# NASA SLR SYSTEMATIC ERROR ANALYSIS

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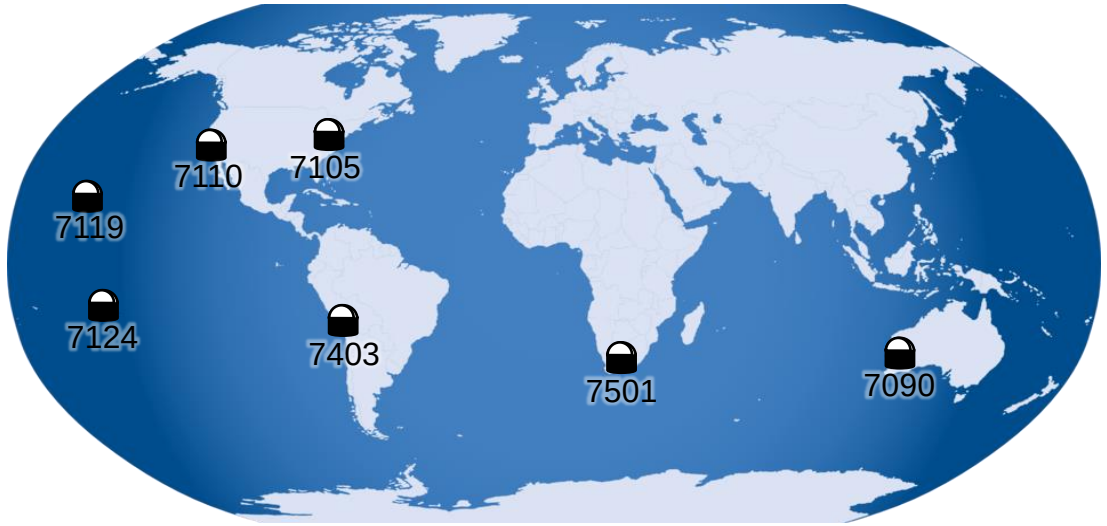
# Current Active NASA SLR Systems in ITRF2020

- **MOBile LAser ranging Systems 4-8 (MOBLAS 4-8):**
  - MOBLAS 4 at Monument Peak, USA (7110, MONL);
  - MOBLAS-5 at Yarragadee, Australia (7090, YARL)
  - MOBLAS-6 at Hartebeesthoek, South Africa (7501, HARL)
  - MOBLAS-7 at Greenbelt, USA (7105, GODL)
  - MOBLAS-8 at Tahiti, French Polynesia (7124, THTL)
- **Transportable Laser Ranging Systems 3-4 (TLRS 3-4)**
  - TLRS-3 at Arequipa, Peru (7403, AREL)
  - TLRS-4 at Haleakala, USA (7119, HA4T)

MOBLAS-7 (7105 GODL) in Greenbelt




TLRS-3 (7403 AREL) in Arequipa

# The SLR System, Subsystems and Components

| Sub-System | Major Component | Sub-Component | Contributes to: | | Bias Characteristic |
|---|---|---|---|---|---|
| | | | NP Jitter | Bias | |
| Local Survey | Calibration Range, System Eccentricities | | No | Yes | Fixed |
| Ranging Machine | Laser (Transmitter) | | Yes | Yes | Fixed |
| | Receiver | Detector Package | Yes | Yes | Fixed |
| | | Time of Flight Device | Yes | Yes | Fixed |
| | Time and Frequency | Frequency Device | No | Yes | Range |
| | | Epoch Timing | No | Yes | Range-Rate |
| | Meteorological System | Sensors | No | Yes | Elevation |
| | Mount/Telescope | Optics/Filters | No | Yes | Fixed |
| | Controller Computer | | N/A | N/A | N/A |
| | Data Reduction | Data Smoothing, Outlier Rejection, NP Creation | Yes | Yes | Fixed |
| | Calibration Target/ Procedures | | No | Yes | Fixed |
| | Aircraft Detection | | N/A | N/A | N/A |
| Geodetic Satellites | Retro-Reflector Array (RRA) | | Yes | Yes | Fixed |
| Data Analysis | Precise Orbit Determination Software | RRA Correction | N/A | Yes | Fixed |

- **Not all components contribute to SLR Norma Point (NP) jitter, but most components can contribute to a bias. SLR biases that are elevation, range or range-rate dependent are the worst types of biases because modeling with a fixed range bias will not remove all the systematics**

# NASA SLR LOCAL SURVEY SUB-SYSTEM

# NASA SLR Local Survey Introduction


Monument 7110

MOBLAS-4 @7110 Monument Peak, CA, USA

7110 Target A

7110 Target C

- **MOBLAS and TLRS occupy a brass monument embedded in the concrete pad. Surveyors indirectly determine the 3-dimensional offsets between the intersection of optical axes (the System Reference Point [SRP]) and the monument and determine the distance between the SRP and the calibration pier(s). The absolute accuracy of the calibration distances from the SRP is 1 to 2 mm. Unfortunately, the SRP and calibration piers are not stable.**
- **For example, 7110 Target A and C distances changed by a few mm in opposite directions between the November 2011 and the May 2018 local survey.**

