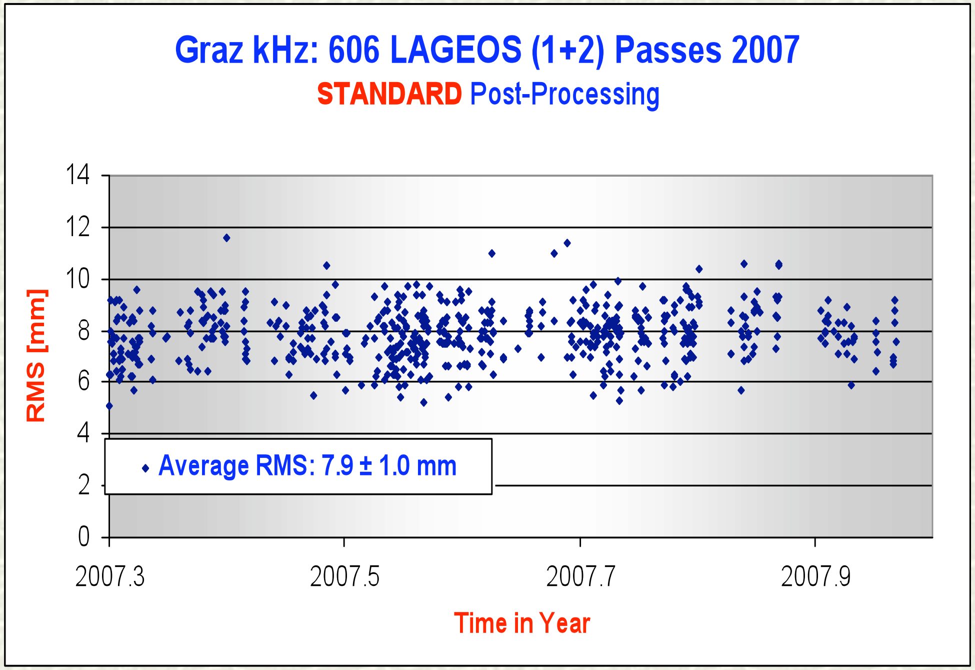


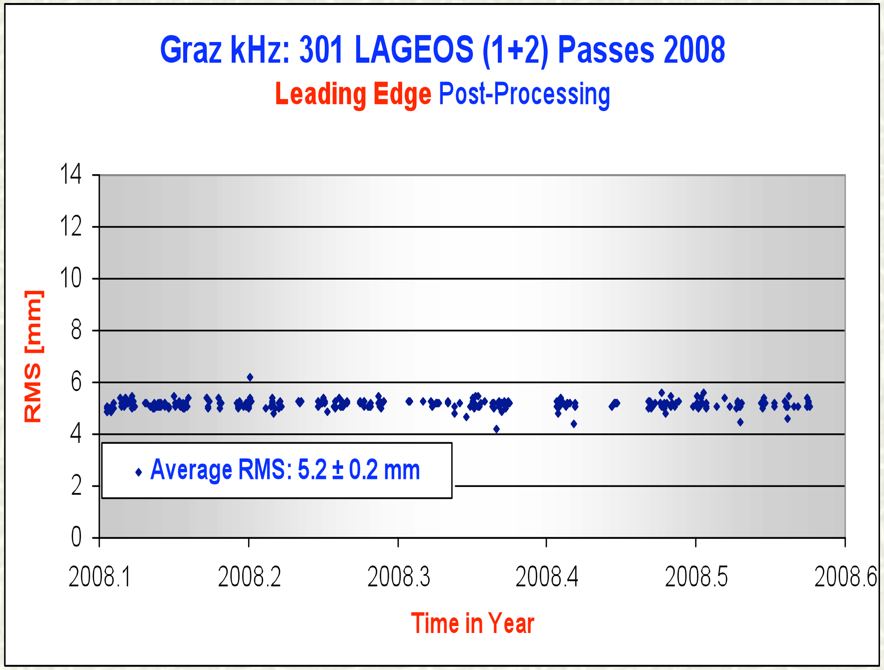


- Standard Post-Processing:
- Until Day 064/2008
- RMS: 15.8 ± 6.1 mm
- NP Scatter: Some CM !!!
- NP: Dist to LE: **cm VARIATIONS**

- Leading Edge Post-Processing:
- Since Day 065/2008
- RMS: 5.3 ± 0.2 mm
- NP Scatter: < 1 mm
- NP Dist to LE: **10.8 ± 0.4 mm**

LE Post-Processing: LAGEOS





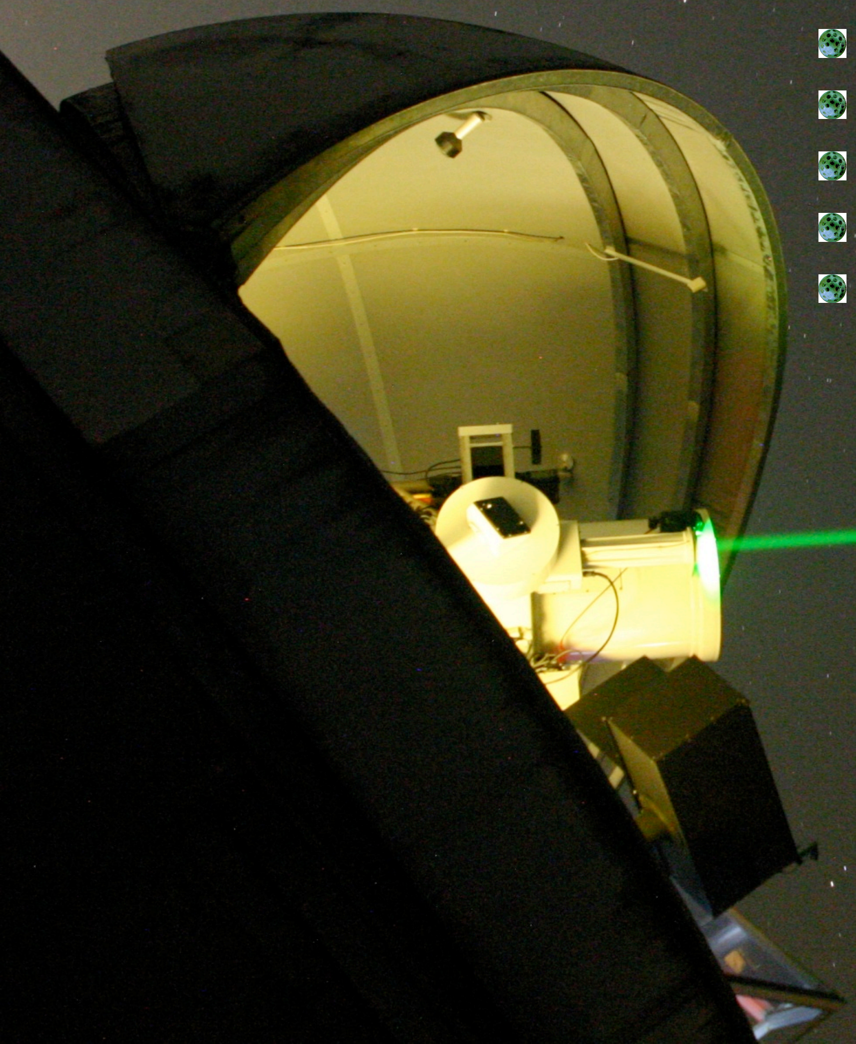
- Standard Post-Processing
- Until Day 037/2008
- RMS: 7.9 ± 1.0 mm
- NP Scatter: > 5 mm
- NP: Dist to LE: > 3 mm **VARIATIONS**

- Leading Edge Post-Processing
- Since Day 037/2008
- RMS: 5.2 ± 0.2 mm
- NP Scatter: < 1 mm
- NP Dist to LE: **10.0 ± 0.8 mm**

LE Post-Processing: Consequences

- About 15% to 50% (average 25%) of returns are rejected;
- Still enough returns remaining (much more than with SPE)
- No Change to Hardware Setup necesary:
  - No Real Time adjustments to keep Return Energy constant;
  - No filter wheels, no offset pointing, no observer training etc.
- ALL NPs now at a constant distance from LE: 10 mm ± <1mm
- CoM Correction: Now constant for EVERY NP !!!
  - Regardless of return energy, Single- or Multi-Photon etc.

Conclusions



- FOR SPHERICAL SATELLITES:

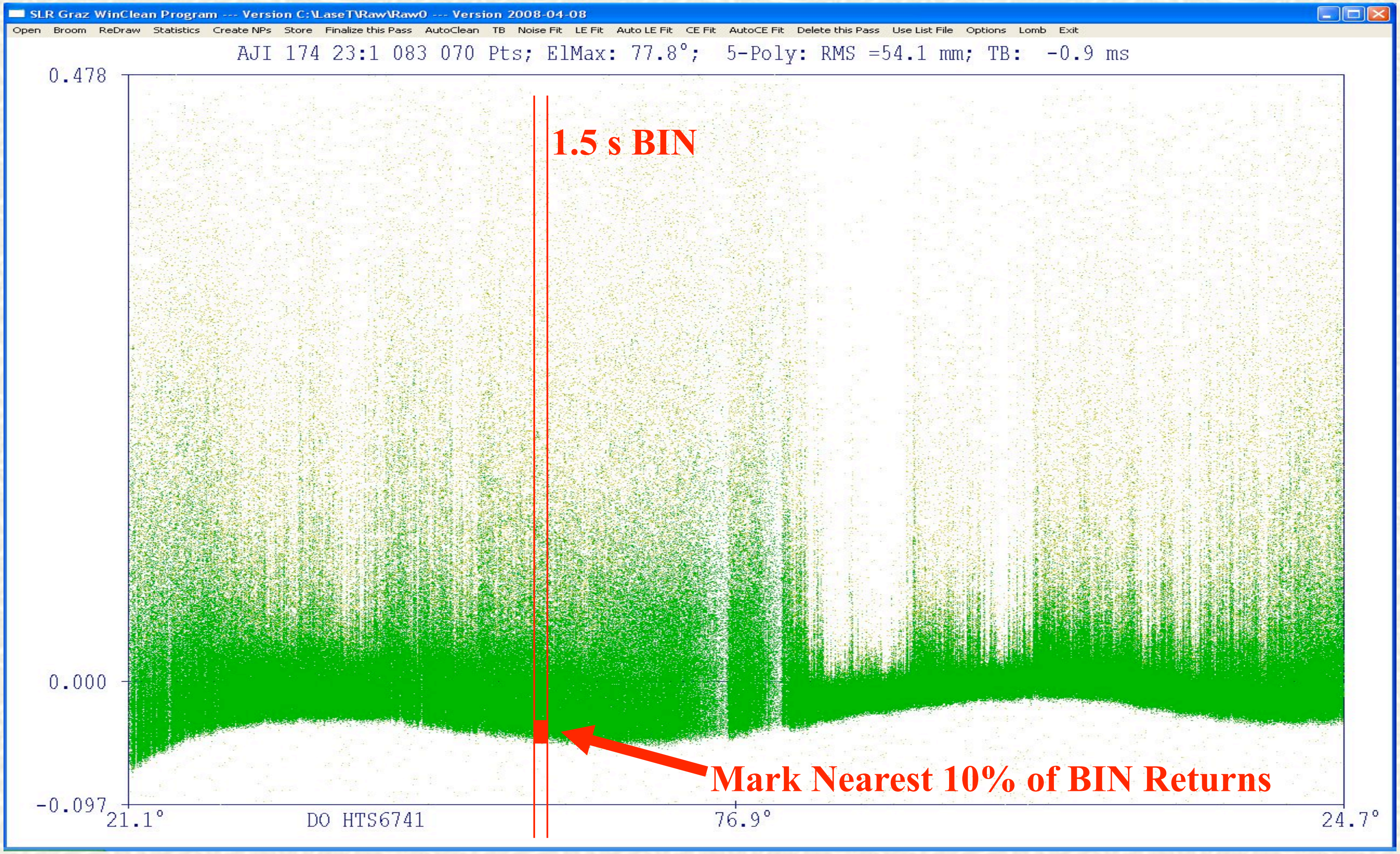
- kHz SLR allows detection of „Leading Edge“ of Returns
- We use this „LE“ as a reference line
- We accept only returns from LE line to 20 mm depth
- This improves NP scatter from CMs to < 1 mm
- Done at the moment for LAGEOS and AJISAI

"Do not look into the laser beam with your remaining eye !"

Thank you ☺

Centimeter Targets: How to do it ...

How to fit to „Leading Edge“



- Divide the pass into BINs; Bin Width eg. 10% of NPW: ie 1.5 s for AJI, 12 s for LAGEOS
- Mark nearest 10% of points in each BIN; fit poly to these marked points ....
- Use these poly coefficients for all points; 2.5/2.2 sigma iteration; apply final limits ...

Analysis of 2022 ILRS Calibration and LAGEOS Moments

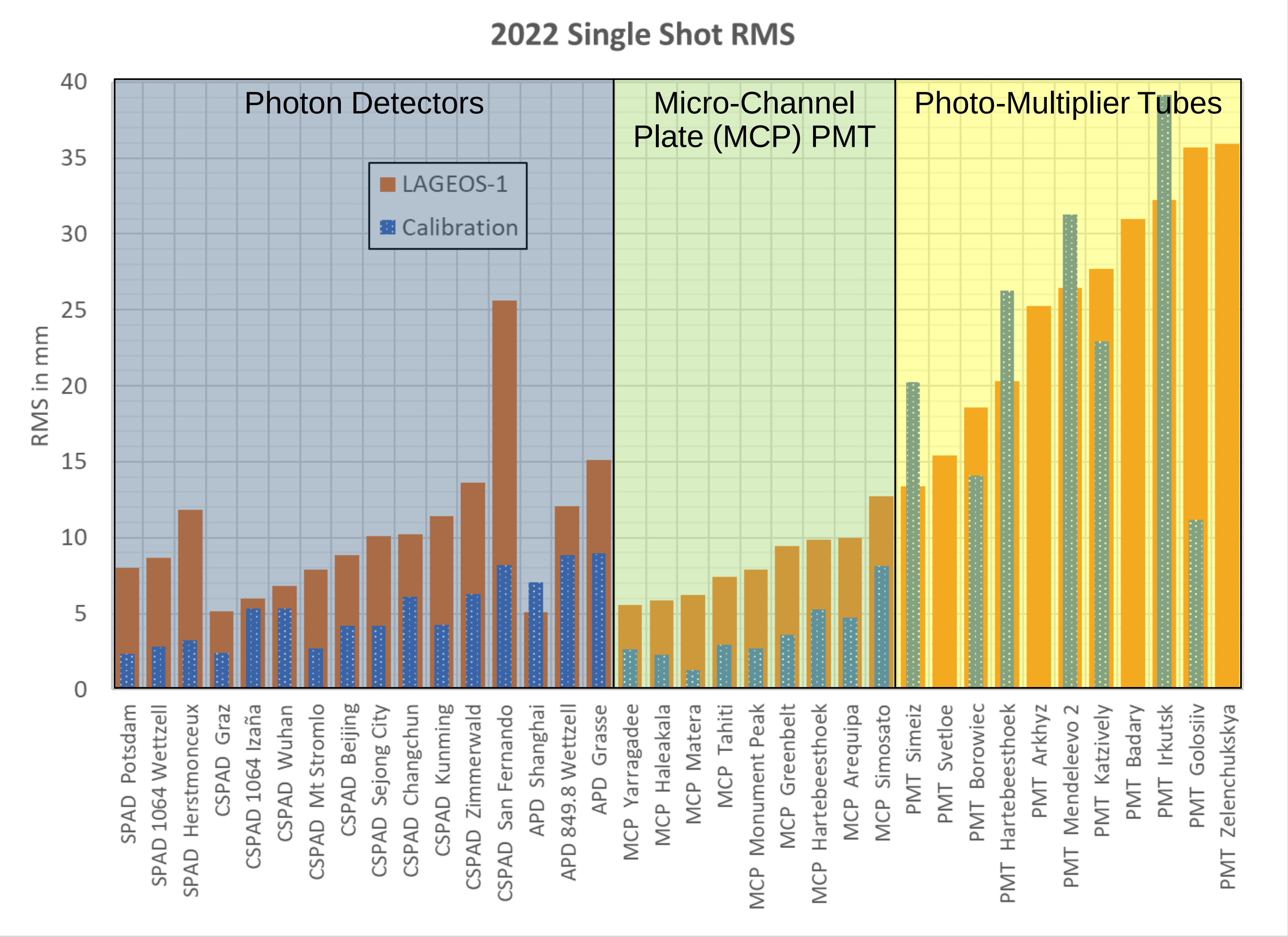
Van Husson

ILRS QCB

March 2023

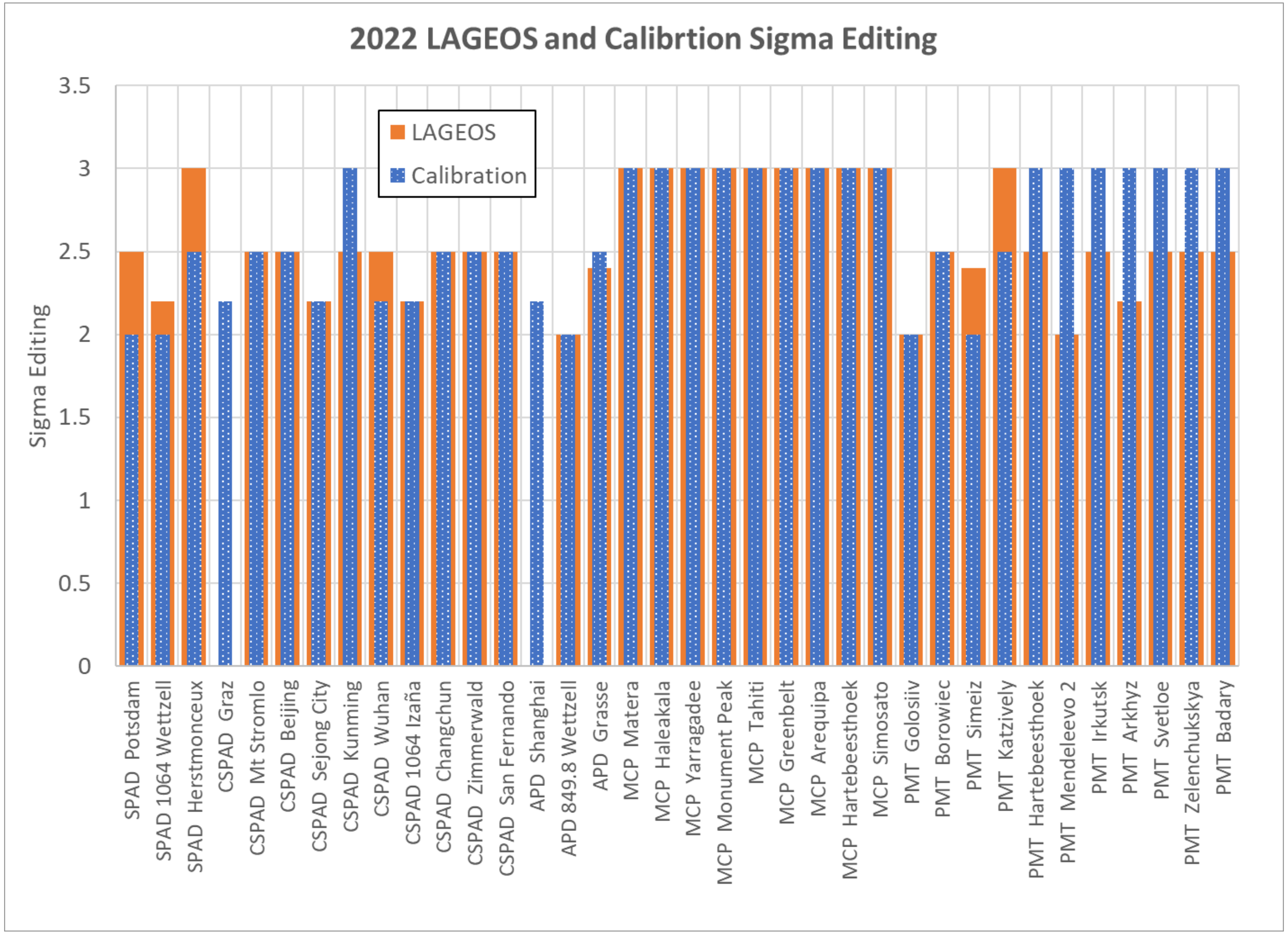
Peraton

2022 Single Shot RMSs



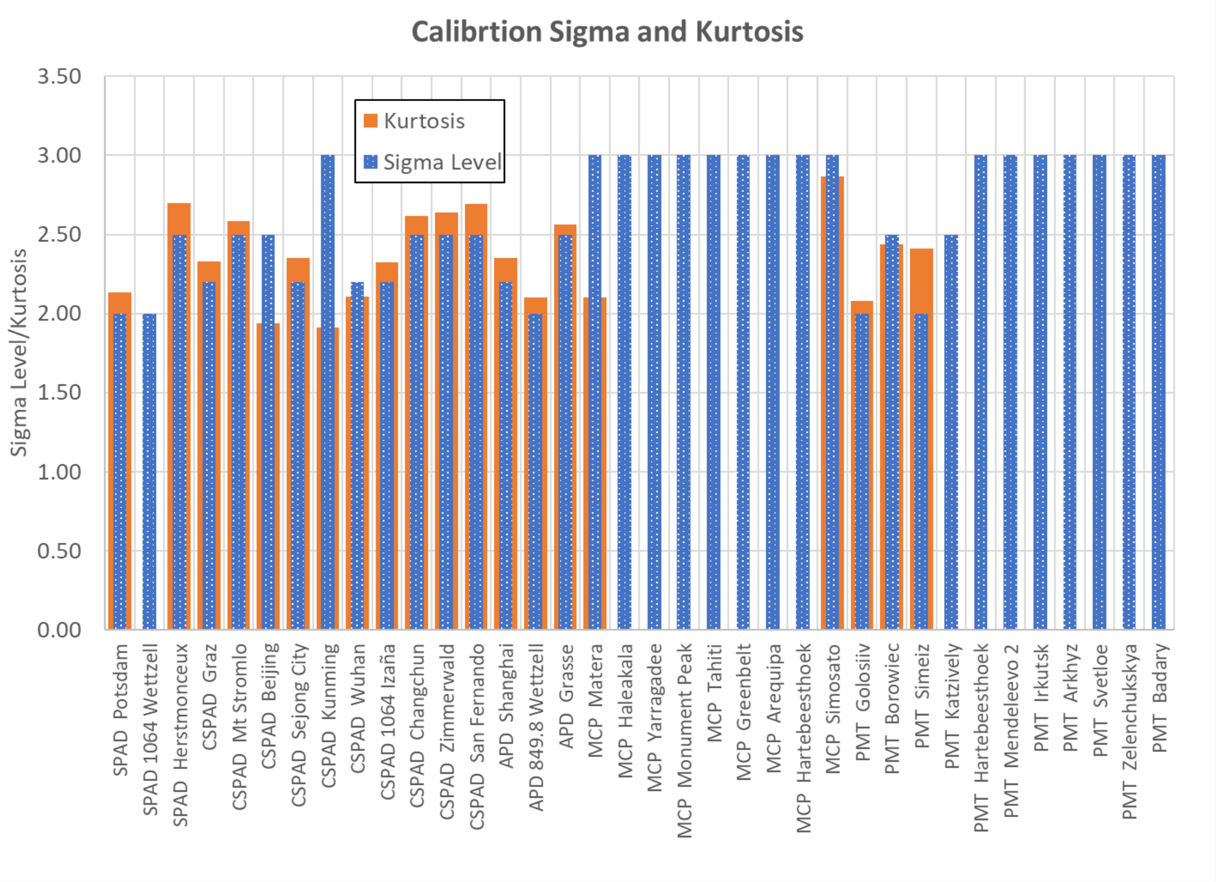
- **LAGEOS and Calibration RMSs are based on CRD 50 and 40 records; respectively**
- **Data is sorted by Detector Type and LAGEOS RMS**
- **All operational stations in 2022 have green lasers except for 7827 Wettzell, 7701 Izana, & 8834 Wettzell which have infra-red lasers**
- **Stations with PMTs have the largest single shot RMSs**
- **Calibration RMS should be less than LAGEOS RMS**
  - Some Russian stations do not provide calibration RMS in their CRD 40 records
  - Some Russian stations and Shanghai have higher calibration RMSs than LAGEOS
  - 7701 Izana and 7396 Wuhan calibration RMSs are less than but close to their LAGEOS RMSs

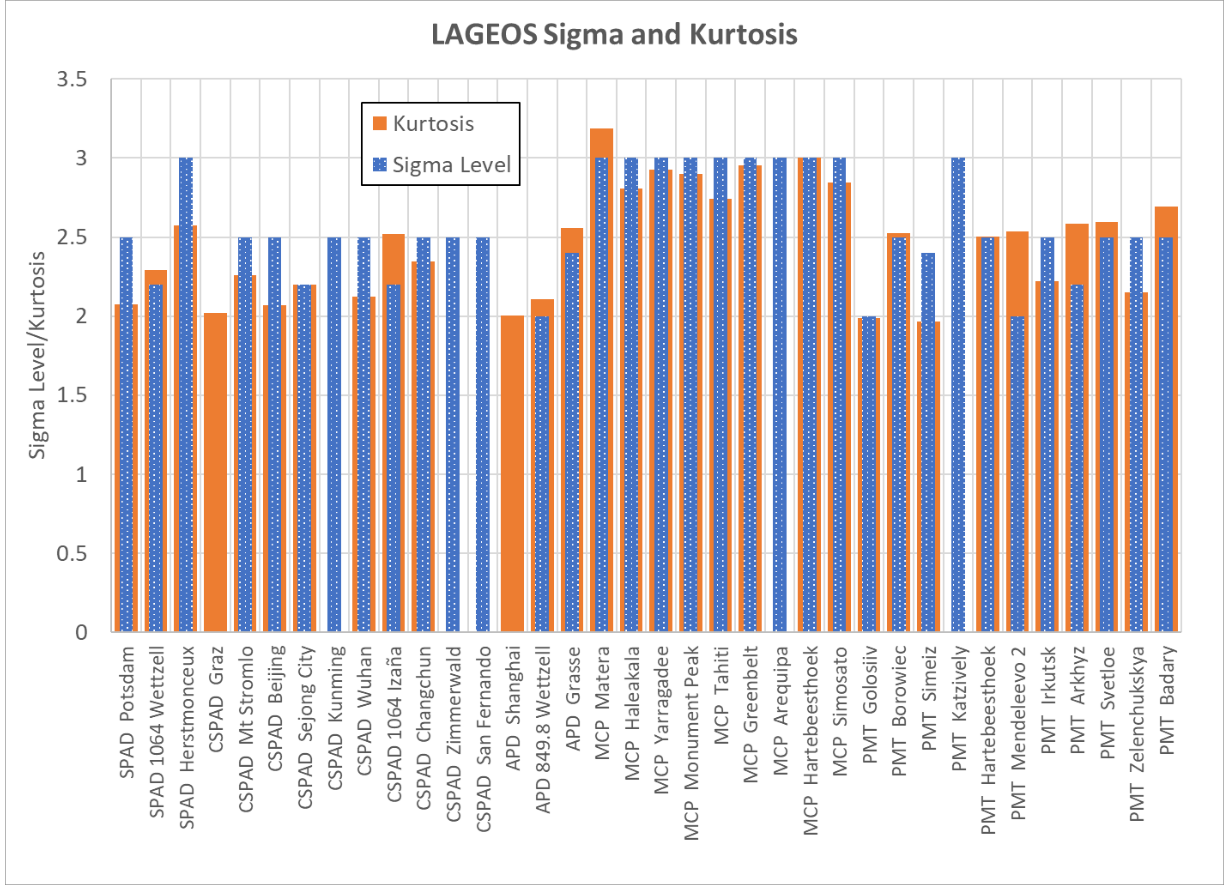
LAGEOS and Calibration Sigma Edit Levels



- Sigma Editing Levels are based on the Site Logs
- Some stations have different editing levels between LAGEOS and calibration
- Two systems, Graz and Shanghai eliminate LAGEOS returns greater than 2cm from the Leading Edge (LE)
- Can calibration and LAGEOS kurtosis be used to verify sigma editing levels?

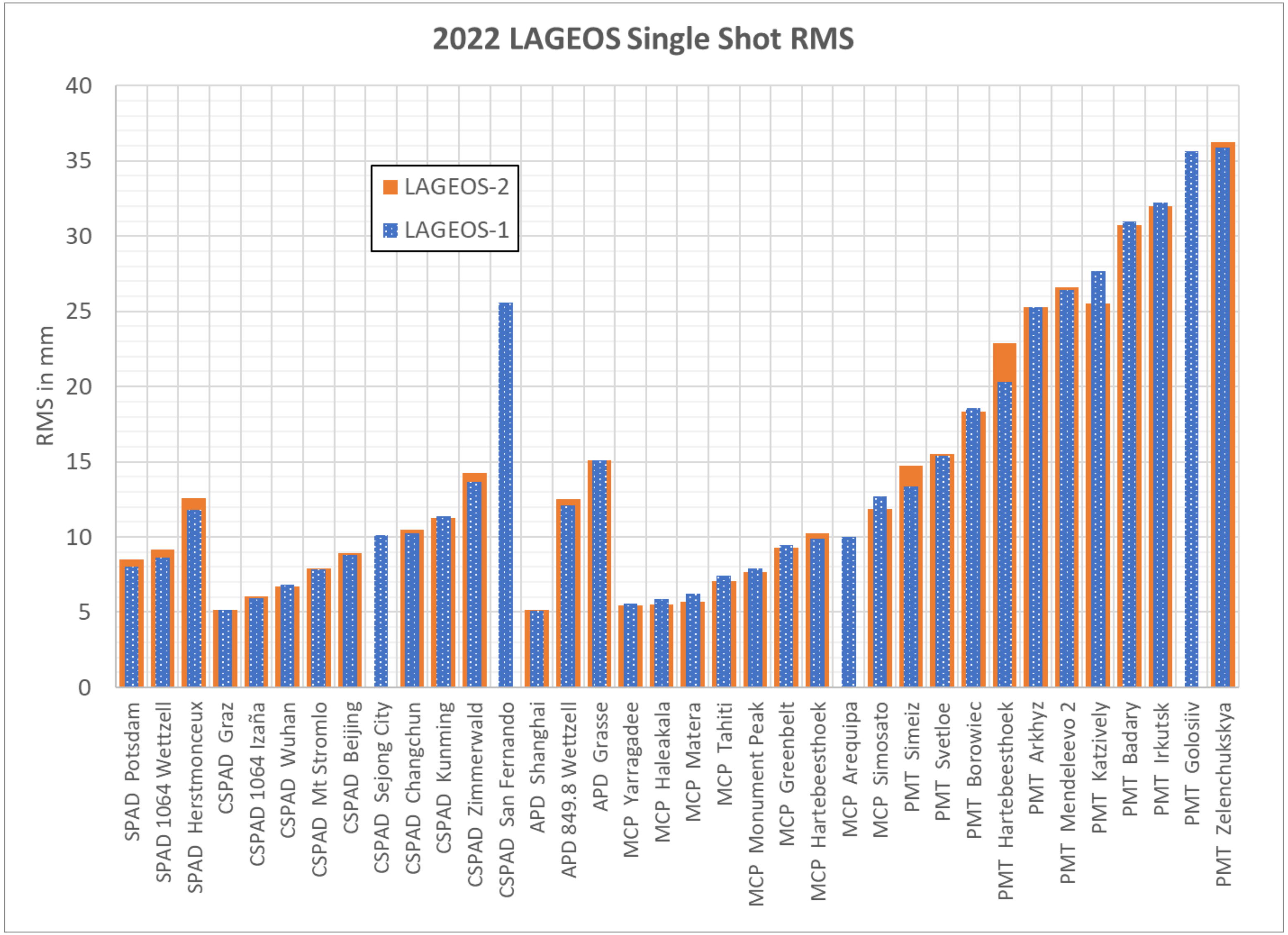
Sigma Level vs Kurtosis





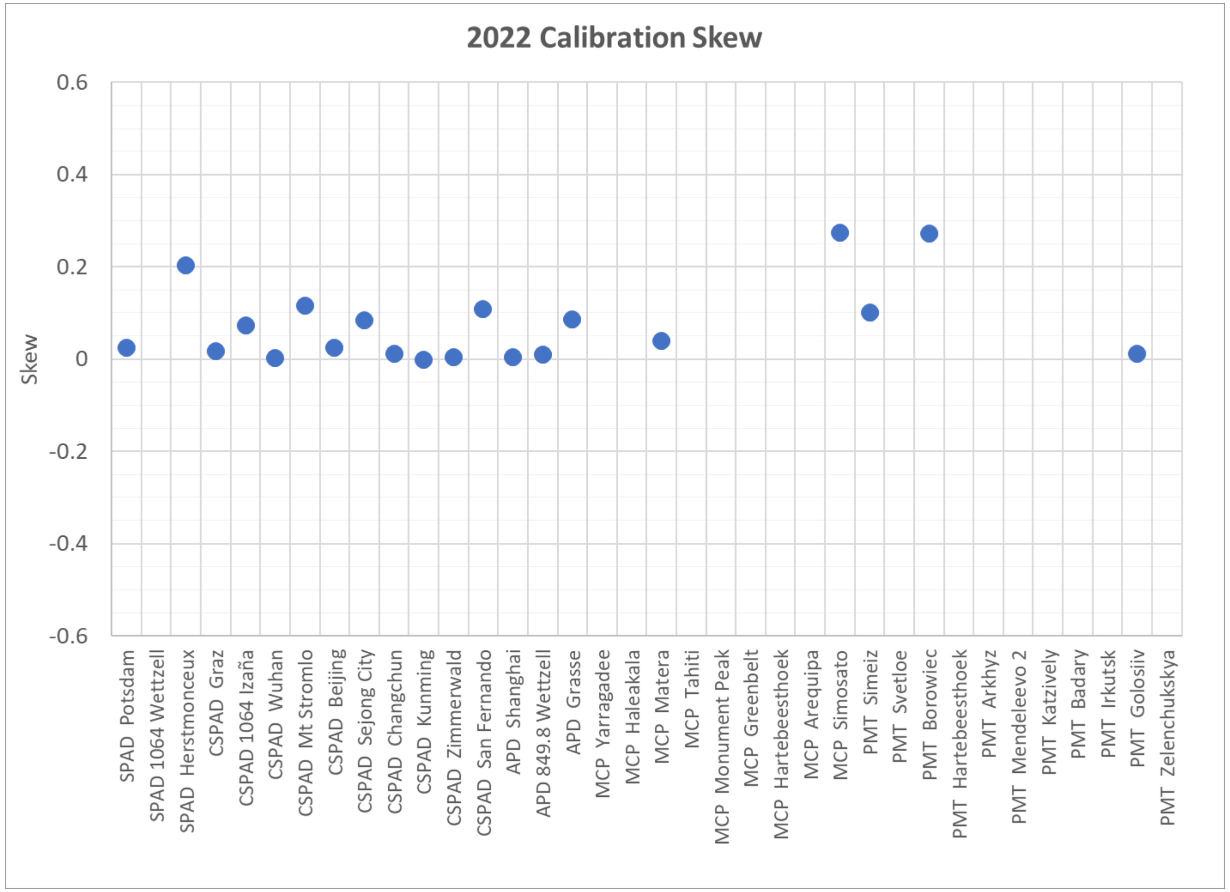
- ❑ **Calibration sigma levels and kurtosis on the left chart. Some stations don't provide calibration kurtosis in their CRD 40 calibration records**
- ❑ **Satellite sigma levels and kurtosis on the right chart. For a few stations, there are significant differences between kurtosis and the sigma levels in their site logs. Graz and Shanghai eliminate LAGEOS returns greater than 2 cm from the Leading Edge (LE)**

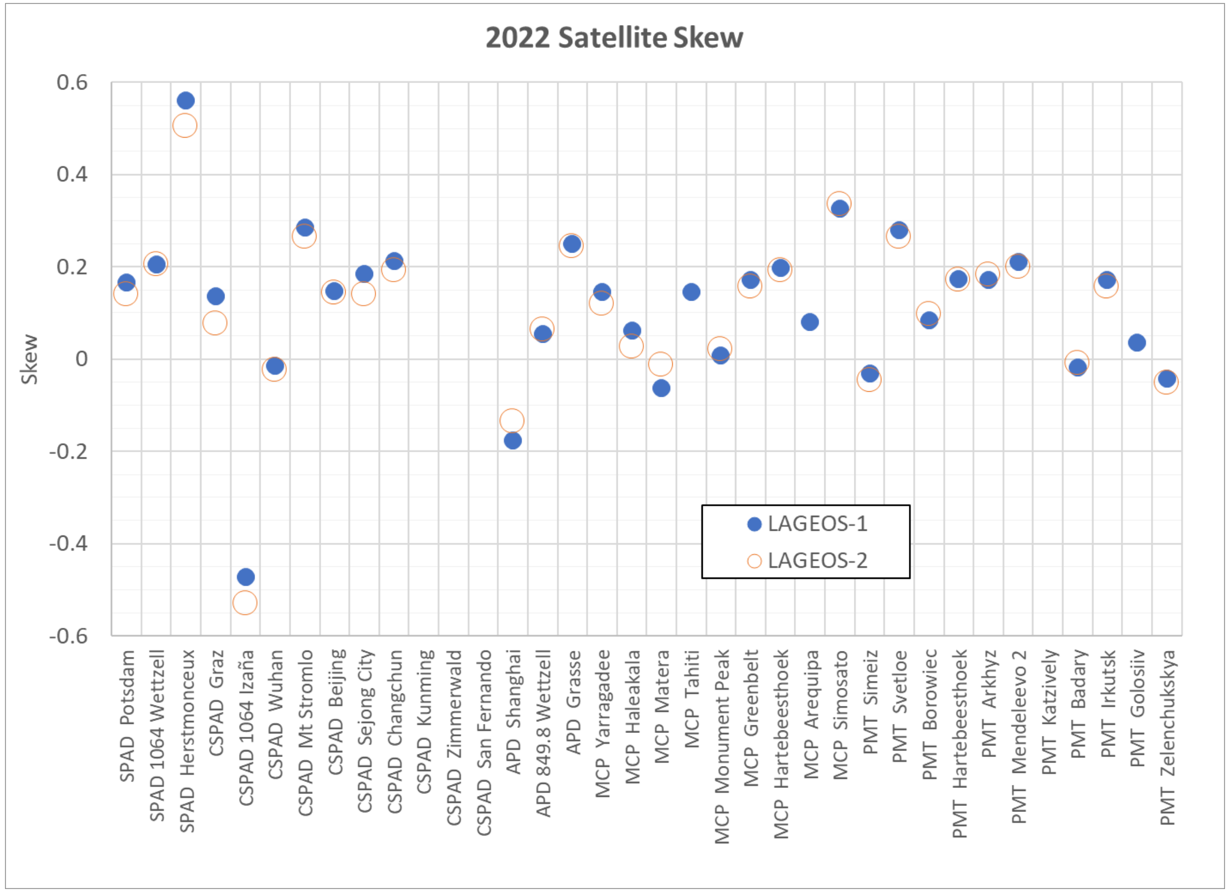
2022 LAGEOS-1 and -2 Single Shot RMSs



- Four stations (Sejong, San Fernando, Arequipa and Golosiiv) have a relatively small LAGEOS-1 and -2 sample size in 2022 for a comparison
- SPAD stations and some PMT stations have higher RMSs on LAGEOS-2

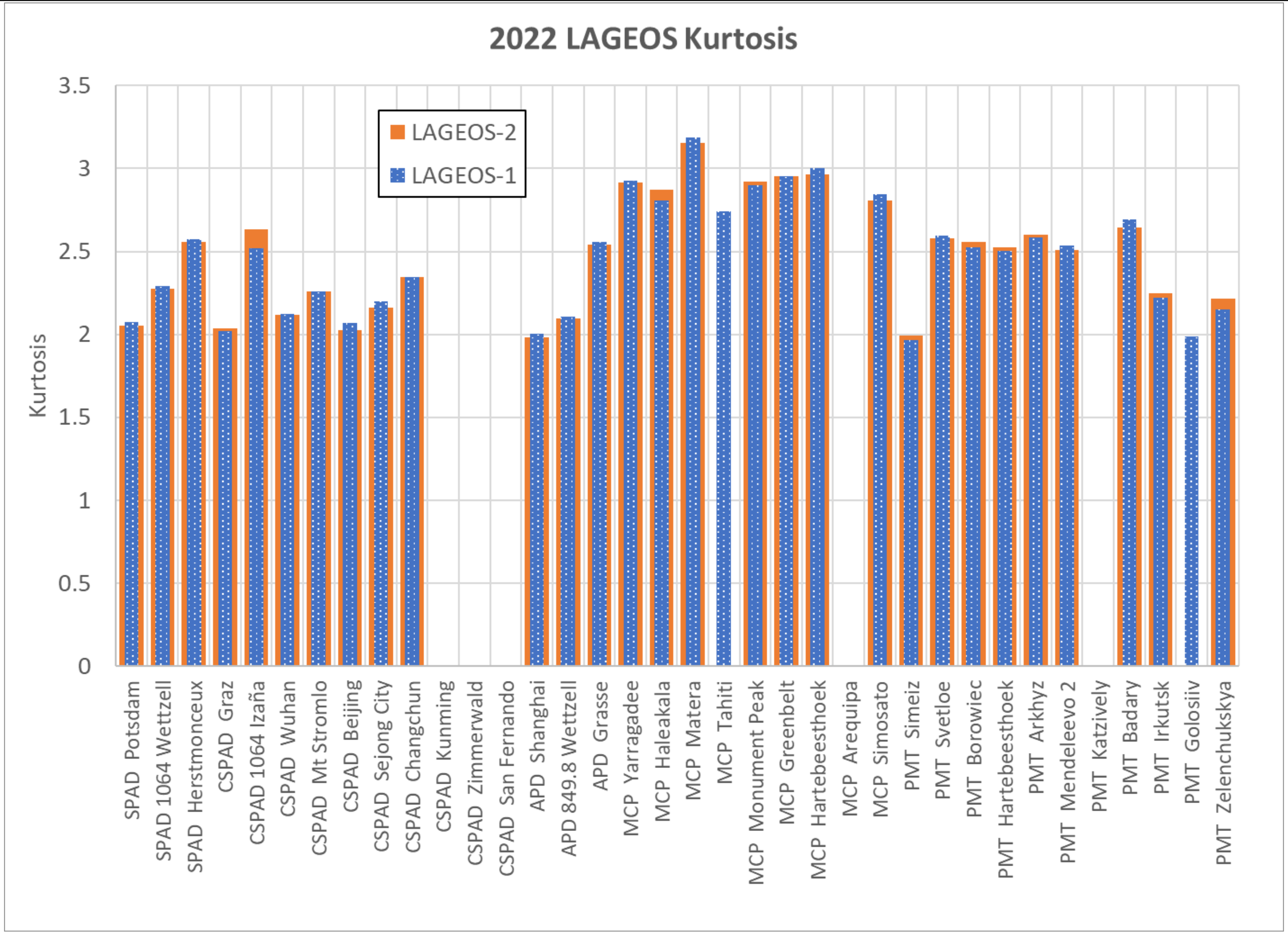
2022 Calibration and LAGEOS Skew





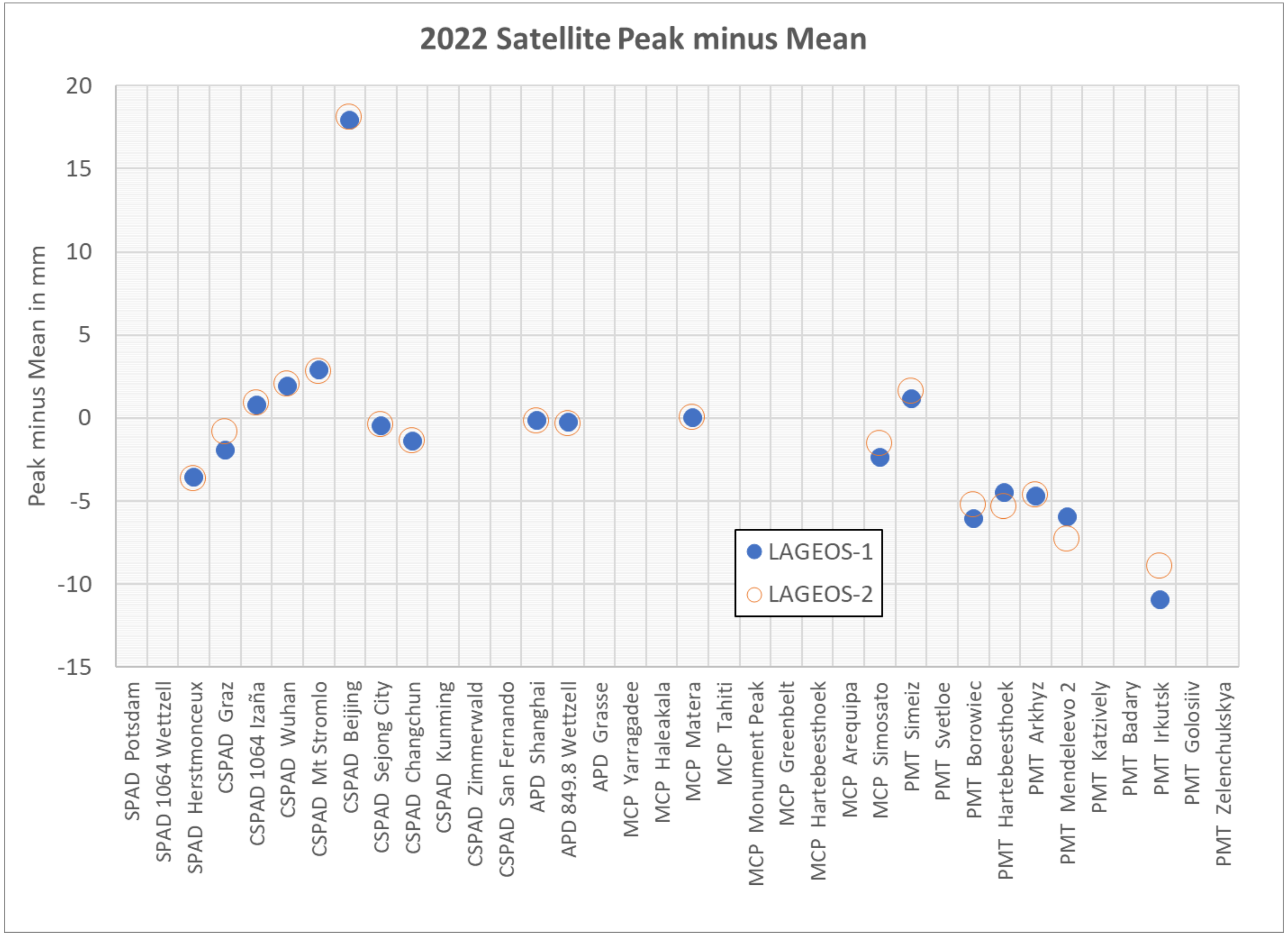
- **Calibration and LAGEOS skew on the left and right charts; respectively. Some stations do not provide calibration or satellite skew in their CRD 40 and 50 records; respectively**
- **LAGEOS-1 and -2 skews are similar. Both calibration and LAGEOS data tend be skewed positive**
- **Why are Izana and Shanghai LAGEOS data skewed negative? Also, the new station in Japan, 7306, also has similar negative skew on LAGEOS but slightly positive calibration skew, very similar to the Izana skew results.**

2022 LAGEOS Kurtosis



- Kurtosis values between LAGEOS-1 and -2 are generally similar

2022 LAGEOS Peak minus Mean



- Some stations do not provide peak minus mean values in their CRD 50 records
- LAGEOS-1 and -2 peak minus mean values are similar. Graz there is an ~1 mm difference between LAGEOS-1 and -2
- Beijing's peak minus mean is twice their LAGEOS single shot RMS. Is Beijing computing peak minus mean properly?
- Izana has a large negative skew (~-0.5) but has a peak minus mean less than 1mm. Does that make sense?