# THE NASA SLR RANGING MACHINE SUB-SYSTEM

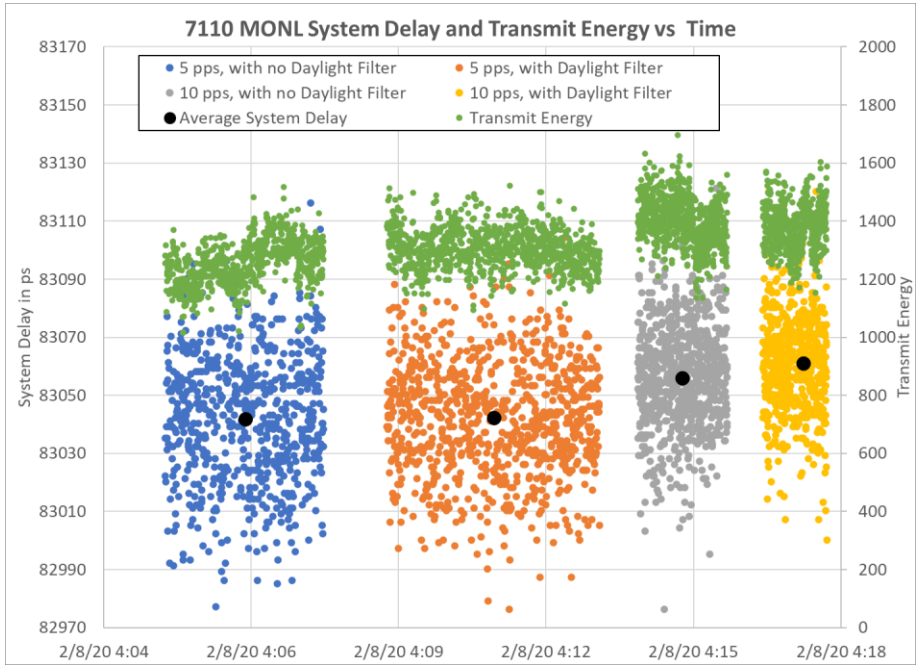
# History of SLR Accuracy Goals and Corresponding NASA SLR Component Upgrades

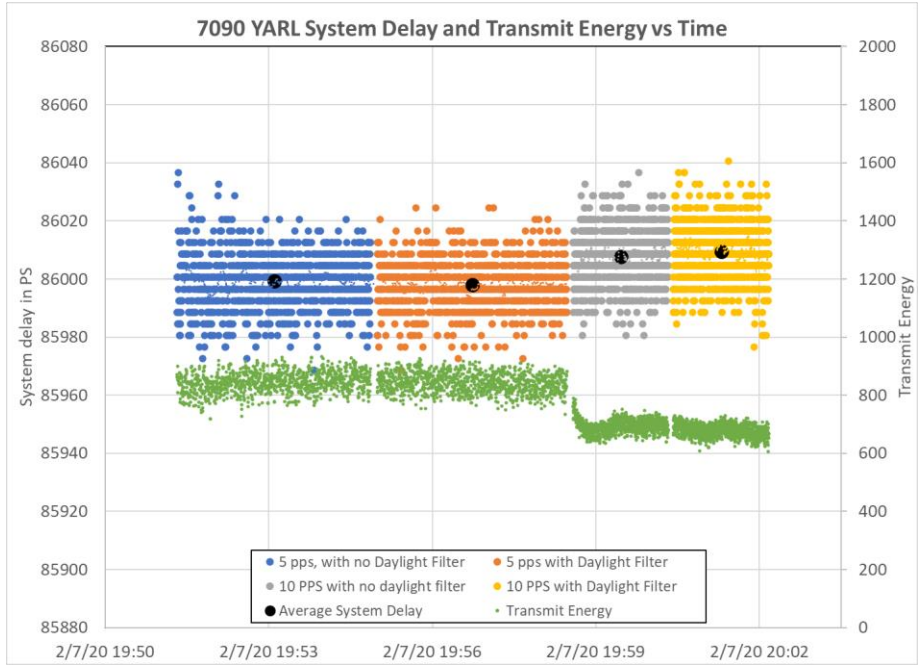
- **The Crustal Dynamics Project (CDP)/NASA SLR accuracy goals were 1 cm in the early to mid 1980's**
- **Geodetic Global Observing System (GGOS) reference frame accuracy requirement is 1 mm and 0.1 mm/year stability [Pearlman, 2013]. Based on these goals, the ILRS derived a requirement that all SLR components be calibrated to sub-mm accuracies [Prochazka, 2015]**