7701 Izana and 7306 Tsukuba NP Analysis

7701 IZ1L Galileo (20-Feb-2023 at 12:19) Normal Point (NP) Comparisons

Source	Seconds of Day	Range in seconds	Obs in Bin	Bin RMS (ps)	Skew	Kurtosis	Peak - mean (ps)	Return Rate (%)	Range Difference (Station - OrbitNP) in mm
OrbitNP	76414.695411605700	0.172950707663	677	106.5	0.14	-0.813	-22.4	0.7	
Station	76414.695411605700	0.172950707662	677	106.5	0.139	-0.813	0.117	0.7	(0.1)
OrbitNP	76666.277911533100	0.172510833877	2462	103.9	0.092	-0.762	-9.4	2.1	
Station	76666.277911533100	0.172510833877	2462	103.9	0.093	-0.761	-0.308	2.1	0.0
OrbitNP	76825.797911519400	0.172245423062	391	106.2	0.04	-0.935	-24.9	1.8	
Station	76825.797911519400	0.172245423062	391	106.1	0.04	-0.936	0.555	1.8	0.0

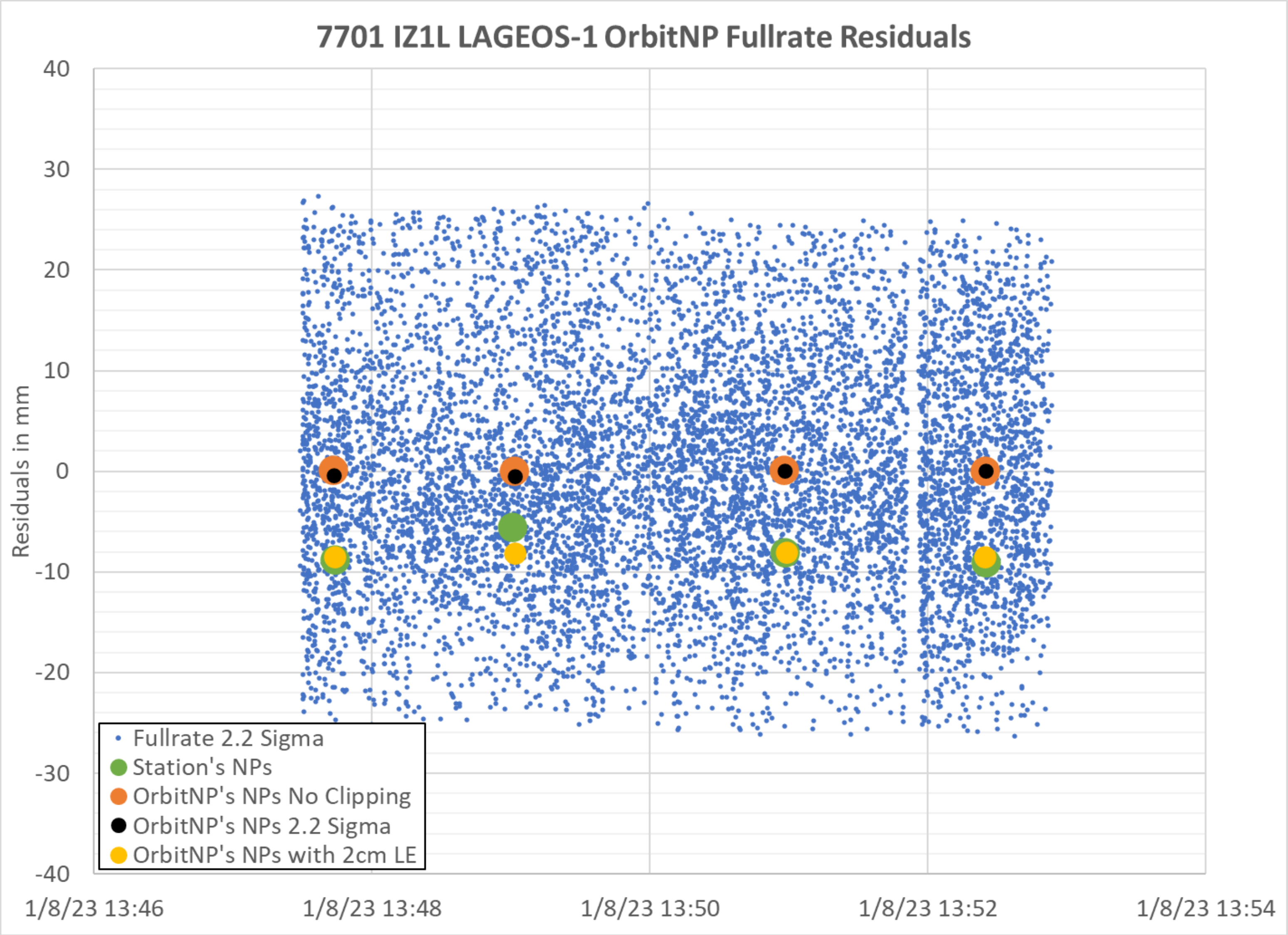
- **Excellent agreement between the station’s and OrbitNP’s generated 7701 Galileo NPs (epochs, Time-of-Flights [ToF], obs), moments (RMS, skew, kurtosis) and return rate. The peak minus mean values differ by 19 ps/2.9mm on average.**

7701 IZ1L LAGEOS-1 (8-Jan-2023 at 13:47) NP Comparisons

Source	Seconds of Day	Range in seconds	Obs in Bin	Bin RMS (ps)	Skew	Kurtosis	Peak - mean (ps)	Return Rate (%)
OrbitNP	49663.520411522700	0.056626979491	926	79.5	0.266	-0.596	-15.8	7.5
OrbitNP	49741.698016614700	0.055106421324	2962	77.5	0.265	-0.542	-19.6	6.2
OrbitNP	49858.288061567300	0.052898849868	3279	74.4	0.072	-0.594	-9.1	6.8
OrbitNP	49944.785411640200	0.051316672625	1604	76.4	0.061	-0.766	-21.8	7.5
OrbitNP 2.2	49663.490411476200	0.056627568422	912	77.2	0.238	-0.605	-11.3	7.4
OrbitNP 2.2	49741.740561586000	0.055105601959	2909	74.7	0.22	-0.558	-16.9	6.1
OrbitNP 2.2	49858.288061567300	0.052898849868	3252	73.1	0.097	-0.635	-10.5	6.8
OrbitNP 2.2	49944.822911561100	0.051315998268	1591	75.2	0.086	-0.808	-22.6	7.4
OrbitNP 2cm LE	49663.827911486300	0.056620943174	529	43	-0.506	-0.651	24.3	4.3
OrbitNP 2cm LE	49741.565561457800	0.055108972279	1730	42.3	-0.626	-0.435	23.2	3.6
OrbitNP 2cm LE	49858.835561540500	0.052888675556	1842	43.2	-0.667	-0.308	22.9	3.8
OrbitNP 2cm LE	49944.372911547100	0.051324091301	899	43.2	-0.576	-0.382	24.7	4.2
Station	49664.095411508900	0.056615692446	512	41.9	-0.52	-0.619	7.235	4.1
Station	49741.020411501200	0.055119472519	1728	42.1	-0.603	-0.433	6.877	3.6
Station	49858.465561599500	0.052895551095	1876	43.6	-0.66	-0.3	7.333	3.9
Station	49945.477911551700	0.051304220965	884	42.7	-0.519	-0.423	7.876	4.1

- **Their site log indicates an edit criterion of 2.2 sigma (all satellites). The fullrate data in the 7701 CRD lies within the +/- 2.2 sigma edit criteria. However; there appears to be an additional Leading-Edge (LE) filter applied prior to NP formation for LAGEOS-1 and -2.**
- **Since the NP epochs are difference, the ranges can't be compared directly. Notice the change in the moments based on the changes in the number of observation per bin between the four different data screening methods.**
- **Do we need a precise orbit to compare the NP ranges?**

7701 IZ1L LAGEOS-1 (8-Jan-2023 at 13:47) Normal Point Comparisons



- **As it turns out, a precise orbit is NOT needed to compare the NP ranges when the NP epochs are NOT the same**
- **The FullRate (FR) residuals from OrbitNP can be used to compare the NP time-of-flights (ToF) by**
  1. Take the normal point epoch and find the corresponding FR ToF and residual
  2. For each normal point epoch take the NP ToF minus (the corresponding FR ToF from the CRD minus the OrbitNP FR residual)
- **The station generated NPs average offset is -8 mm which seems to indicate an ~2 cm LE filter has been applied**

7306 TKBL LARES-2 (21-Feb-2023 at 10:33) Normal Point Comparisons

Source	Seconds of Day	Range in seconds	Obs in Bin	Bin RMS (ps)	Skew	Kurtosis	Peak - mean (ps)	Return Rate (%)	Range Difference (Station - OrbitNP) in mm
OrbitNP	38007.976541717800	0.055556357990	248	56.1	0.045	-0.446	-4.1	0.2	
Station	38007.976541717800	0.055556357989	248	55.9	0.033	-0.426	1.289	0.2	(0.1)
OrbitNP	38141.226541642900	0.054715507883	129	60.1	-0.138	-0.736	4.8	0.1	
Station	38141.226541642900	0.054715507883	129	60.1	-0.128	-0.759	0.311	0.1	0.0
OrbitNP	38219.202541714800	0.054280586743	3776	58.7	0.065	-0.705	-6.2	3.2	
Station	38219.202541714800	0.054280586742	3776	58.7	0.063	-0.706	0.252	3.2	(0.1)
OrbitNP	38343.342541661400	0.053679374288	3413	59.2	0.078	-0.677	-4.2	2.8	
Station	38343.342541661400	0.053679374289	3413	59.2	0.077	-0.684	-0.499	2.8	0.1
OrbitNP	38441.602541704100	0.053285836758	2443	58.4	0.076	-0.68	-6.2	3.2	
Station	38441.602541704100	0.053285836758	2443	58.4	0.074	-0.675	-0.938	3.2	0.0
OrbitNP	39698.079391708300	0.055108460961	231	61.5	0.419	0.2	-5.9	0.2	
Station	39698.079391708300	0.055108460962	231	56.5	0.03	-0.881	-4.429	0.2	0.1
OrbitNP	39774.984391682100	0.055615204194	669	61.7	0.142	-0.539	-13	0.6	
Station	39774.984391682100	0.055615204185	669	57.3	0.114	-0.704	-0.597	0.6	(1.3)
OrbitNP	39894.930391608900	0.056483385647	1167	69.4	0.066	-0.496	-2.7	1.1	
Station	39894.930391608900	0.056483385638	1167	57.3	0.083	-0.634	-0.209	1.1	(1.3)

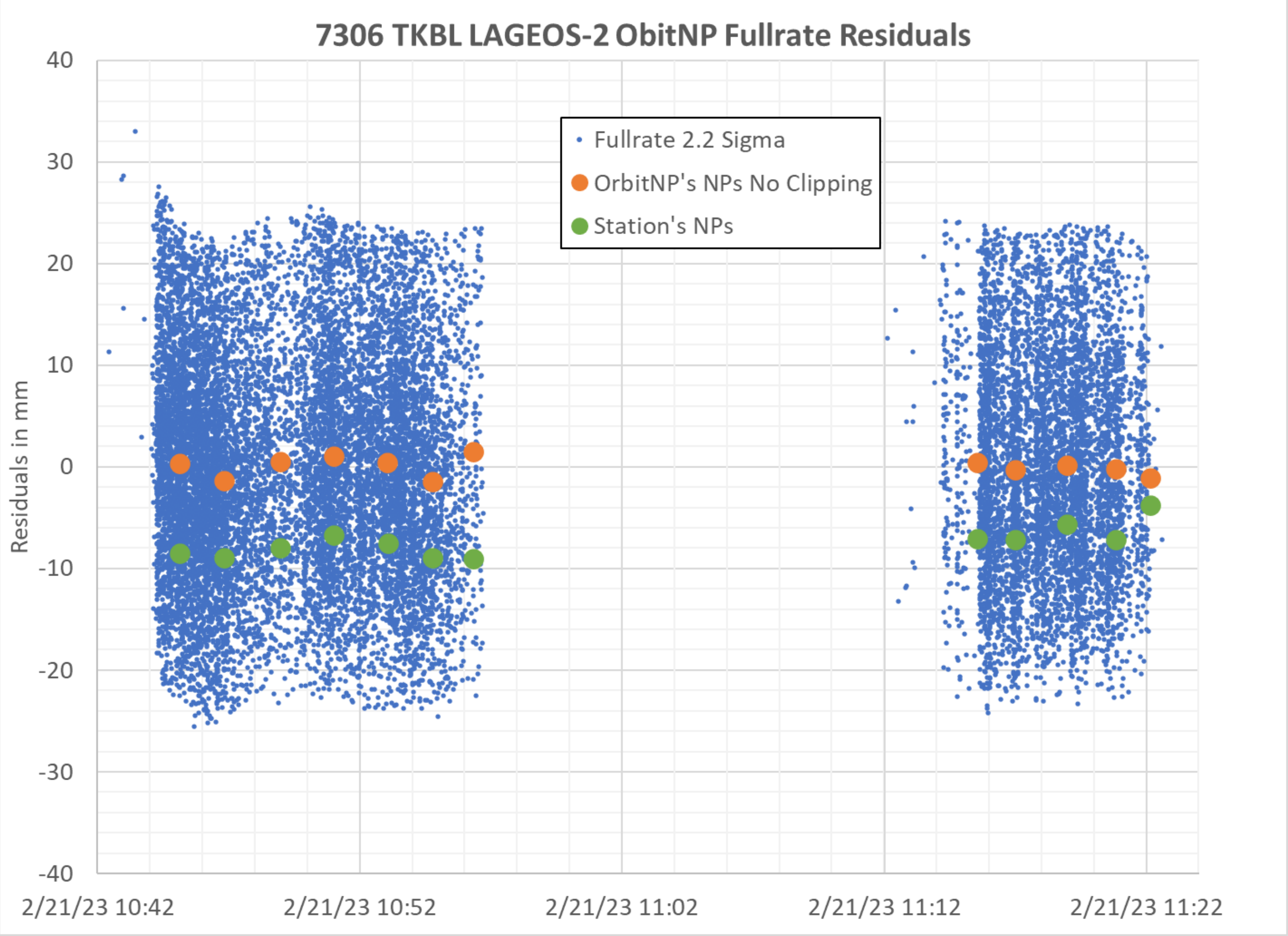
- **7306 LARES-2 NP epochs and observations in each NP bin agree exactly. There are some differences in the moments and peak minus means. The last two -1.3 mm (-9ps) NP ToF differences appear to be caused by bin RMS differences.**

7306 TKBL LAGEOS-2 (21-Feb-2023 at 10:42)
Normal Point Comparisons

Source	Seconds of Day	Range in seconds	Obs in Bin	Bin RMS (ps)	Skew	Kurtosis	Peak - mean (ps)	Return Rate (%	Range Difference (Station - OrbitNP) in mm
Orbit NP	38707.146421629200	0.050023773379	3022	72.7	0.163	-0.62	-10.4	2.6	
Orbit NP	38809.122541637500	0.048526905896	2320	71.8	0.135	-0.603	-11.4	1.9	
Orbit NP	38937.701541628000	0.046744979537	1148	72.6	0.152	-0.709	-10.4	1	
Orbit NP	39060.098541706100	0.045174463691	2139	73.1	0.159	-0.65	-11.8	1.8	
Orbit NP	39183.303541653500	0.043735545450	2192	70.7	0.084	-0.646	-13.3	1.8	
Orbit NP	39285.908541673200	0.042659197835	1407	72.4	0.219	-0.688	-20.6	1.2	
Orbit NP	39380.325541719100	0.041776492339	140	79.5	0.074	-0.932	-20.1	0.3	
Orbit NP	40531.291391671400	0.041371126069	827	71.4	0.054	-0.683	-8.1	0.7	
Orbit NP	40619.179391678800	0.042134651650	1882	72.1	0.199	-0.77	-21.2	1.6	
Orbit NP	40738.508391586400	0.043318399967	2126	68.1	0.207	-0.642	-16.1	1.8	
Orbit NP	40849.090391692400	0.044553352639	1213	69.6	0.233	-0.712	-22.3	1	
Orbit NP	40928.196391676900	0.045510542960	38	58.6	0.577	-0.187	-8.1	0.1	
Station	38708.246391700000	0.050007269523	1653	40.1	-0.484	-0.634	4.636	1.5	
Station	38808.459541674400	0.048536411631	1381	42.5	-0.573	-0.578	4.448	1.2	
Station	38938.765541658600	0.046730772362	646	40.7	-0.423	-0.769	5.38	0.5	
Station	39059.509541621800	0.045181699191	1225	41.3	-0.535	-0.56	5.142	1	
Station	39183.854541635900	0.043729457715	1255	40.9	-0.615	-0.367	4.677	1	
Station	39285.208541672200	0.042666138820	834	40.6	-0.393	-0.617	6.713	0.7	
Station	39380.016541603300	0.041779203428	70	40	-0.461	-0.746	4.476	0.2	
Station	40531.291391671400	0.041371126019	456	41	-0.541	-0.545	6.002	0.4	(7.5)
Station	40619.683391668900	0.042139303629	1149	40.4	-0.388	-0.65	7.297	1	
Station	40737.517391627200	0.043307911048	1354	40.1	-0.443	-0.609	5.873	1.1	
Station	40850.119391638500	0.044565423507	767	40.1	-0.316	-0.643	7.495	0.6	
Station	40928.196391676900	0.045510542942	33	40.6	-0.065	-1.172	11.714	0.1	(2.7)

- **Unlike LARES-2, the number of LAGEOS obs in a bin are quite different and all, but two NP epochs are different**
- **OrbitNP can be used to determine the range differences between these two set of NPs when the epochs don’t match (see next slide)**

7306 TKBL LAGEOS-2 (21-Feb-2023 at 10:42) Normal Point Comparisons



- **The 7306 site log indicates only a 2.2 sigma edit criteria, same as station 7701, BUT**
- **The station's mean NP offset is minus 7.4 mm which seems to suggest a LE filter is being applied to 7306 LAGEOS data; like what we say in station 7701's LAGEOS data**
- **Assuming a 2.2 sigma edit, current LAGEOS-1 and LAGEOS-2 Center of Mass (CoM) corrections for 7701 @1064 nm are:**
  - LAGEOS-1: 247.5
  - LAGEOS-2: 247.0
- **Shanghai (7821) and Graz (7839) LAGEOS CoMs based on 2cm LE are:**
  - LAGEOS-1: 251.2 and 250.4
  - LAGEOS-2: 251.0 and 250.3

7827 SOSW Wettzell NP Analysis

7827 SOSW Wettzell Background

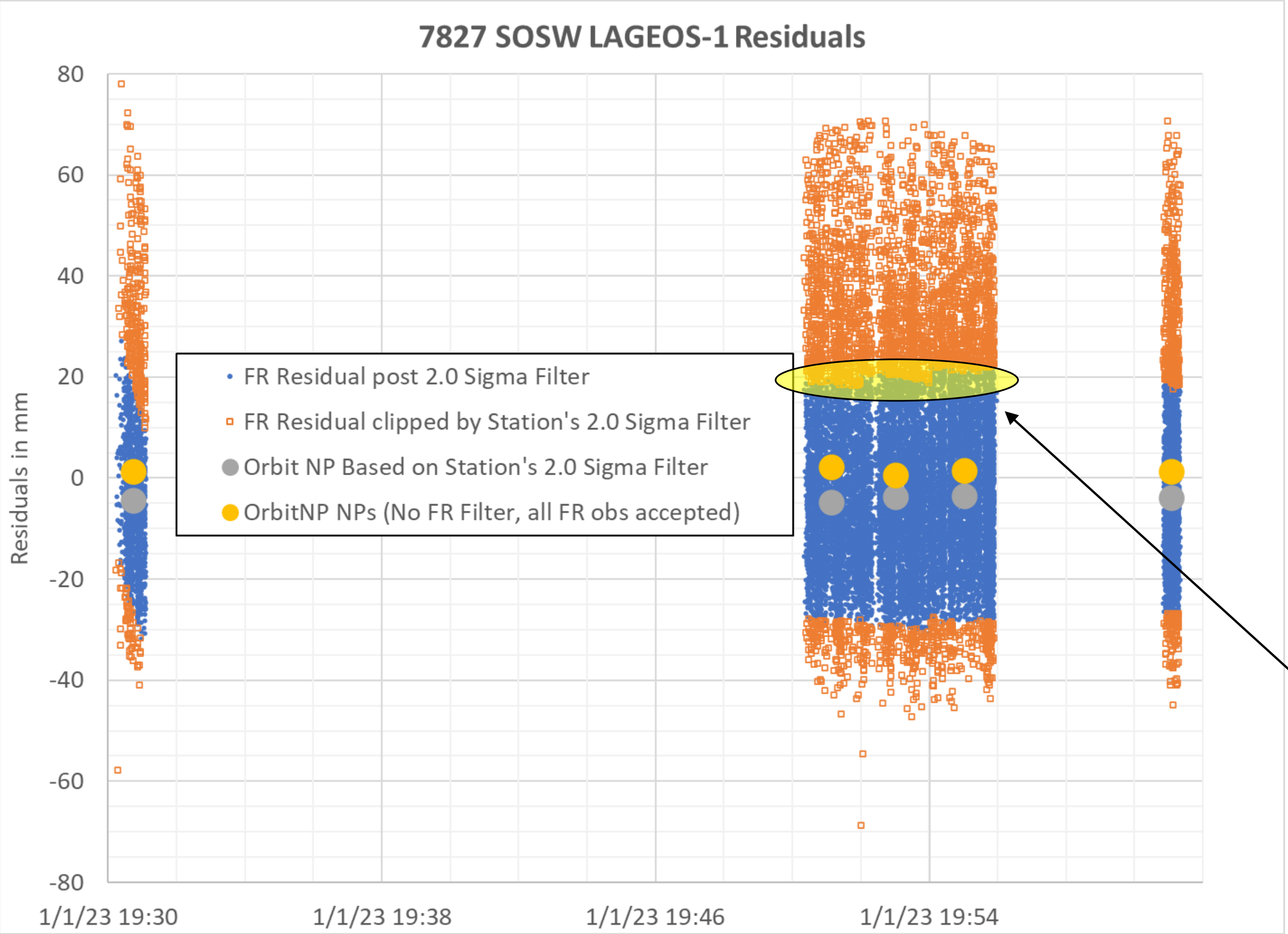
- At previous QCB meetings, we have discussed that 7827 does not adhere to the Herstmonceux algorithm in terms of the normal point epoch
- According to Stefan, the 7827 NP epoch is "not the average of epochs of measurements in the normal point closest to a fullrate observation epoch, but the epoch of the observation which is closest in residual to the normal point"
- This is why the OrbitNP generated NPs epochs based on the 7827 fullrate CRD are different from the station generated NPs, which prevents a direct comparison of the NP Time-of-Flights (ToFs)

7827 SOSW LAGEOS-1 (01-Jan-2023 at 19:30) NP Comparisons

Source	Seconds of Day	Range in seconds	Obs in Bin	Bin RMS (ps)	Skew	Kurtosis	Peak - mean (ps)	Return Rate (%)
Station	70238.502004493600	0.049805783377	1234	76.6	0.048	-0.925	-4.3	9.2
OrbitNP	70244.502004481800	0.049717434469	1234	75.8	0.104	-0.84	-17.1	2.4
Station	71447.985004494900	0.043520472765	3173	78	0.052	-0.926	-1.4	0.8
OrbitNP	71470.138004489200	0.043660526567	3173	78.4	0.054	-0.921	-11.3	3.2
OrbitNP	71582.401004490600	0.044505850858	4102	83.2	0.035	-0.873	-2.3	3.4
Station	71638.749004481000	0.045012186065	4102	83.1	0.038	-0.885	-0.5	13.2
OrbitNP	71702.476004491900	0.045647340211	4994	83.5	0.05	-0.892	-13.1	4.2
Station	71727.532004486500	0.045914549677	4994	83.6	0.046	-0.895	-2.2	8.4
OrbitNP	72065.813004490200	0.050368881144	1609	75.6	0.041	-0.855	-6.3	5.5
Station	72071.197004483900	0.050450952159	1609	75.5	0.033	-0.845	-1.6	12.4

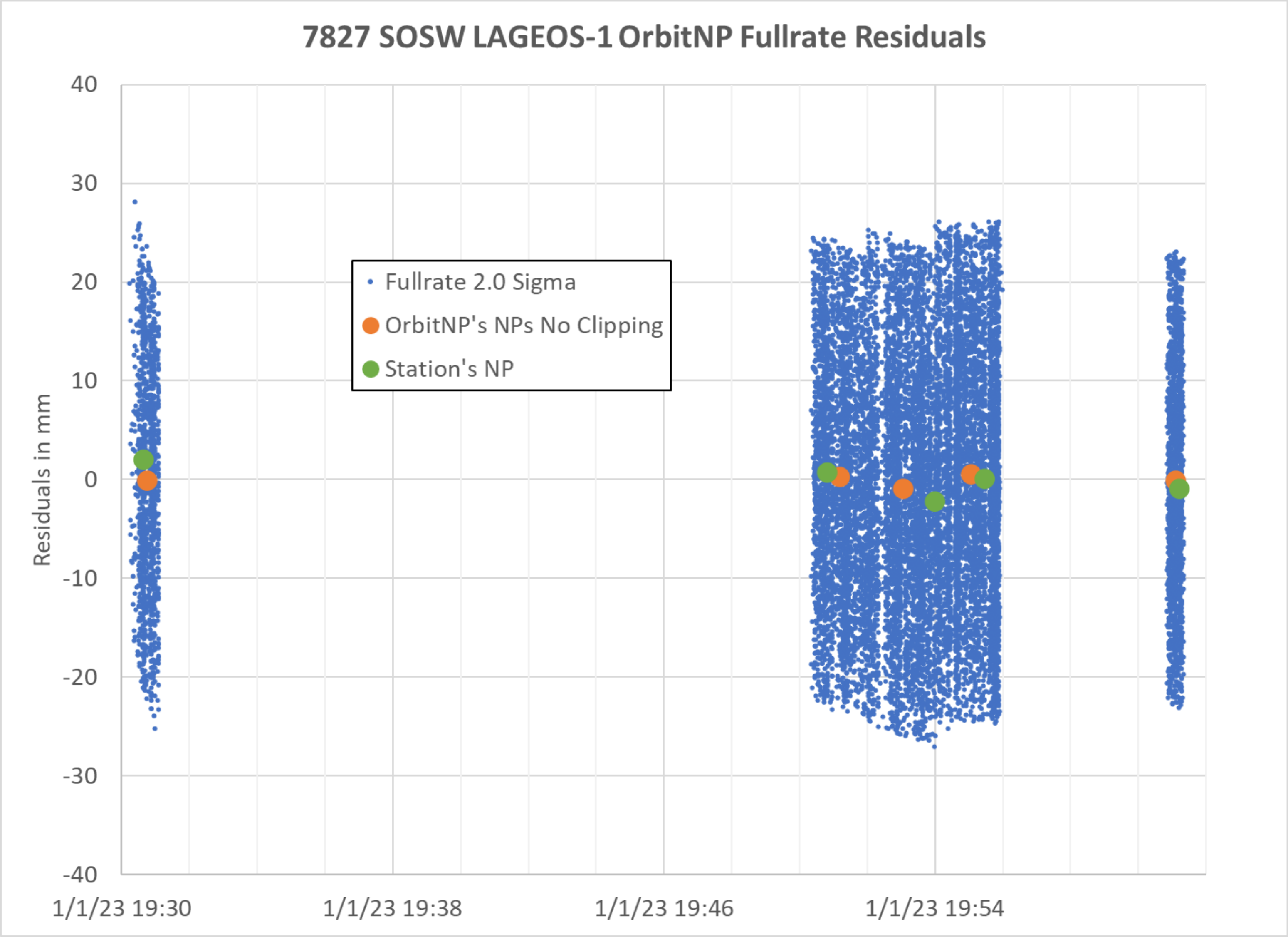
- **Comparisons of station and OrbitNP generated NPs based on 7827 fullrate CRD data**
- **NP Epochs don’t match**
- **Obs agree exactly; Bin RMSs are nearly the same; skews and kurtoses are similar**
- **Kurtosis is 2.1 (2.1 – 3 = -0.9), which is close to the 2.0 sigma editing criteria in the 7827 site log**
- **Average Peak minus Mean difference is 8 ps or 1.1 mm**
- **Return rates are different**

7827 SOSW LAGEOS-1 (01-Jan-2023 at 19:30) NP Comparisons



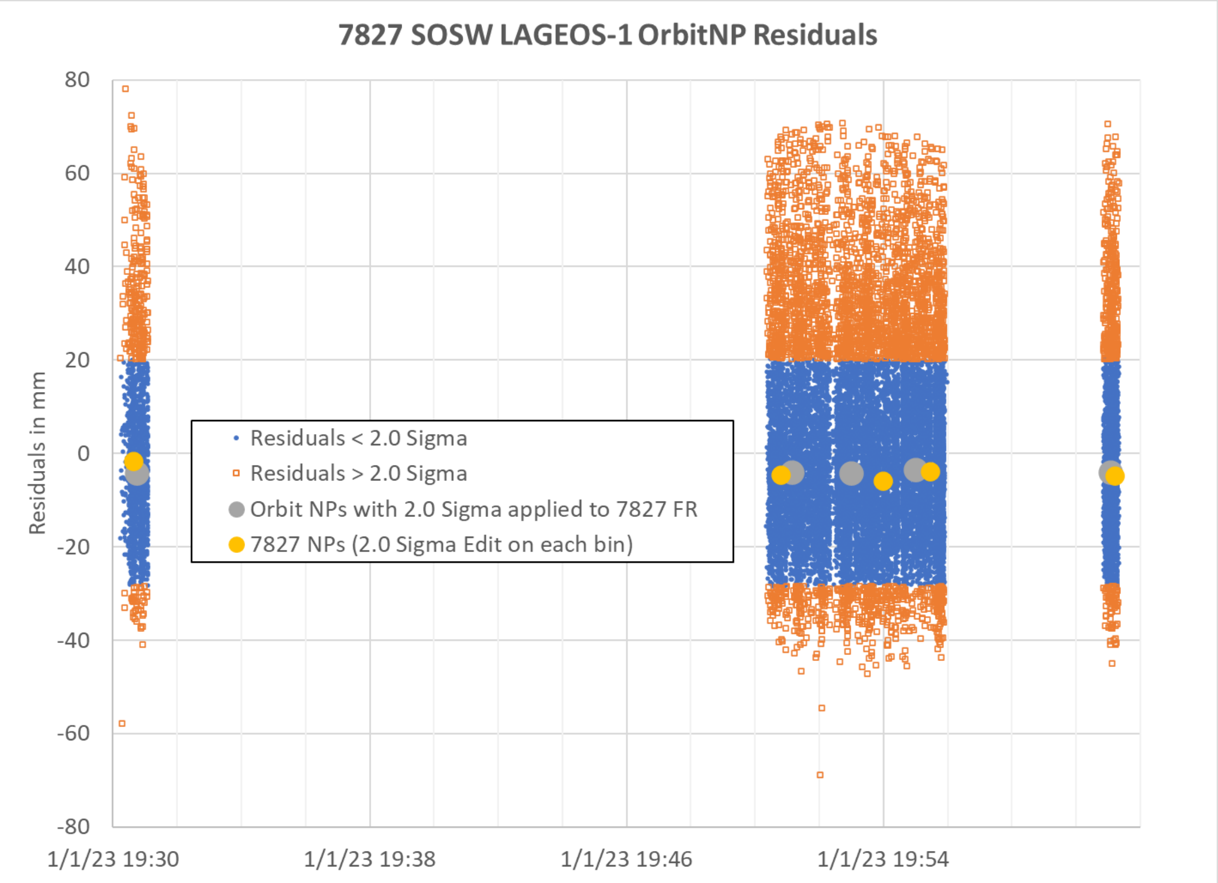
- OrbitNP 7827 fullrate residuals based on the 7827 fullrate data
- Small open squares are 7827 fullrate data marked as noise and excluded returns in the CRD
- Small circles are fullrate data marked as data (i.e. within +/- 2.0 sigma)
- Large circles are OrbitNP generated NPs based on the all the residuals (orange and blue)
- Large circles are OrbitNP generated NPs based on a 2.0 sigma filter
- The mean offset between the two sets of NPs is 5.4 mm
- There are small discontinuities in the +/- 2.0 sigma residuals at the NP two-minute boundaries. See next slide.

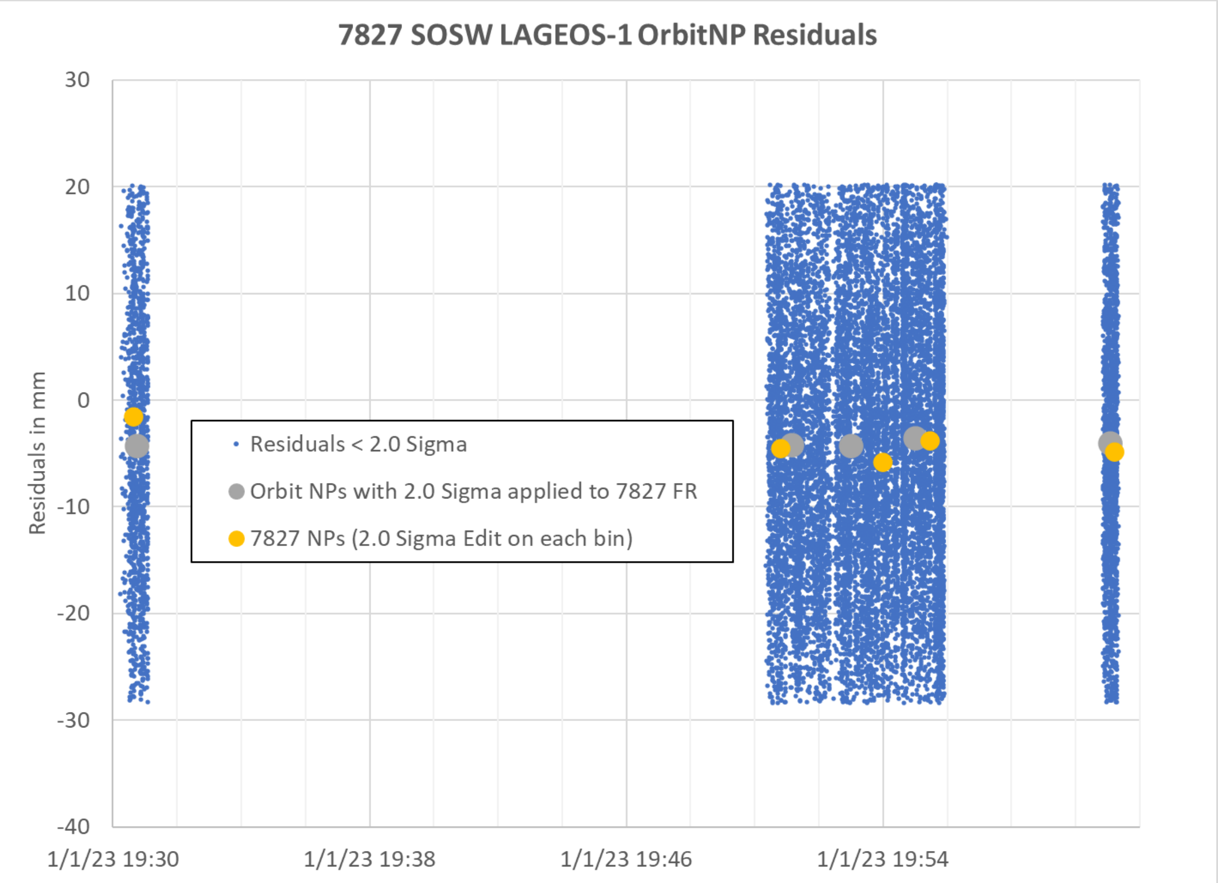
7827 SOSW LAGEOS-1 (01-Jan-2023 at 19:30) NP Comparisons



- Only the OrbitNP fullrate residuals from the 7827 fullrate CRD with a filter flag set to a '2' (data). Same blue circles as previous slide.
- The large orange circles are the OrbitNP generated NPs, while the large green circles are the station generated NPs. This shows the differences in the NP epochs between the two different NP algorithms.
- Note: the drift in the fullrate residuals within a NP two-minute bin and the apparent discontinuities in the residuals from one bin to the next.
- Instead of using a 2.0-sigma filter being applied to the entire pass, the station applied a 2.0-sigma filter to each two-minute bin

7827 SOSW LAGEOS-1 (01-Jan-2023 at 19:30) NP Analysis





- **Left chart are the OrbitNP 7827 fullrate residuals based on 2.0 sigma edit over the entire pass. Right chart is a zoom of the filtered residuals. Note: there are no discontinuities at the 2-minute bin boundaries.**
- **Large yellowish and gray circles are the station and OrbitNP generated NPs; respectively.**

Bin Start Time	NP Difference in mm
1/1/2023 19:30	2.78
1/1/2023 19:48	-0.20
1/1/2023 19:50	-1.41
1/1/2023 19:52	-0.10
1/1/2023 20:00	-0.68
Average	0.08
Standard Deviation	1.60

Conclusions

- **The CRD NPs and calibration moments (RMS, skew, kurtosis) can be used as a sanity check on the calibration and satellite data screening techniques listed in the site logs**
- **OrbitNP can be used for the following:**
  1. to determine the data screening employed by the stations using the station's CRD data (fullrate and NPs)
  2. to determine the impact of different data screening techniques on the satellite Center of Mass (CoM) correction
  3. to determine the impact of different NP algorithms
- **Stations 7701 and 7306 are using an undocumented LE filter on LAGEOS (-1,-2) but not LARES-2 nor other satellites. Action: These are both DIGOS systems and their site logs need an update so that new LAGEOS CoM corrections can be calculated**
- **Station 7827 SOSW NP algorithm is different from the Herstmonceux algorithm in two ways (selecting the epoch and applying a sigma filter to each NP bin versus the entire pass)**
- **If fullrate residuals are not flat prior to NP formation, clipping can induce random and/or systematic errors in the NPs**

ITRF2020 SLR Scale Analysis

Van S. Husson

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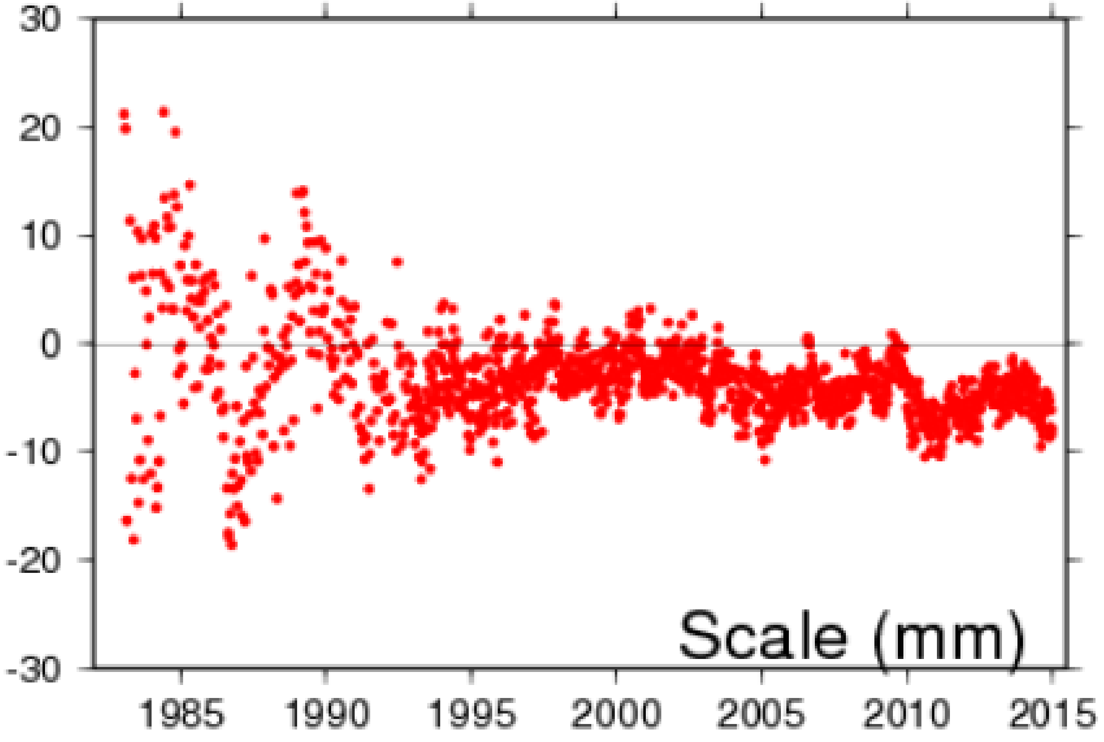
ILRS Quality Control Board

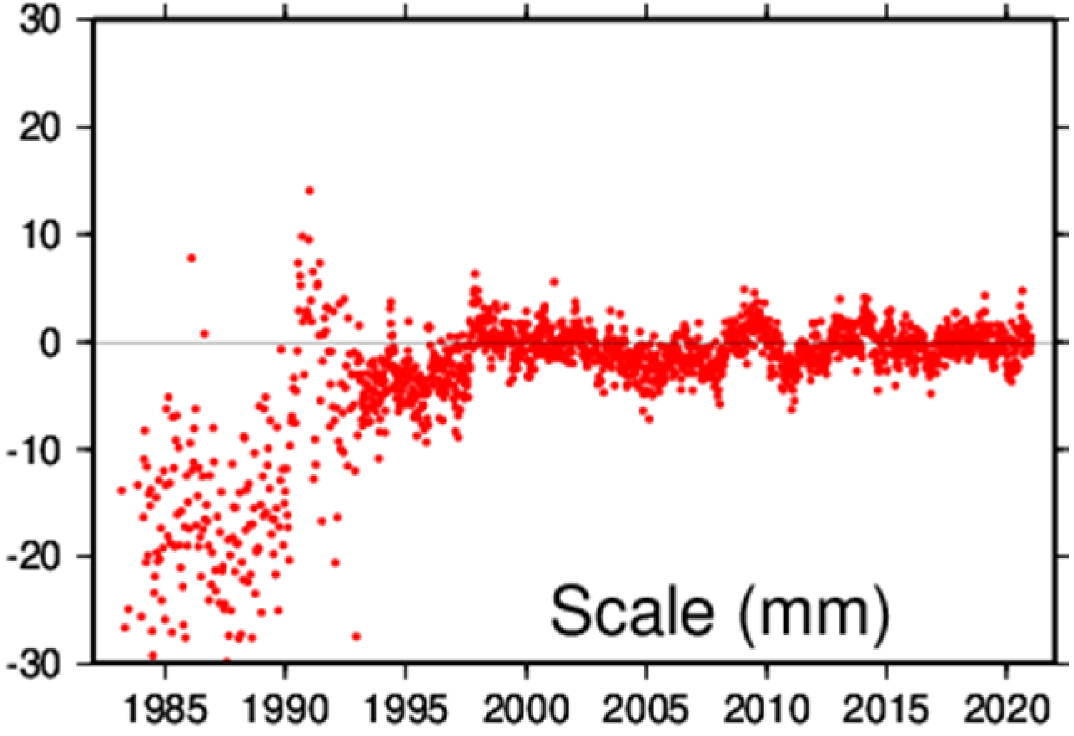
18-Jan-2023

ITRF2014 and ITRF2020 SLR Scales

ITRF2014 SLR Scale



ITRF2020 SLR Scale

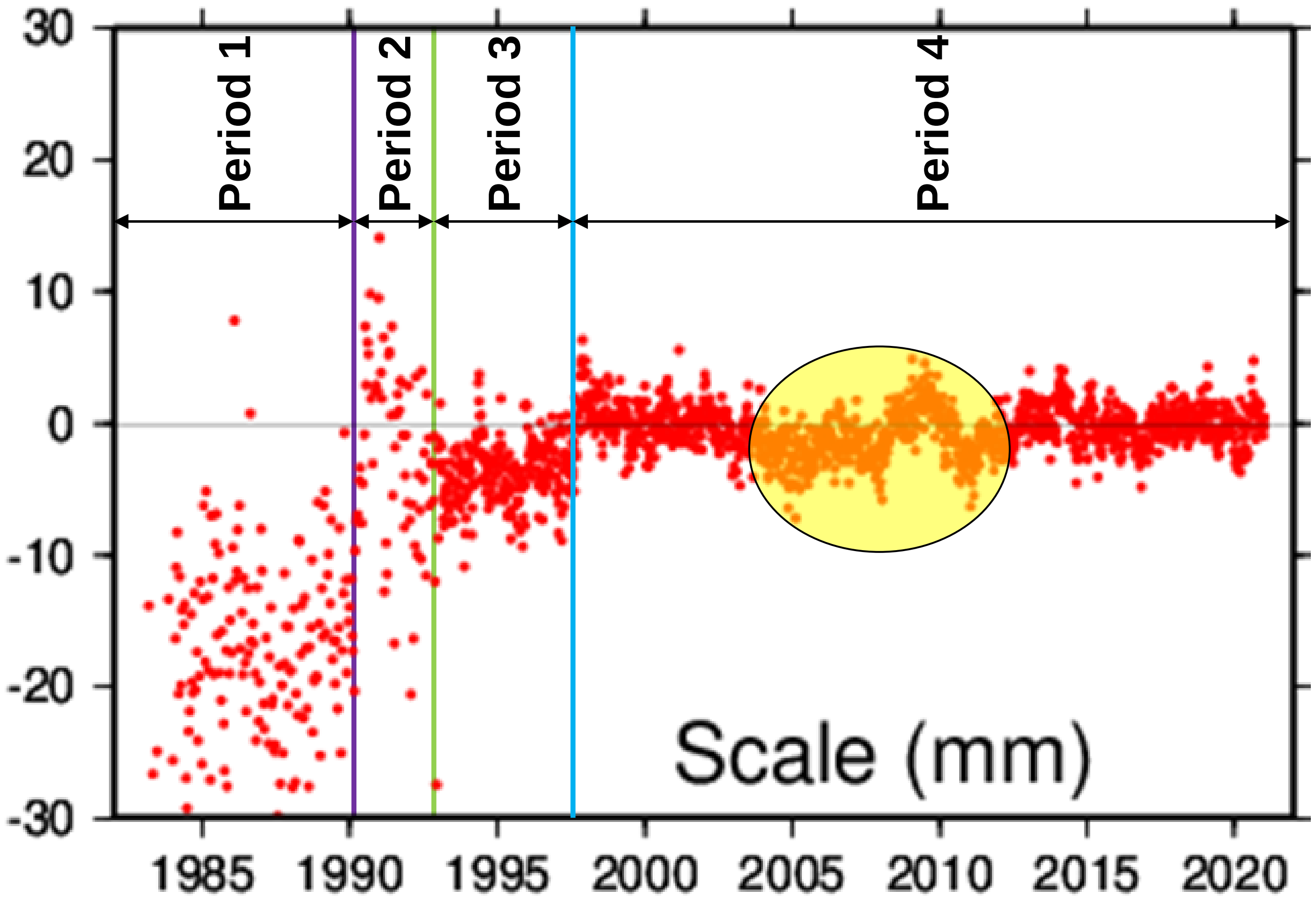


- ❑ **ITRF2020 scale residuals since July 1997 are centered around zero. The ITRF2020 scale estimates have some systematic variations**

Potential Causes of Systematics in the SLR ITRF2020 Scale Results

- Changes in the satellite constellation
- Poor spatial and temporal tracking coverage from the ILRS Core sites
- Unmodelled systematic errors (tropospheric, epoch, signal strength, counter non-linearities, frequency) in the Core sites

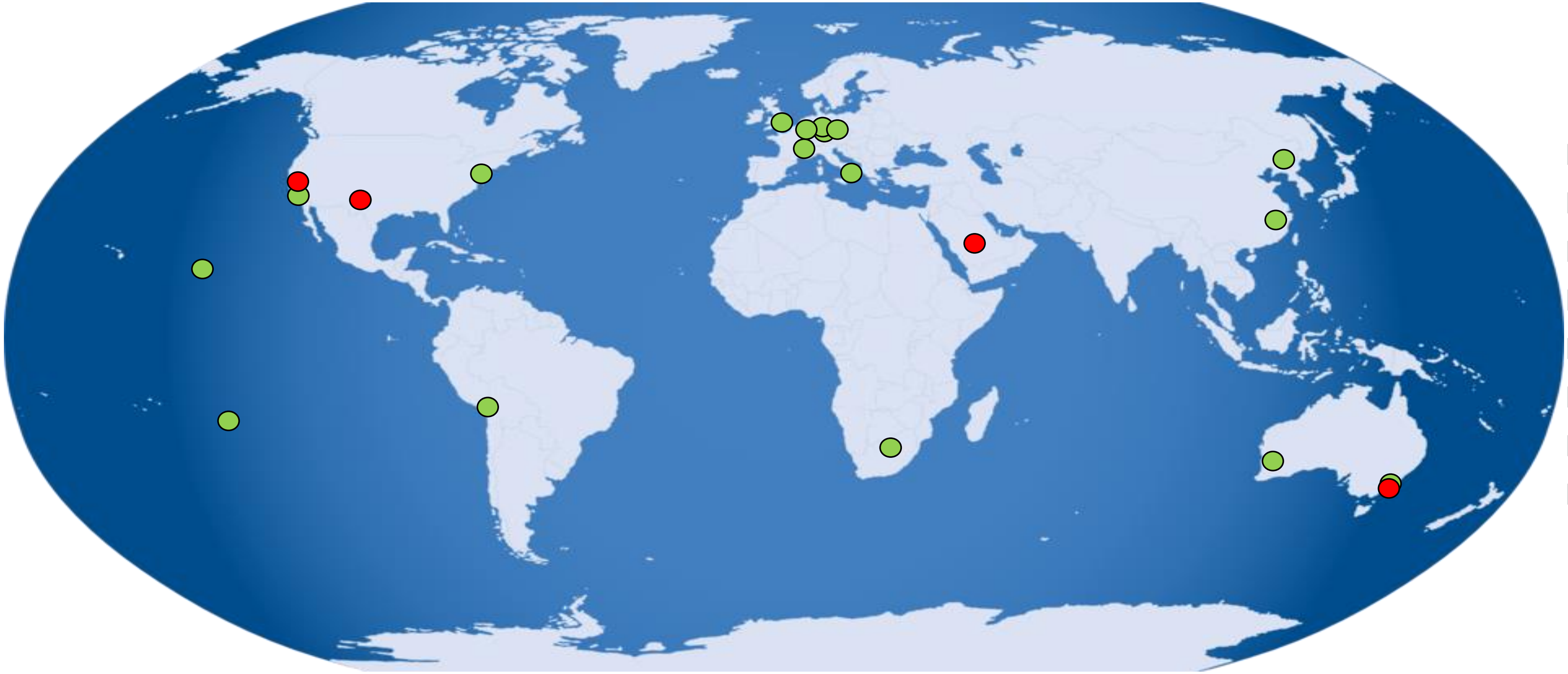
ITRF2020 SLR Scale Estimates and Satellites



- Four distinct periods, 1st three periods are due to changes in the satellite constellation
- Period 1: LAGEOS-1 only (1983 to early March 1990)
  - Scale estimates mostly negative
- Period 2: Etalon -1 and -2 added (early March 1990 to November 1992)
  - Scale estimates distributed around zero, but slightly negative
- Period 3: LAGEOS-2 added (November 1992 to July 1997)
  - Scale estimates mostly negative, decrease in scatter
- Discontinuity in the scale estimates in July 1997
- Period 4: no change in satellites (July 1997 to end of 2020)
  - Scale estimates scattered around zero with some systematics (2004 to 2011)

Analysis of LAGEOS and Etalon Tracking from Core Sites

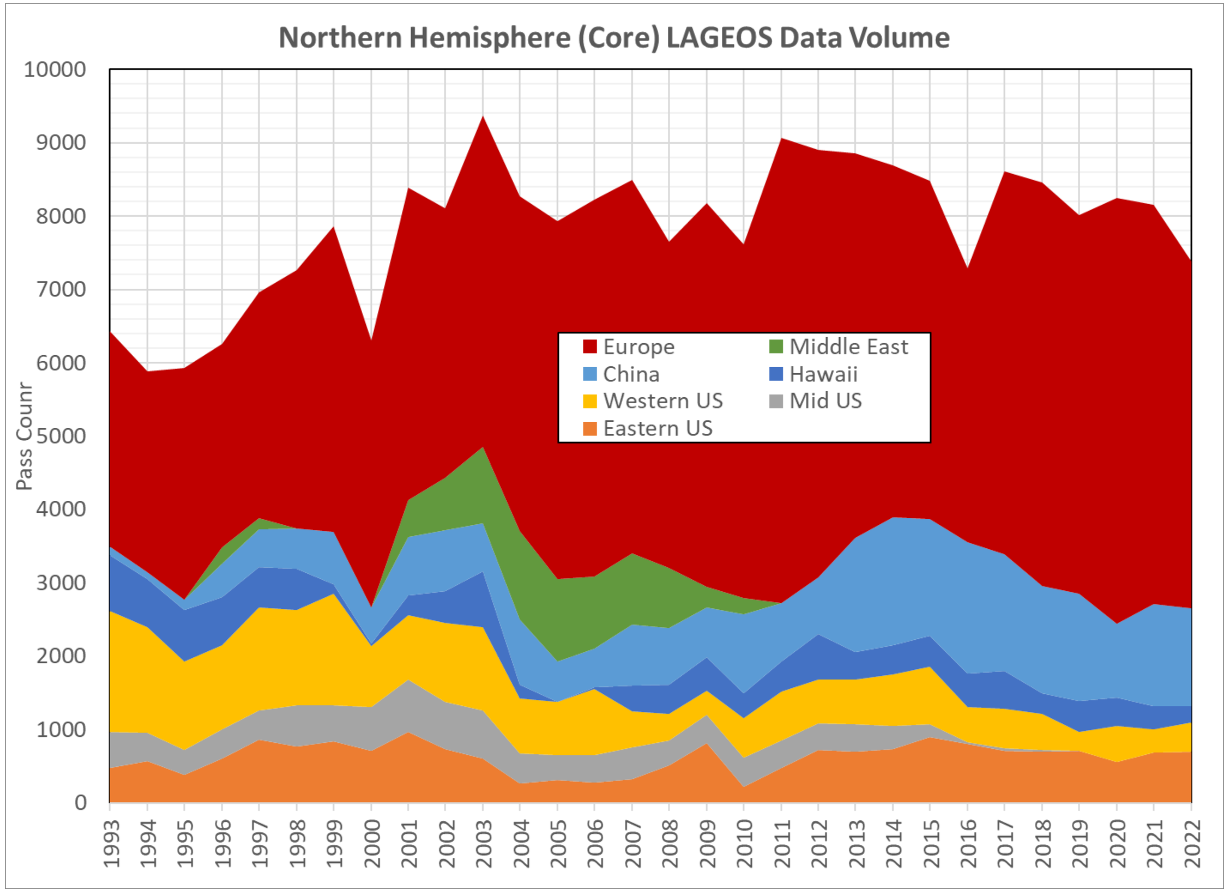
ITRF2020 SLR Core Site Locations

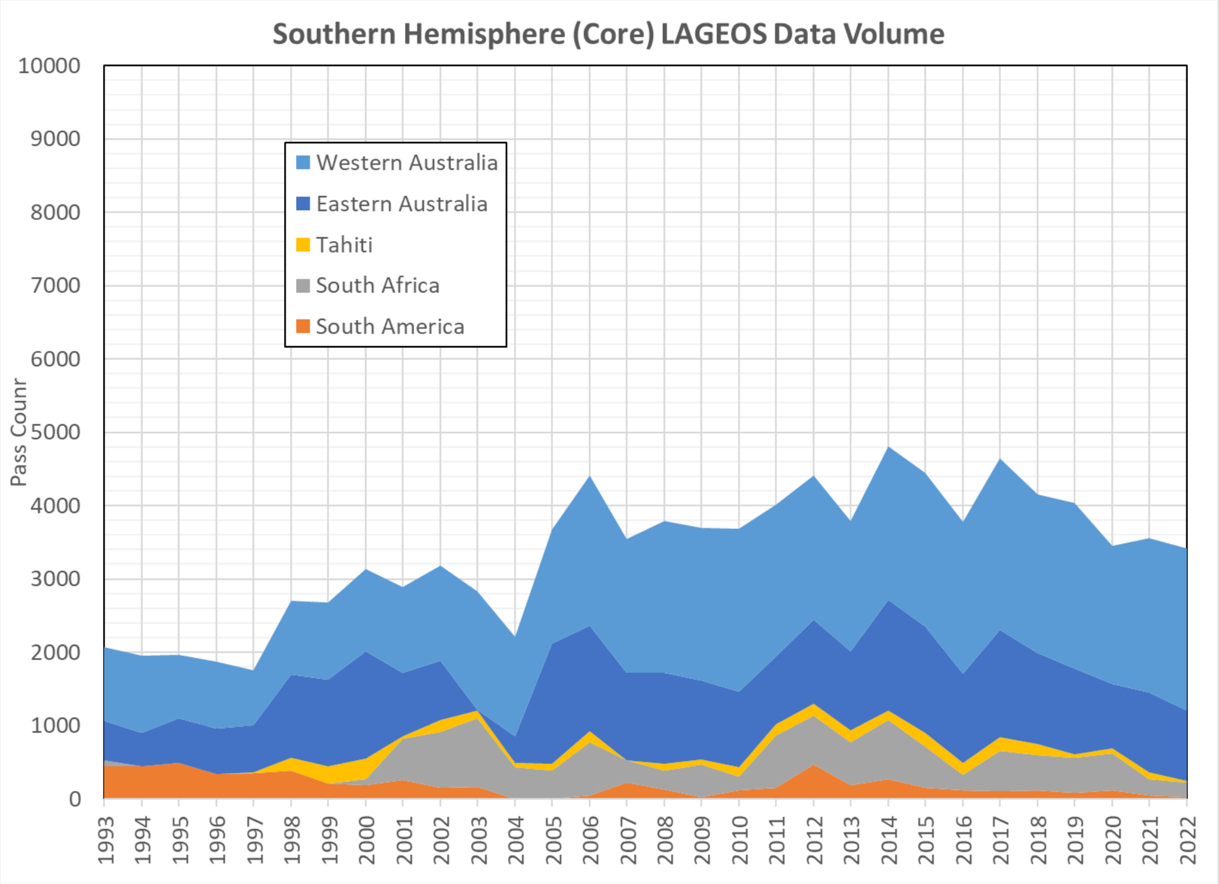


- 4 N. American sites
- 1 S. American site
- 2 Pacific sites
- 3 Australian sites
- 2 Chinese sites
- 1 Middle Eastern site
- 1 African site
- 7 European sites

Sites in RED (Quincy, McDonald, Riyadh, Orroral Valley) currently don't have SLR systems

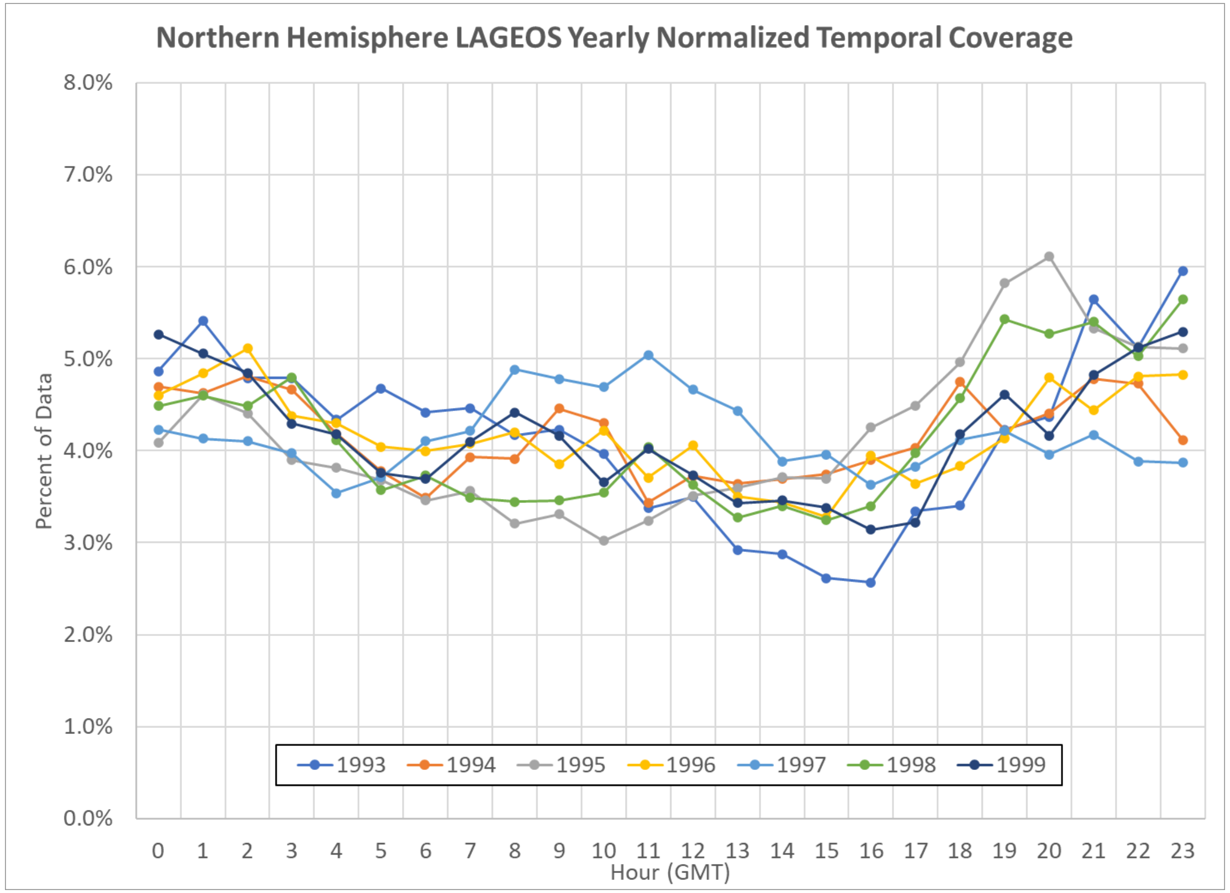
LAGEOS (-1, -2) Yearly Pass Totals by Hemisphere

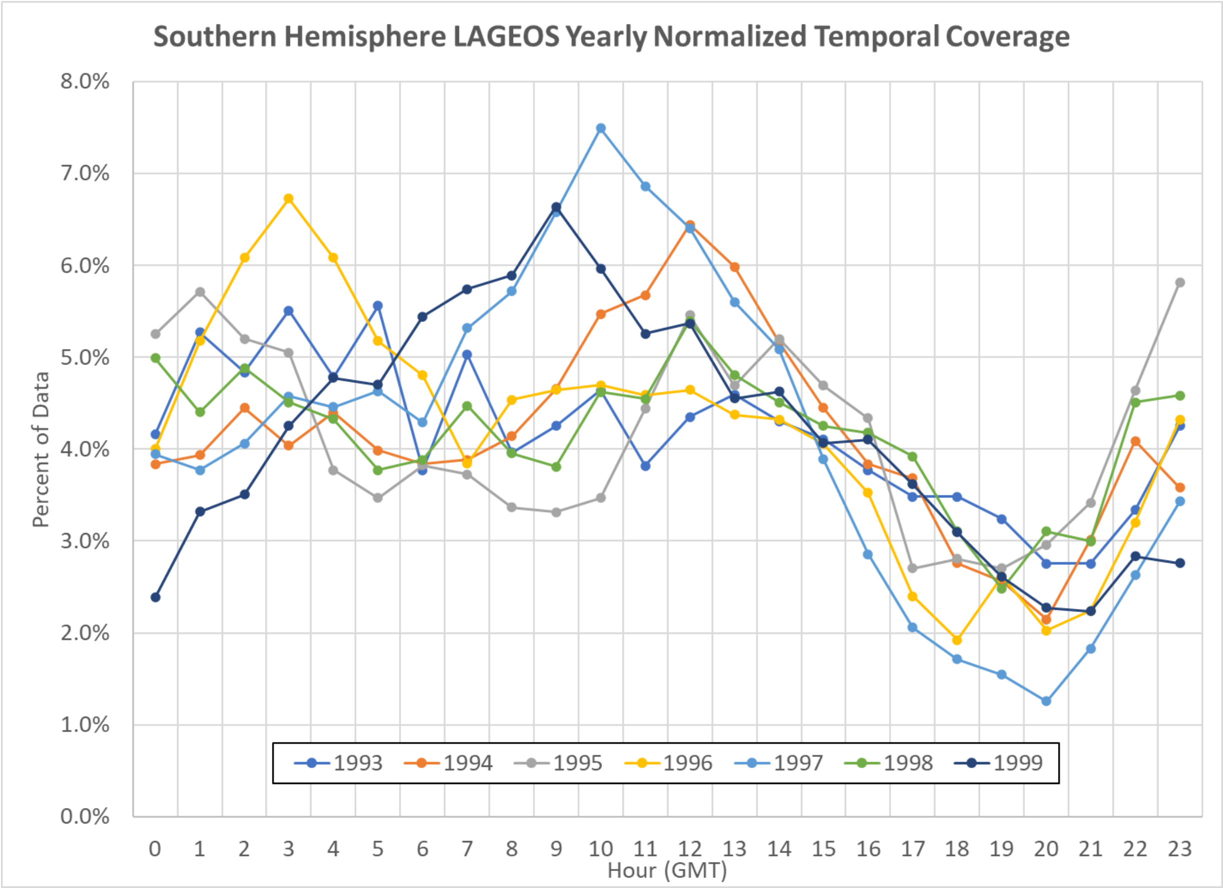




- ❑ **Stacked areas charts of yearly LAGEOS pass totals from the Core Sites (Northern and Southern hemispheres)**
- ❑ **There is 2 to 3x more LAGEOS data from the Northern Core Sites than the Southern Core Sites**

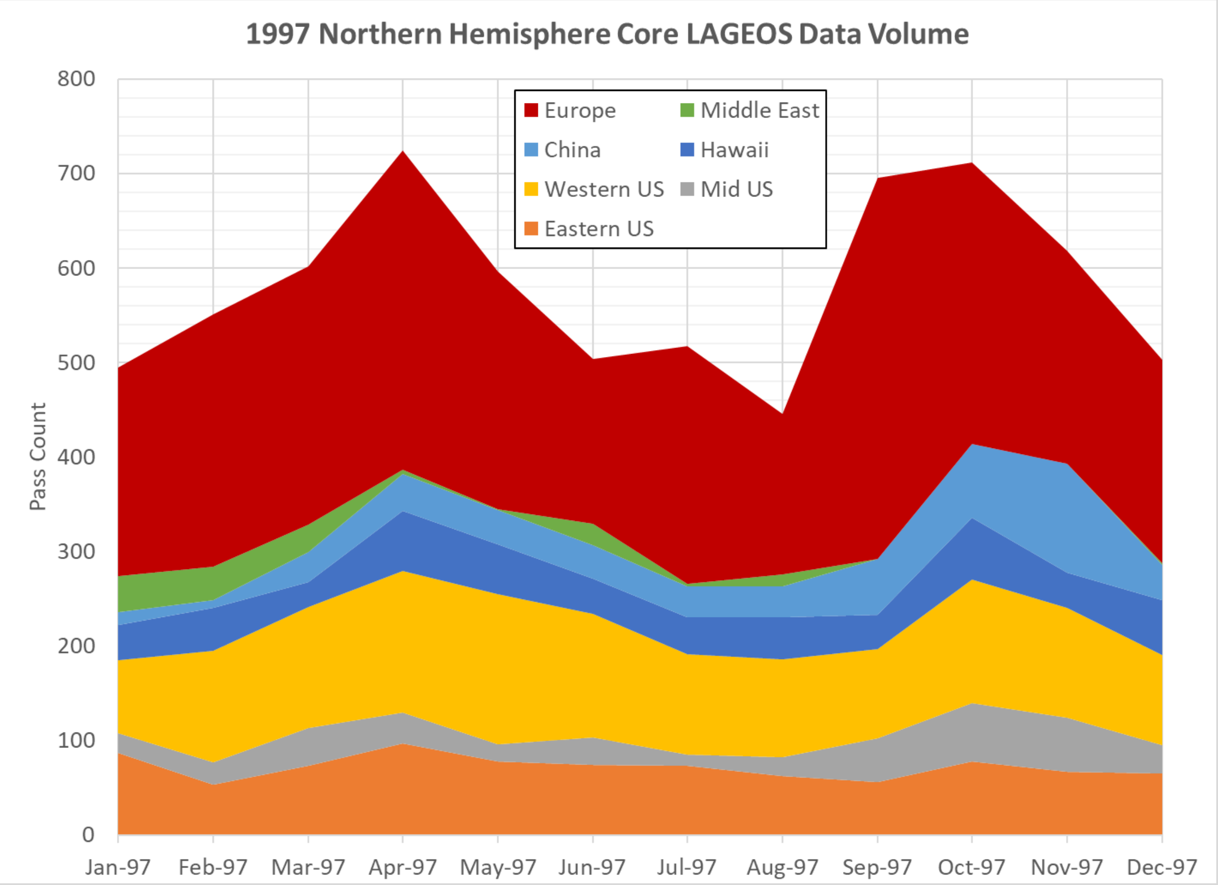
LAGEOS Yearly Normalized Core Site Temporal Coverage

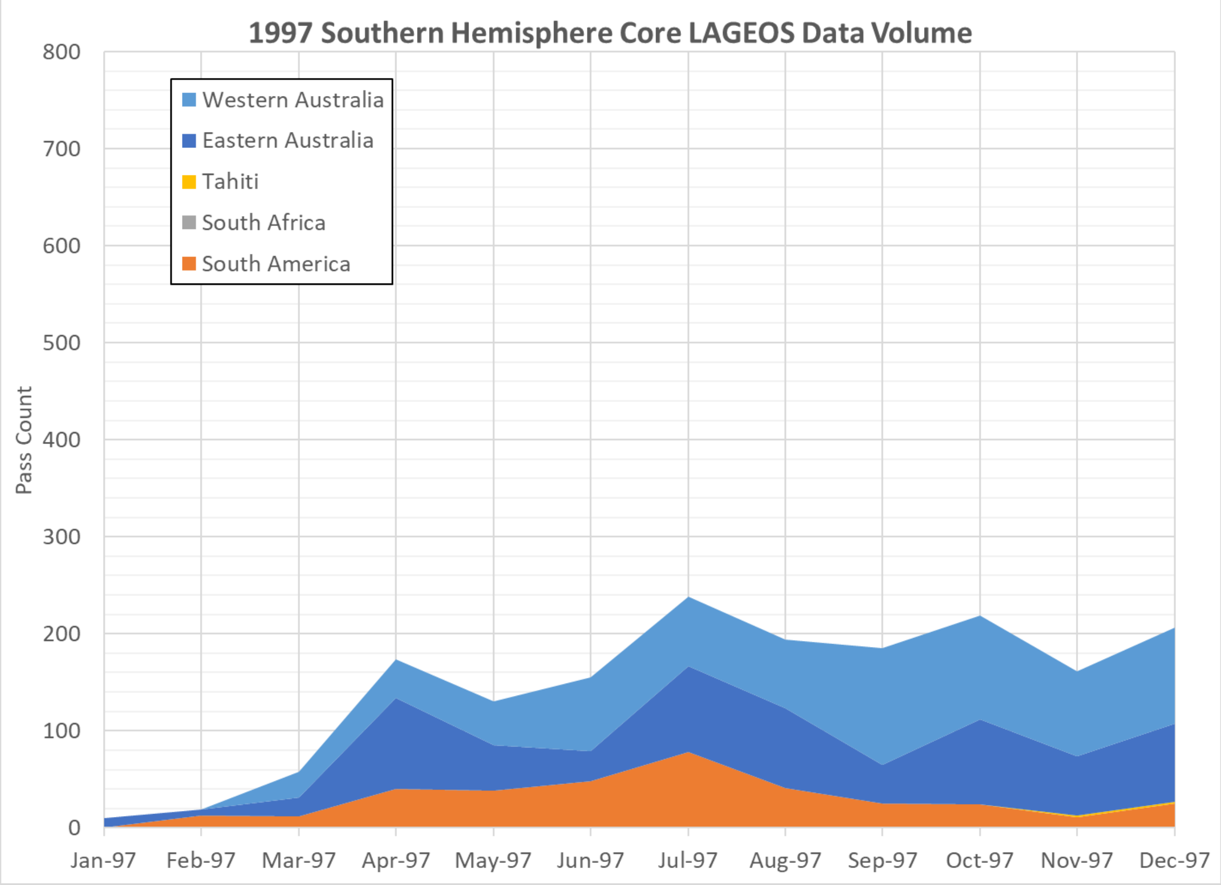




- The southern hemisphere has more temporal variations than the northern hemisphere in the years 1993-1999
- The year 1997 (the light blue series on the right chart) had the most temporal variation in the southern hemisphere. 1997 is the year where the discontinuity appeared in the SLR Scale

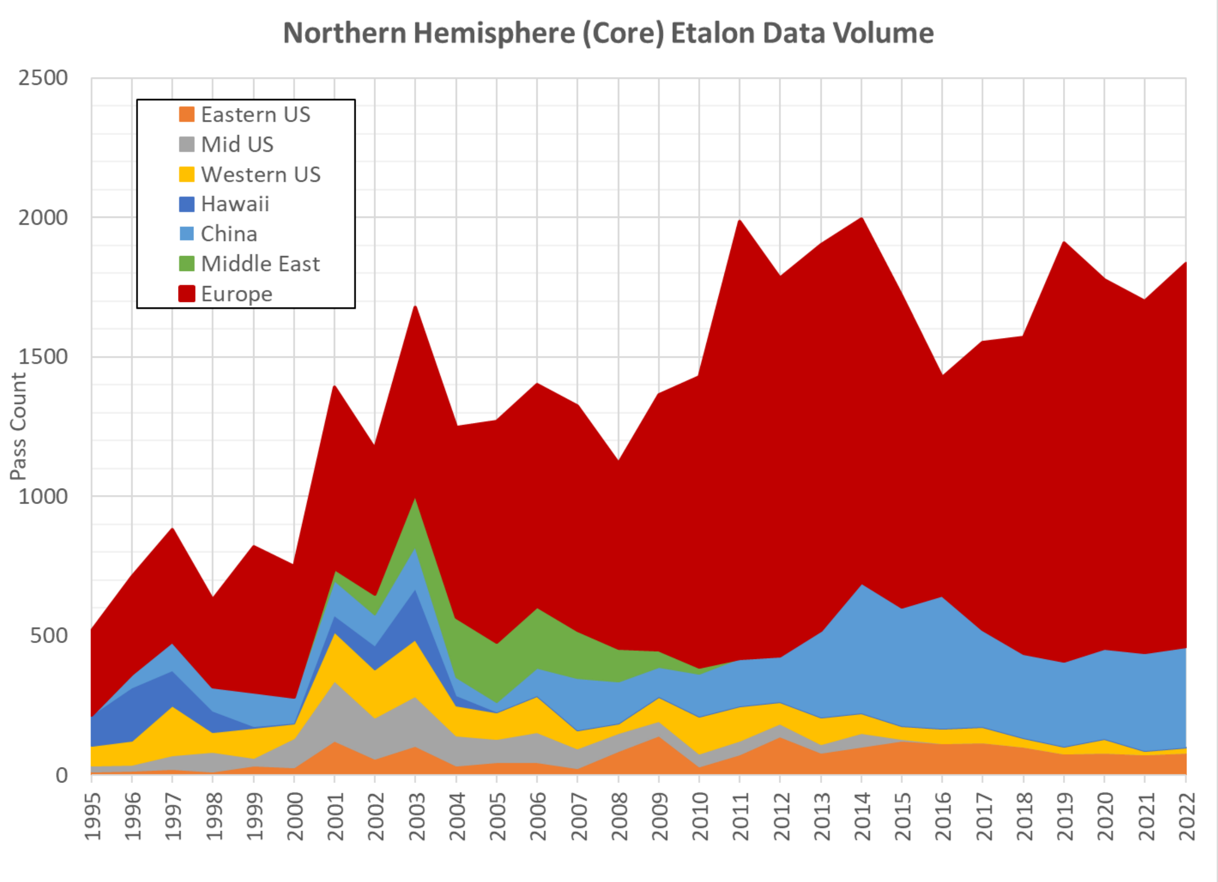
LAGEOS (-1, -2) 1997 Monthly Pass Totals by Hemisphere

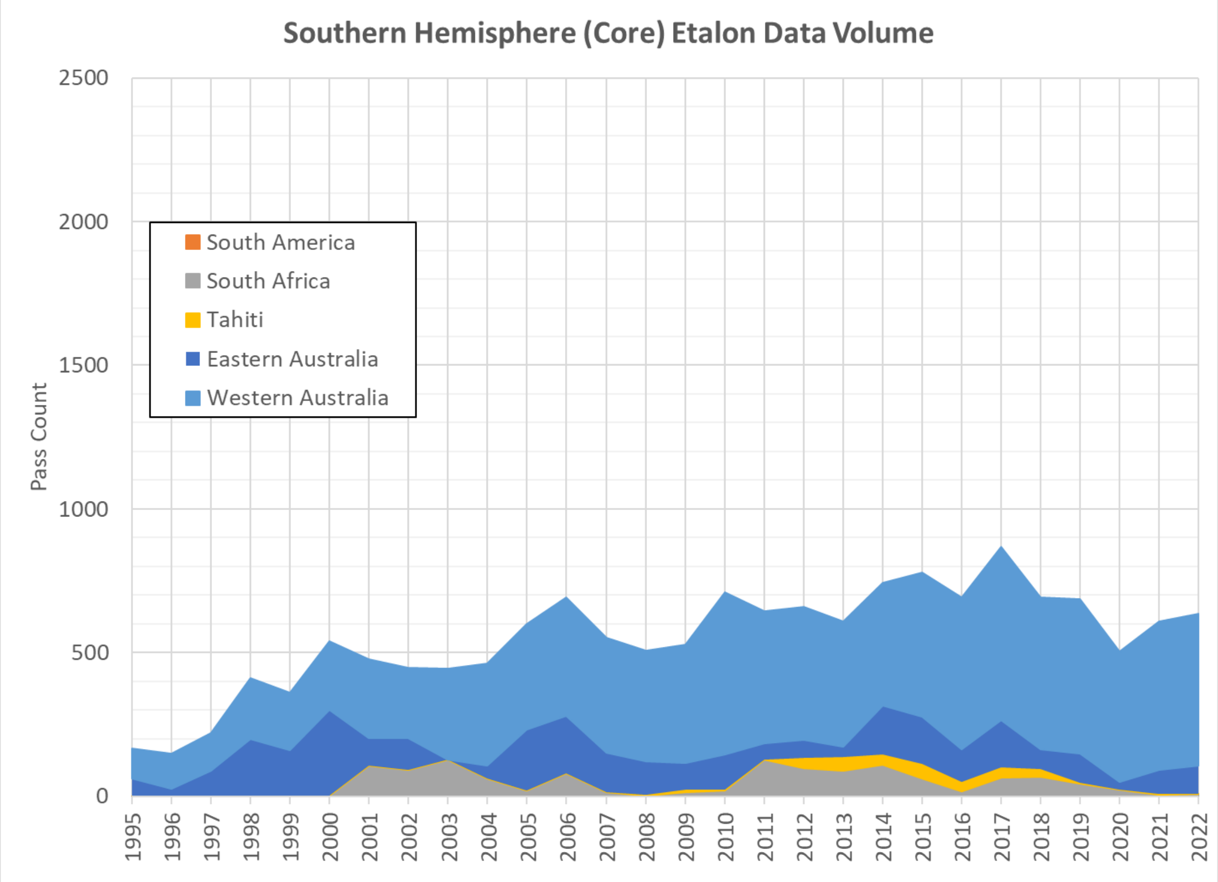




- **Stacked areas charts of LAGEOS1997 Monthly pass totals from the Core Sites (Northern and Southern hemispheres)**
- **Only data from 3 southern hemisphere sites in 1997 and two were Australian (7834 ORRL and 7090 YARL) Southern hemisphere LAGEOS data peaked in July 1997, which coincides with the change in SLR scale**

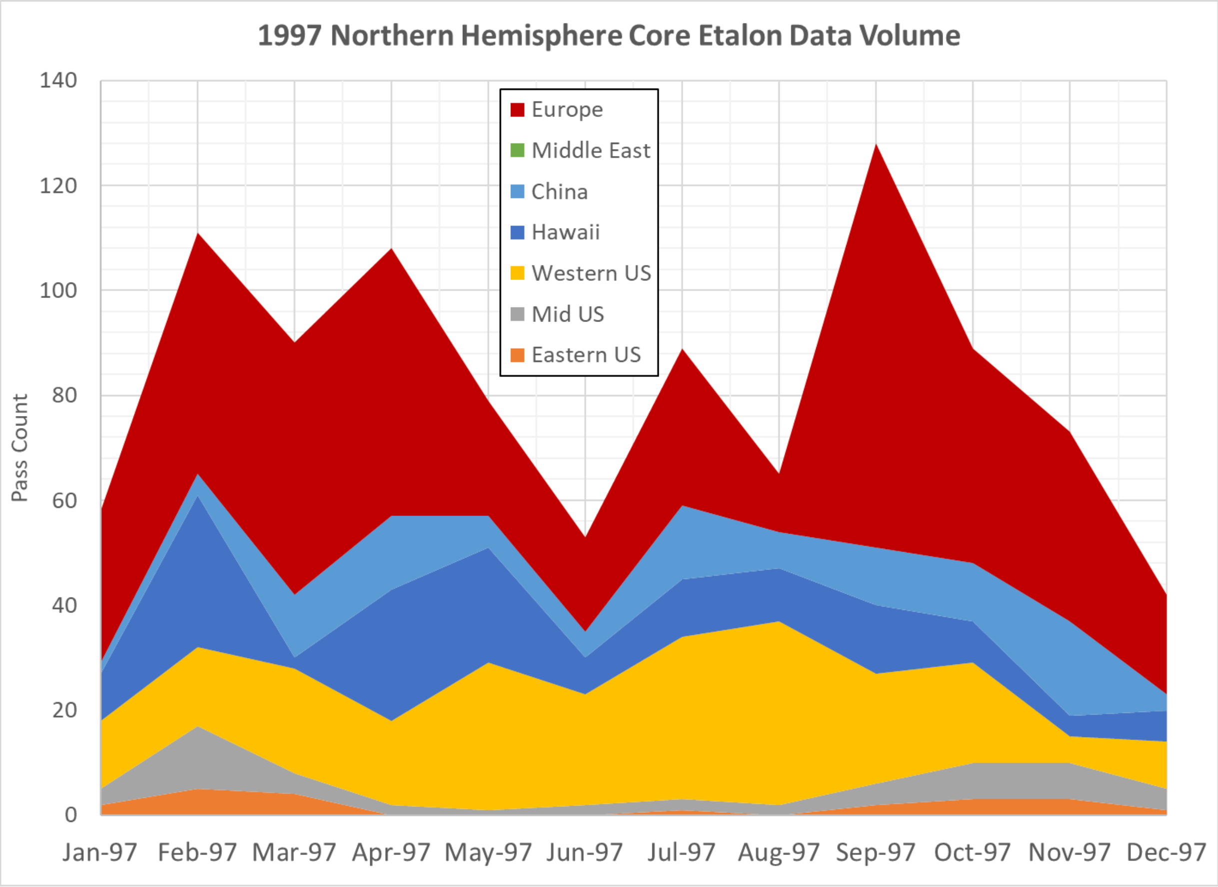
Etalon (-1, -2) Yearly Pass Totals by Hemisphere

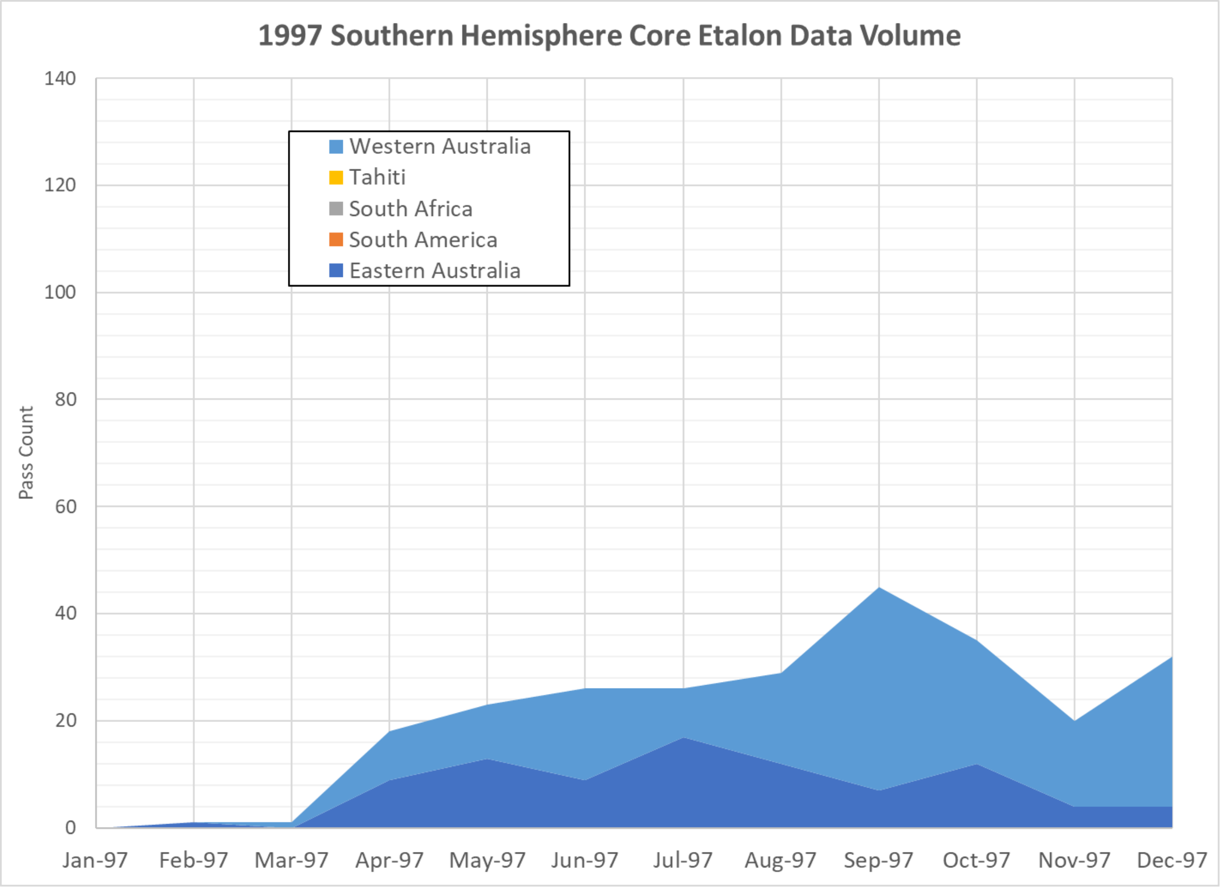




- **Stacked areas charts of yearly Etalon pass totals from the Core Sites (Northern and Southern hemispheres)**
- **There is 2 to 4x more Etalon data from the Northern Core Sites than the Southern Core Sites**

Etalon (-1, -2) 1997 Monthly Pass Totals by Hemisphere





- **Stacked areas charts of Etalon1997 Monthly pass totals from the Core Sites (Northern and Southern hemispheres)**
- **Only data from 2 southern hemisphere sites in 1997 and both were Australian (7834 ORRL and 7090 YARL)**

Systematic Errors

Core Sites in 1997 and their System Components and Changes

Location	Barometer	GPS Steere	Detector	Timer	System Changes in 1997
McDonald, TX USA	Setra	No	MCP	TD811 + UT Timer	27-Aug-97: Crystal Oscillator replaces Cesium
Monument Peak, CA, USA	MET3	No	MCP	HP5370B	
Yarragadee, Australia	MET3	No	MCP	HP5370B	Jan-Feb 1997: Controller Computer Upgrade, no data
Greenbelt, MD USA	MET3	No	MCP	HP5370B	
Quincy, CA USA	MET3	No	MCP	HP5370B	10-May-1997: last pass
Arequipa, Peru	Setra	No	MCP	HP5370B	
Haleakala, Hawaii	unknown	No	MCP	HP5370B	
Graz, Austria	MET3	Yes	CSPAD	HP5370B & multi SR620	1997: Many counter, time and frequency changes
Changchun, China	unknown	unknown	PMT	HP5370B	Jan-Feb 1997: No data; 18-Aug-1997: C-SPAD replaces PMT, new MET, new time and frequency device, new survey
Shanghai, China	China	unknown	SPAD	HP5370B	01-Oct-1997: installed crystal oscillator
Grasse, France	unknown	unknown	PMT	SR620	04-Sep-1997: CSPAD installed, CoM changed by 3.3mm
Herstmonceux, United Kingdom	Nimbus	Yes	SPAD	SR620	17-Apr-1997: new cal target 04-Jun-1997 new MET 22-Oct-1997: swapped SPADs
Zimmerwald, Switzerland	Digiquartz	Yes	PMT	SR620	01-Jan-1997: Laser change 532 to 423, 1.8 mm CoM change, new MET Jan-Jun 1997: only 9 LAGEOS passes 01-Jul-1997: Crystal oscillator installed 21-Dec-1997: changed to internal calibration; 2 detectors (PMT and SPAD) in use Note: No ITRF2020 residuals in 1997
Wettzell, Germany	Digiquartz	unknown	MCP & SPAD	unknown	
Orroral Valley, Australia	Weathertronics	Yes	PMT, APD, SPAD	Event Timer	02-Mar-1997: has 3 different detectors (PMT, APD and SPAD1) 15-Apr-1997: new APD installed
Riyadh, Saudi Arabia	Weathertronics	Yes	CSPAD	EOS Event Timer	
Potsdam, Germany	Druck	Yes	PMT	SR620	

Legend
*
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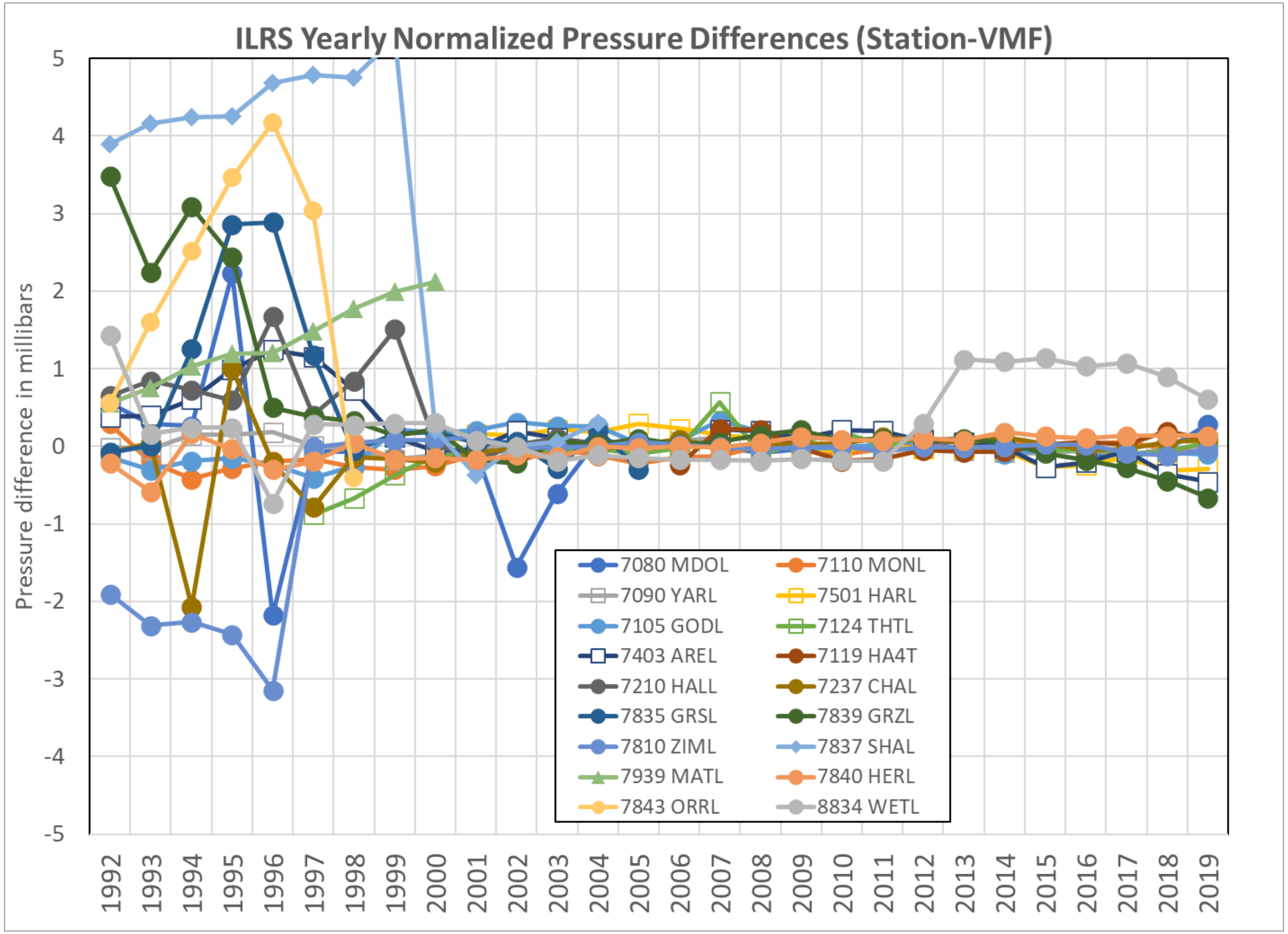
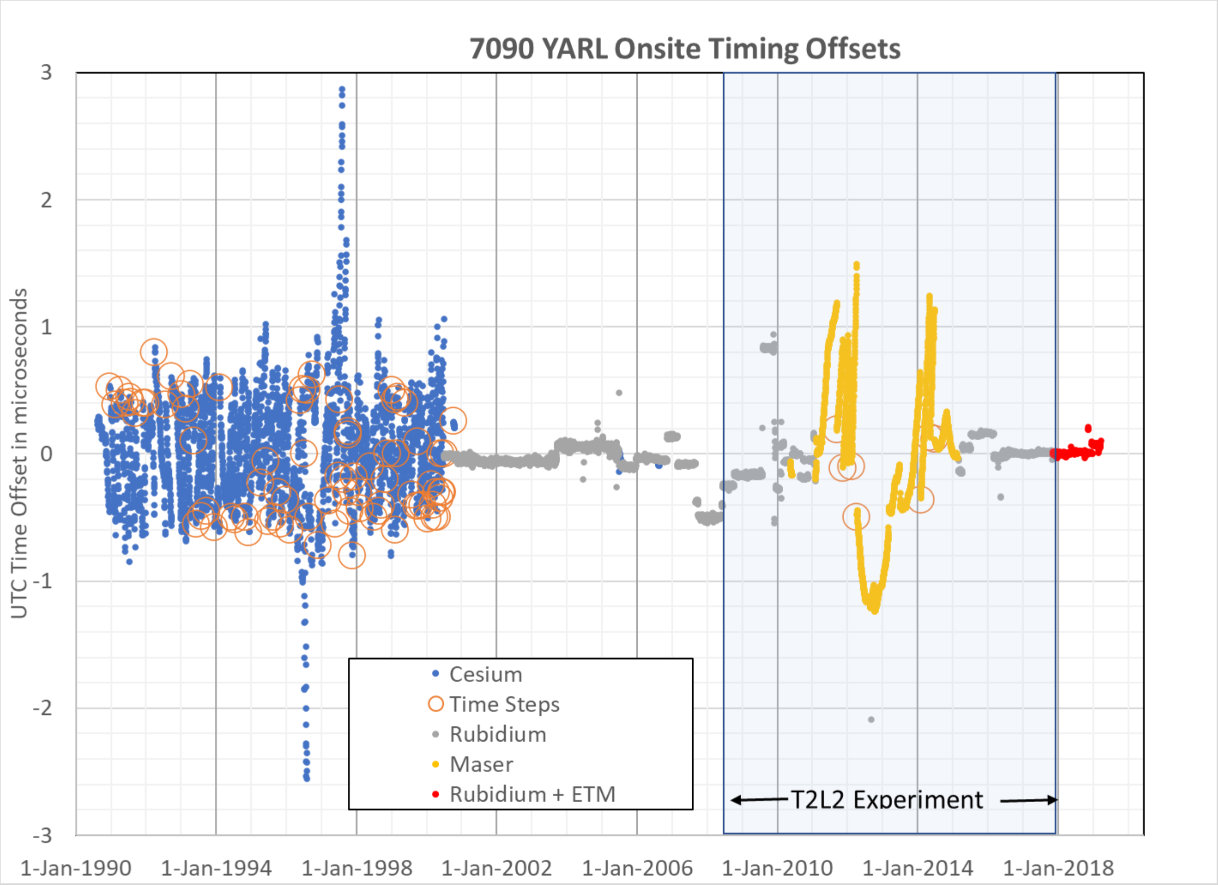
- **Listed here are key hardware components of the core sites in 1997 than can induce systematic errors (Tropospheric, Epoch, Signal Strength, Timer Non-linearities)**
- **Legend: The lighter the shade of green, the increased potential for systematics**

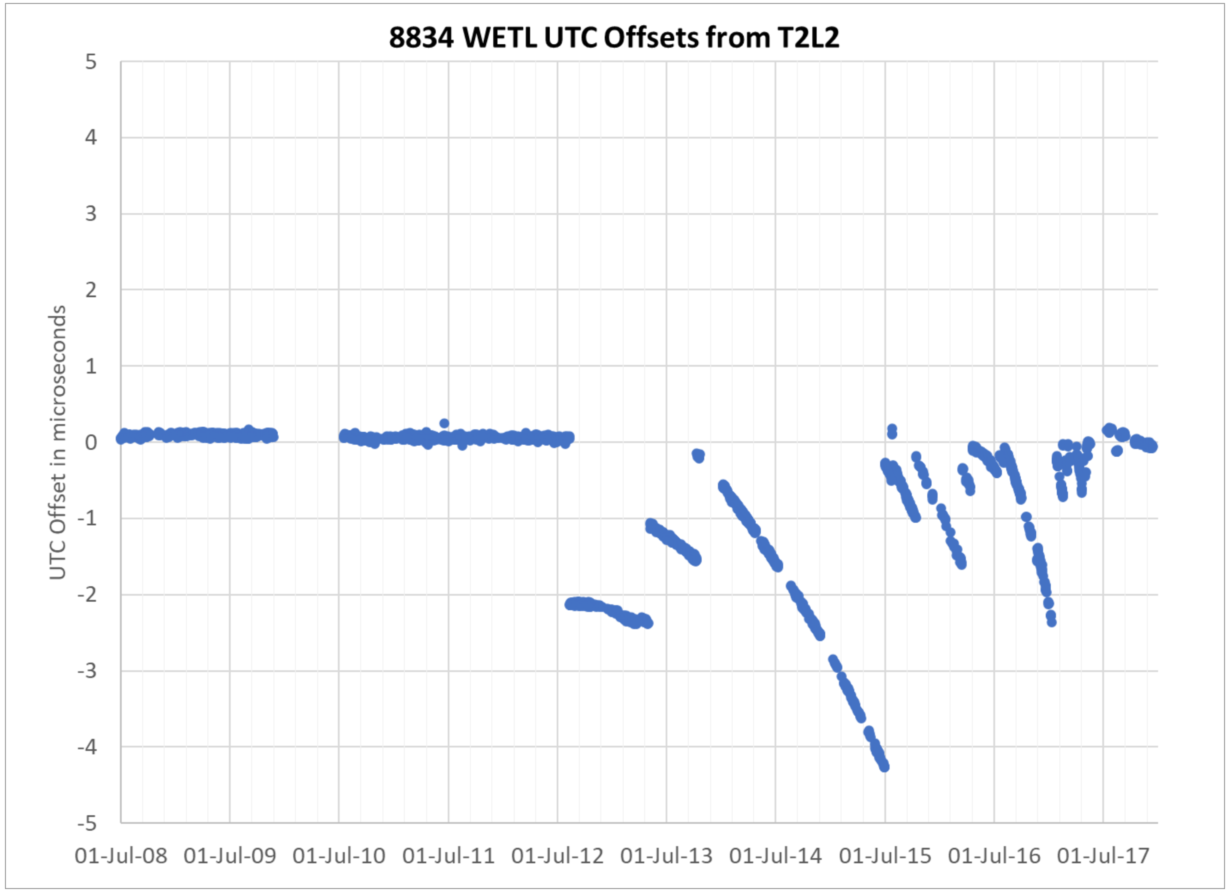
Tropospheric Biases in SLR Core Sites



- A yearly time series of barometric errors in our core sites from 1992 to August 2019 based on comparing station's barometric data to the Vienna Mapping Function for optical frequencies (VMF3o)
- VMF3o is based on Numerical Weather Models (NWMs) provided by the European Centre for Medium-Range Weather Forecasts (Boisits et al., 2020) DOI:10.1007/s00190-020-01385-5

Epoch Errors

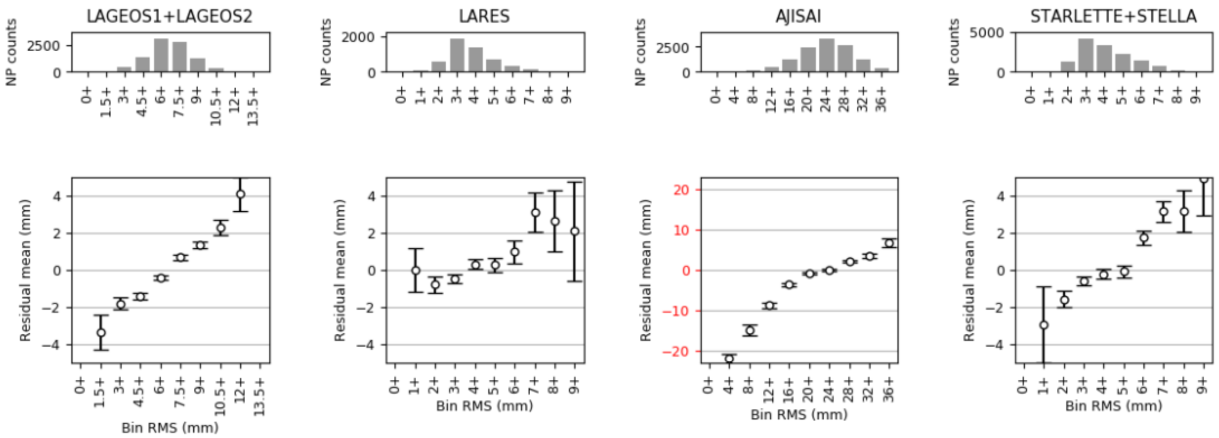




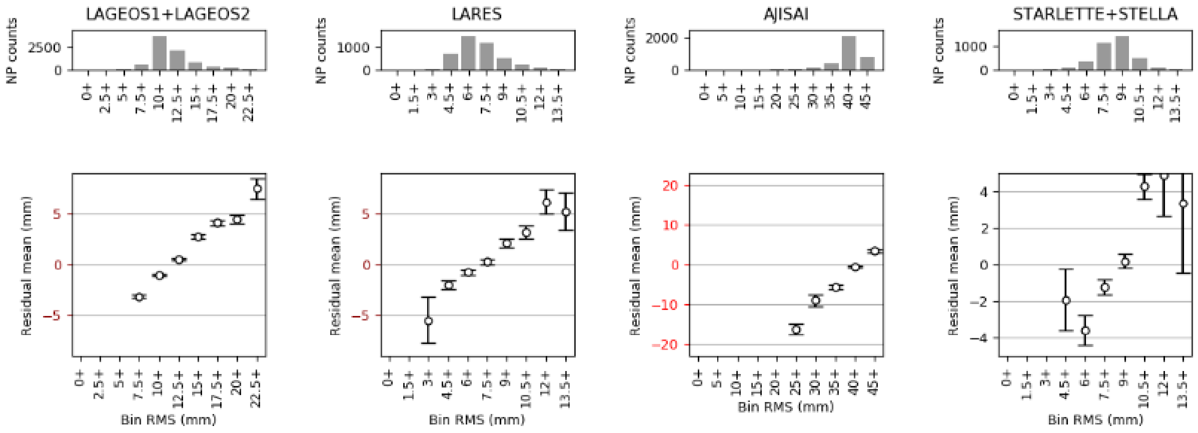
- 7090 and 8834 epoch errors are based on onsite timing data and Time Transfer by Laser Link (T2L2) data (Exertier et al., 2017; https://doi.org/10.1016/j.asr.2017.05.016); respectively
- Some frequency devices were/are synched to GPS and some were/are not
- 7090 epoch were distributed around 0, but not 8834. Are the accuracy of epochs known before and after T2L2?

Detector Systematics

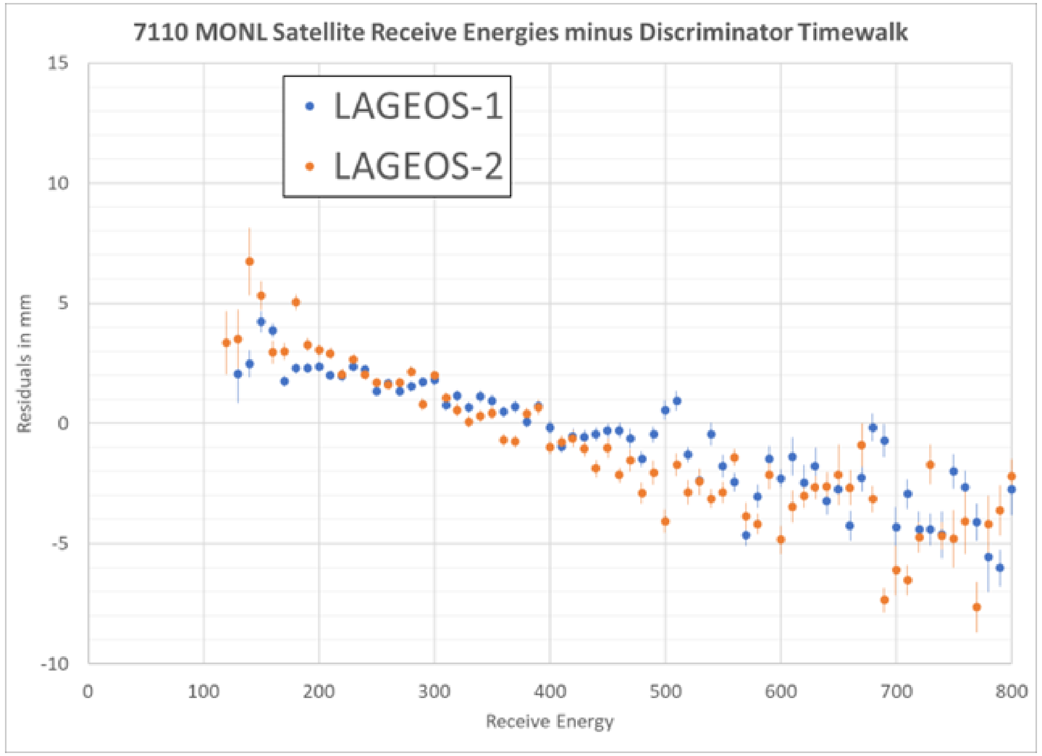
7825: wrt Single-Shot RMS **Mt. Stromlo: C-SPAD**



7840: wrt Single-Shot RMS **Herstmonceux: SPAD**

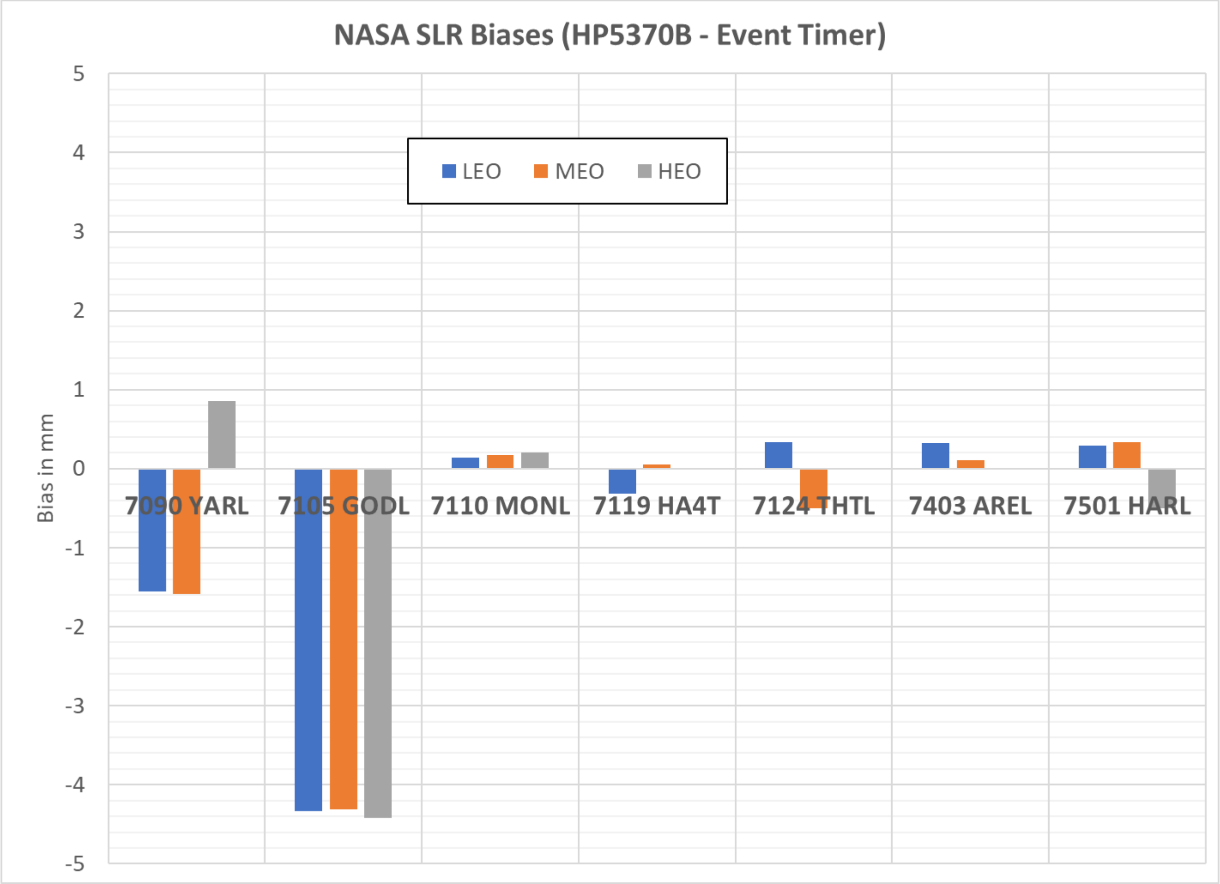


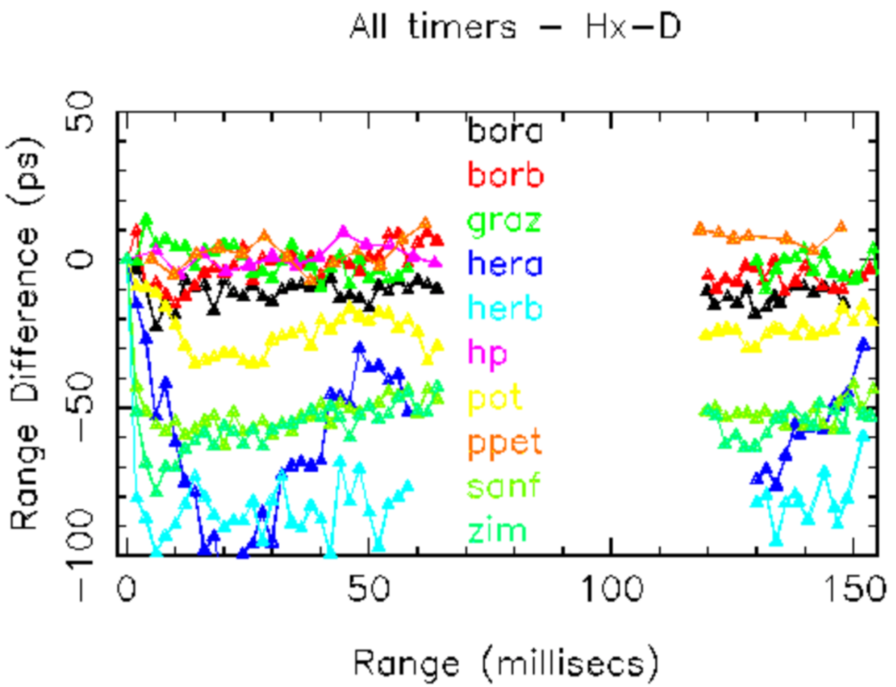
Monument Peak: MCP-PMT



- **SPAD (Otsubo, 2018) and MCP-PMT detector systematics on the left and right; respectively**

Timer Systematics





- HP5370B (Varghese et al., 2019) and SR620 (Gibbs et al., 2002) Time Interval Unit (TIU) range biases on the left and right; respectively

Conclusions

- **Items one and two below have had the most significant impact on ITRF2020 SLR Scale results**
    1. Changes in the SLR satellite constellation
    2. Spatial and temporal tracking outages from the ILRS Core sites
    3. Unmodelled systematic errors (e.g. tropospheric, epoch, amplitude variations, counter non-linearities) in the Core sites

SPAD LAGEOS RMSs vs Range

Van Husson

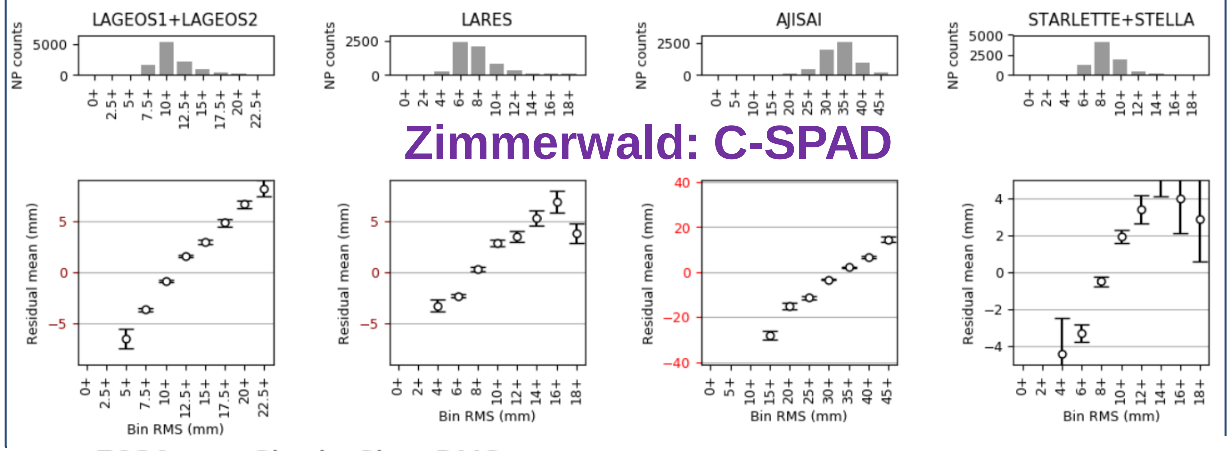
ILRS QCB

March 2023

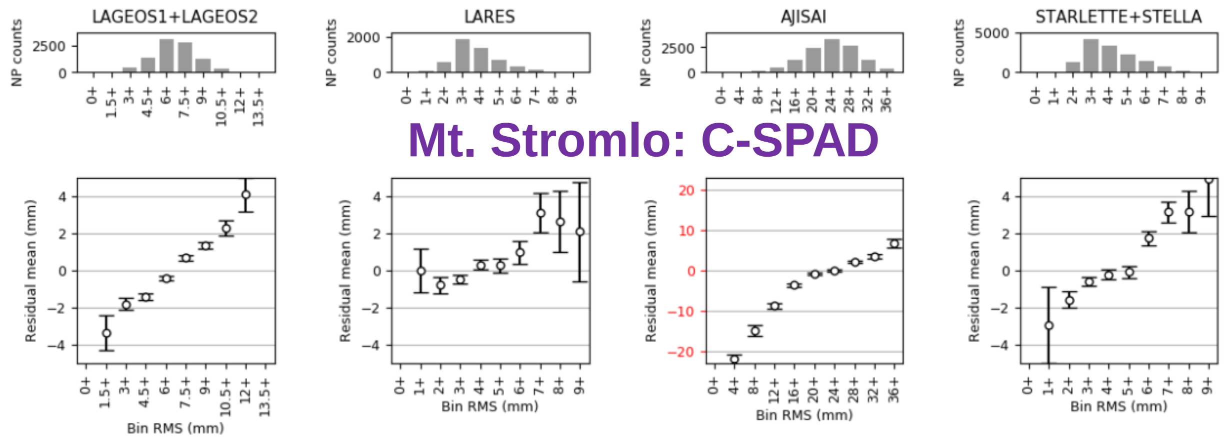
Peraton

Background: Range Residual and Single Shot RMS Dependency with SPAD Systems

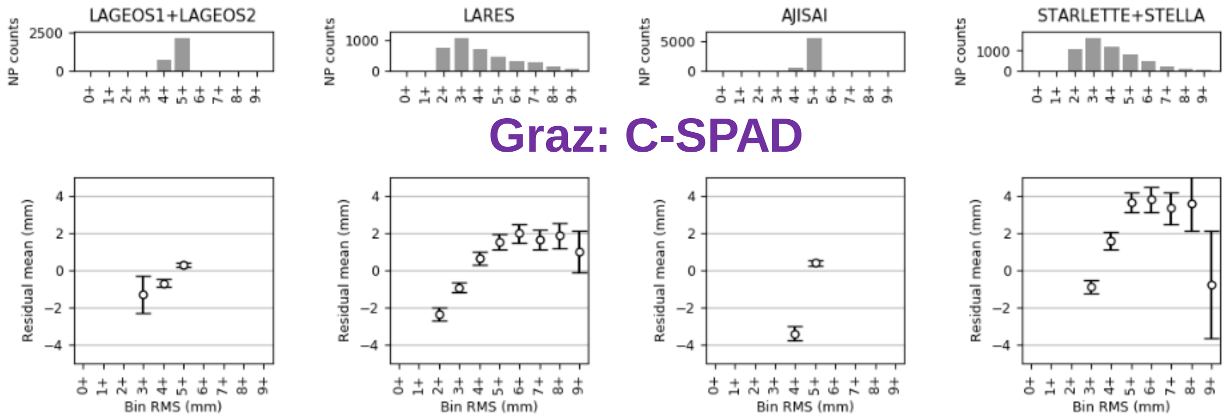
7810: wrt Single-Shot RMS



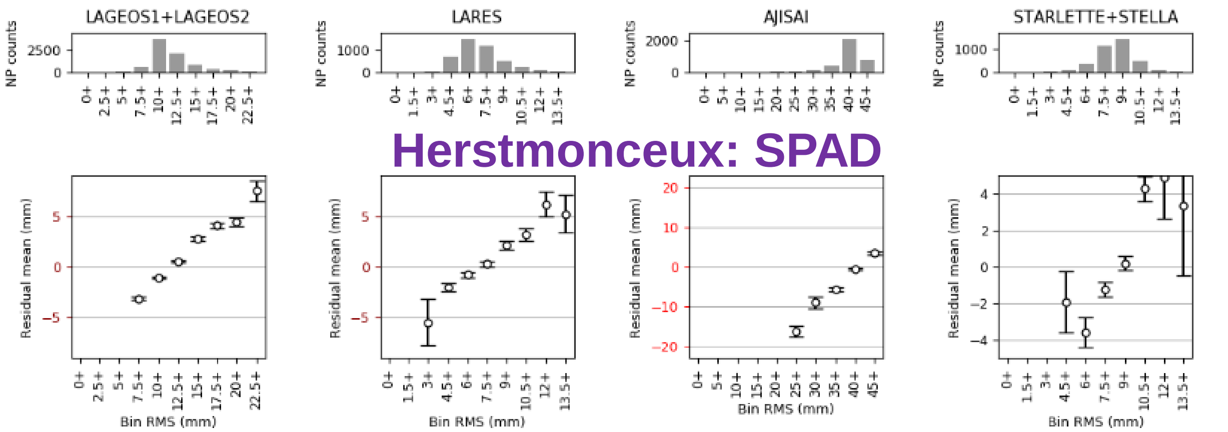
7825: wrt Single-Shot RMS



7839: wrt Single-Shot RMS

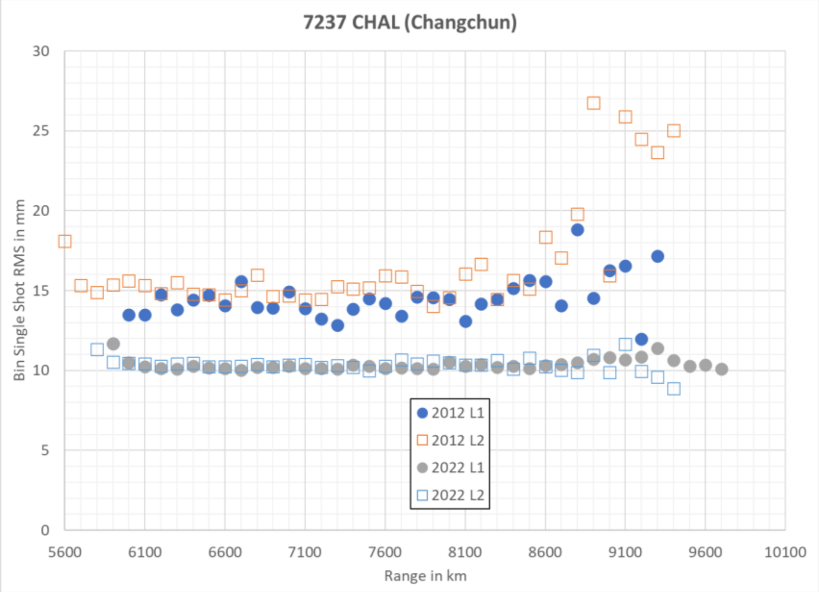


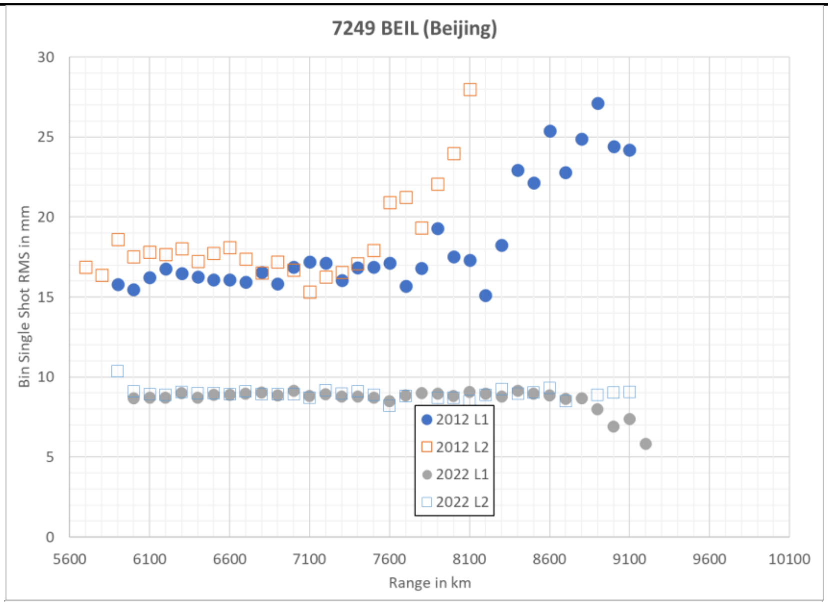
7840: wrt Single-Shot RMS

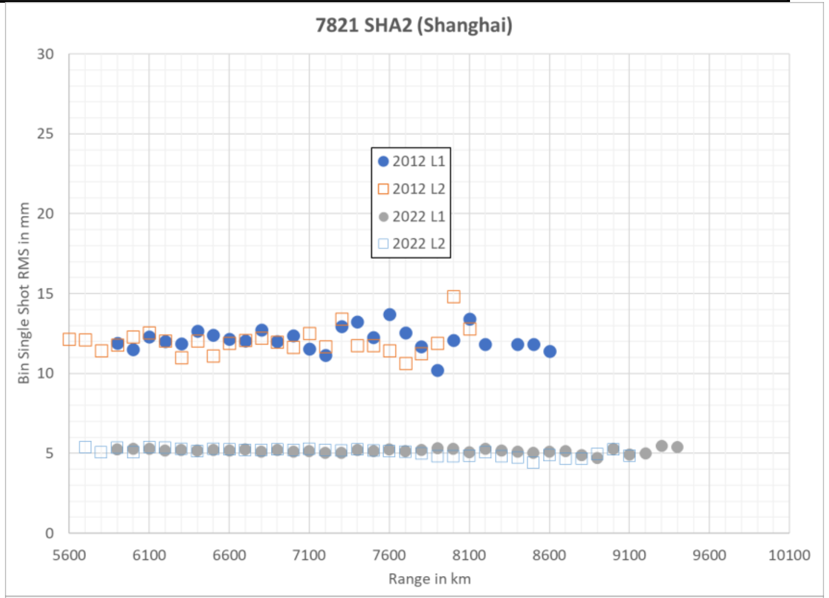


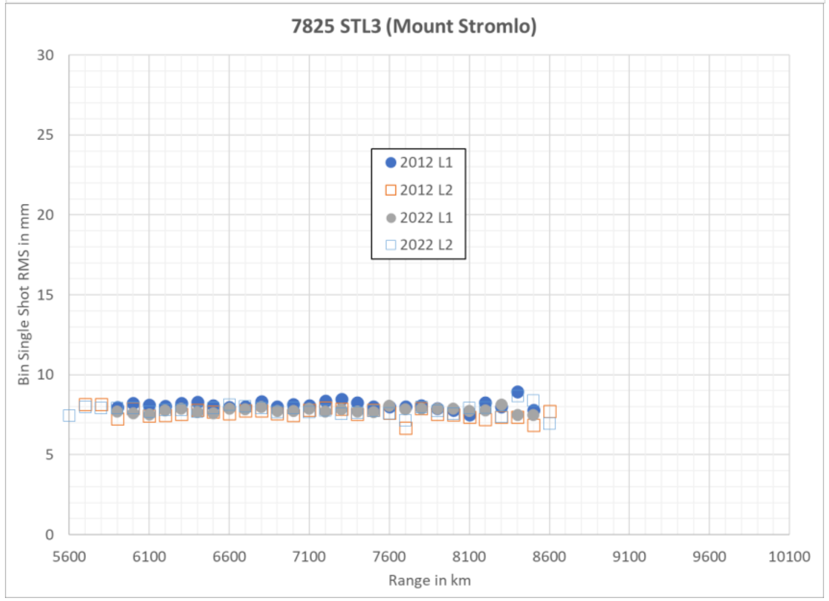
- ❑ **This slide based on Toshi's yearly aggregate analysis was presented at the June 2021 QCB meeting, which begs the question is the LAGEOS RMS dependency elevation dependent for this type of detector?**

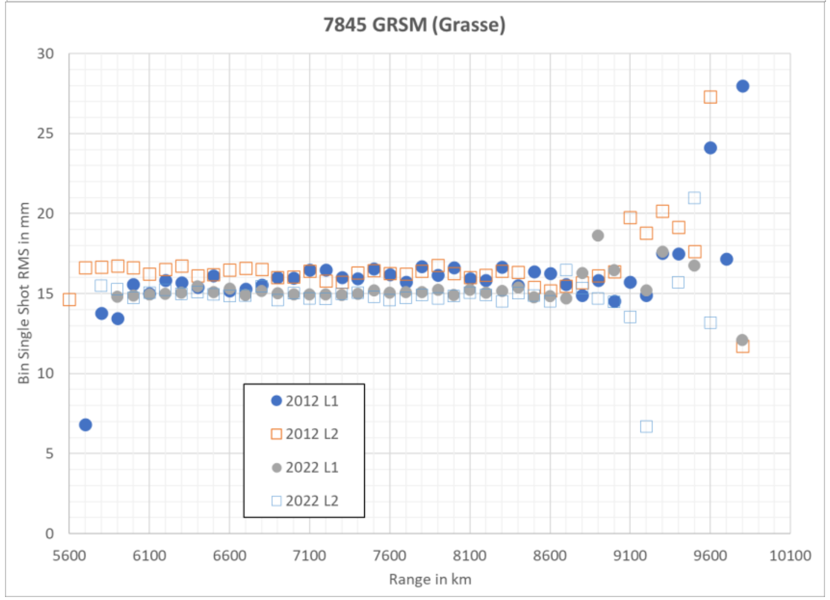
2012 and 2022 LAGEOS Bin RMSs vs Range

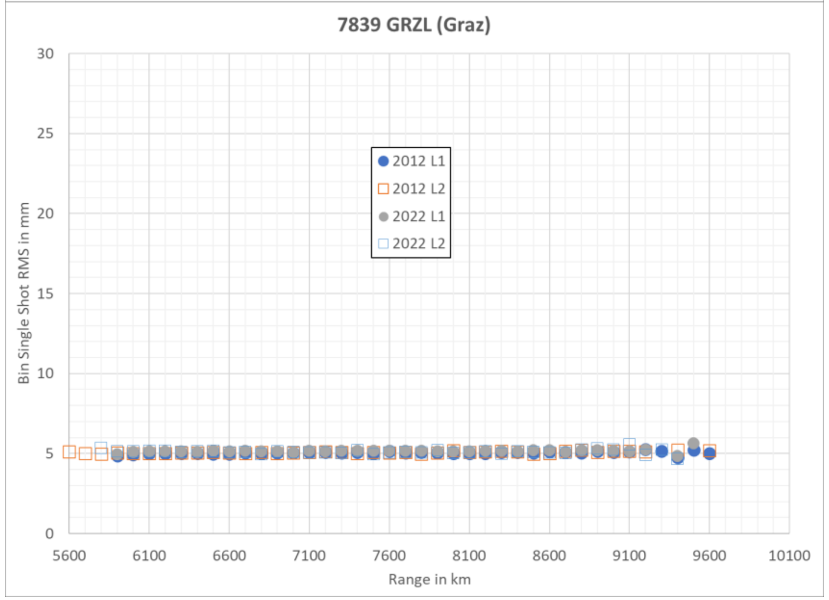




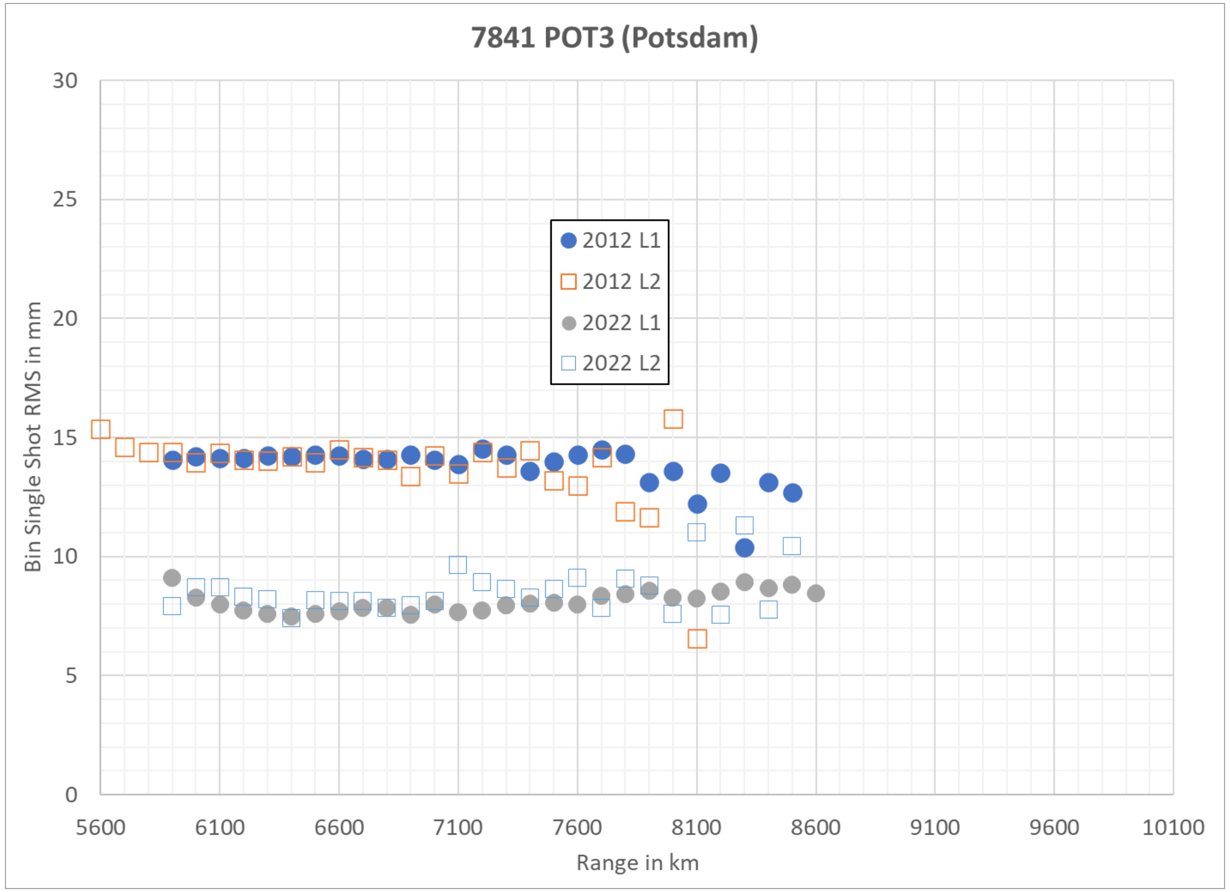


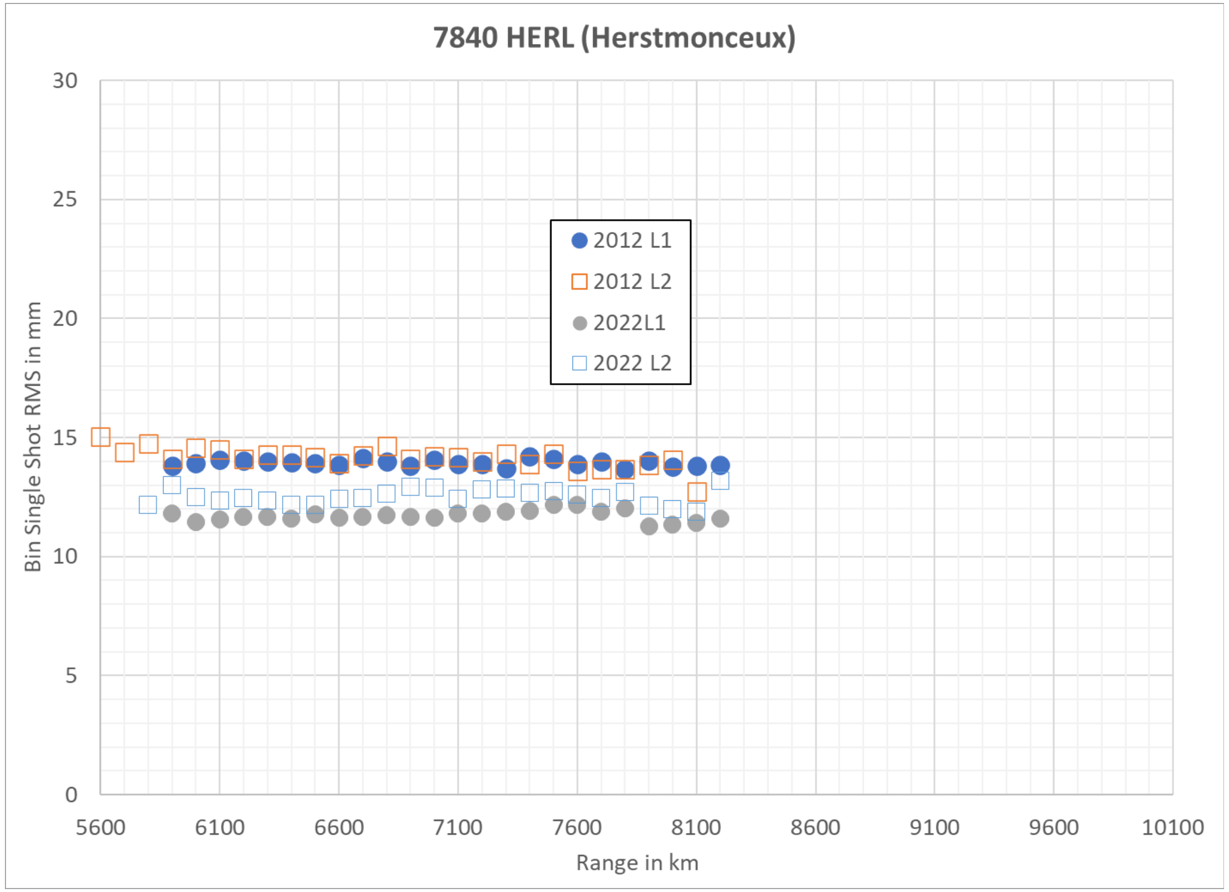






2012 and 2022 LAGEOS Bin RMSs vs Range





Conclusions

- There is no dependency between LAGEOS single shot RMS and range
- Of the eight systems shown, two (Shanghai and Graz) have employed 2 cm LE filtering on LAGEOS
- Some of these systems track LAGEOS well below 20 degrees
- Herstmonceux is the only system which shows a clear distinction between LAGEOS-2 and LAGEOS-1 RMSs in 2022