| Period | Laser/Controller | Receiver/ Mode of Operation | Time/ Frequency | Cal Target Range/Type | Met System | Total Component Systematics |
|---|---|---|---|---|---|---|
| 1979-1983 | Non-mode Locked | PMT, HP5370A, CFD, Multi-photon | Loran-C/ Cesium | 2-3 km, board | Setra | 5-10 cm, <2 µs |
| 1983-1987 | **Mode Locked (5Hz)** 200 ps pulse width | **MCP-PMT**, HP5370B | GPS/ Cesium | 2-3 km, prism on pier | | <=10 mm, <1 µs |
| 1987-1992 | | | | **200 m pier** | | <=9 mm, <1 µs |
| 1992-1995 | HEO Mods (4 Hz) | | | | **MET3** | <=6 mm, <1 µs |
| 1995-2001 | 10 Hz (MOBLAS LEOs only) | 2nd Receiver (MOBLAS HEO only) | GPS/ **Rubidium** | | | <=6 mm, <.2 µs |
| 2001-2016 | 150 ps pulse width | MCP replacement | | | MET4 | <=6 mm, <.2 µs |
| 2016 to … | 10 Hz (LAGEOS) | **1 ps Event Timer** | | | | <=3 mm, <.7 µs |

# Laser Systematics (Ranging at 5 and 10 MHz)

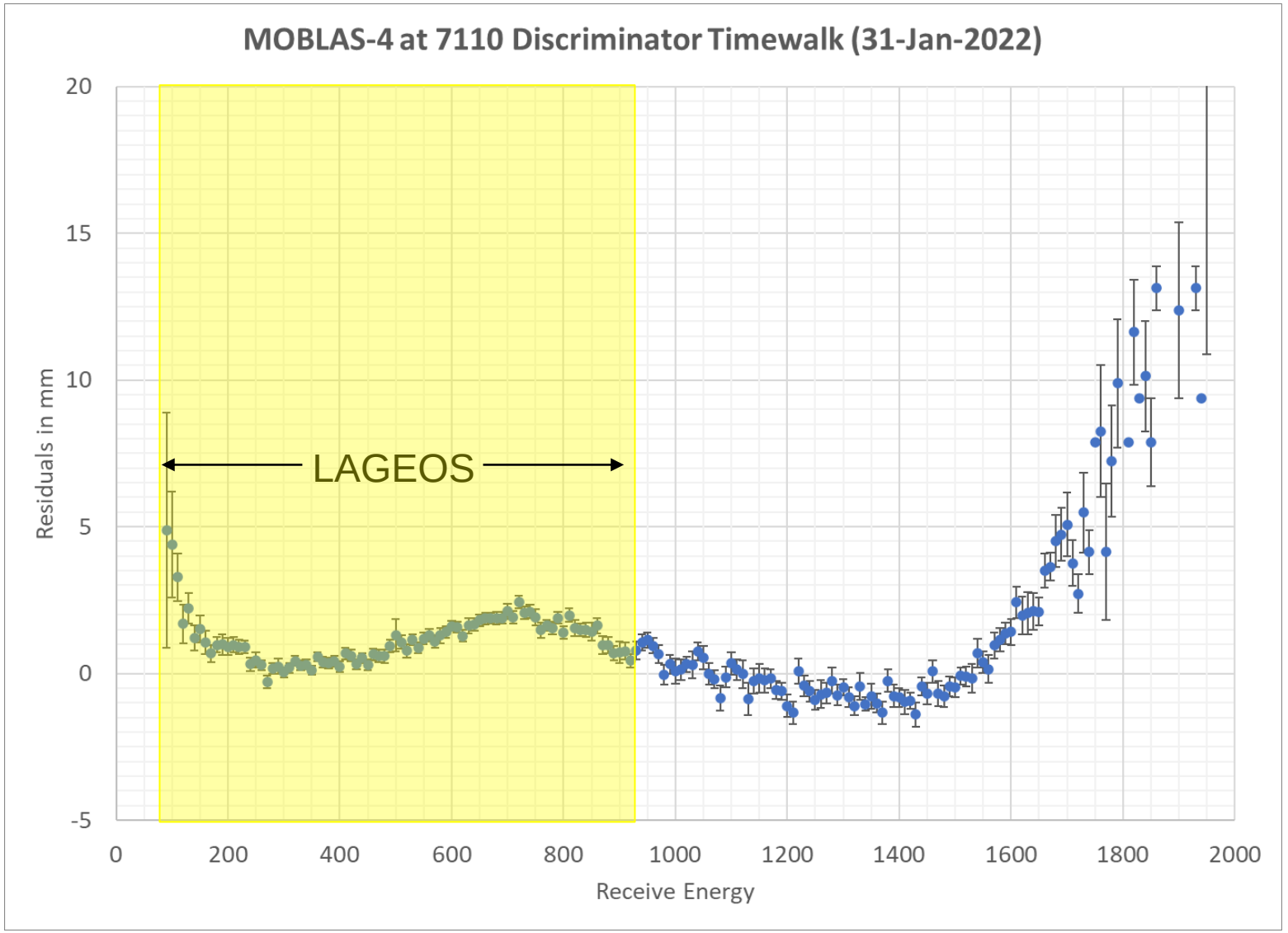
| | Calibration & LEO | LAGEOS | HEO |
|---|---|---|---|
| Pre Event Timer Module (ETM) | 10 Hz | 5 Hz | 4 Hz |
| Post Event Timer Module (ETM) | 10 Hz | 5 and/or 10 Hz | 4 and/or 5 Hz |



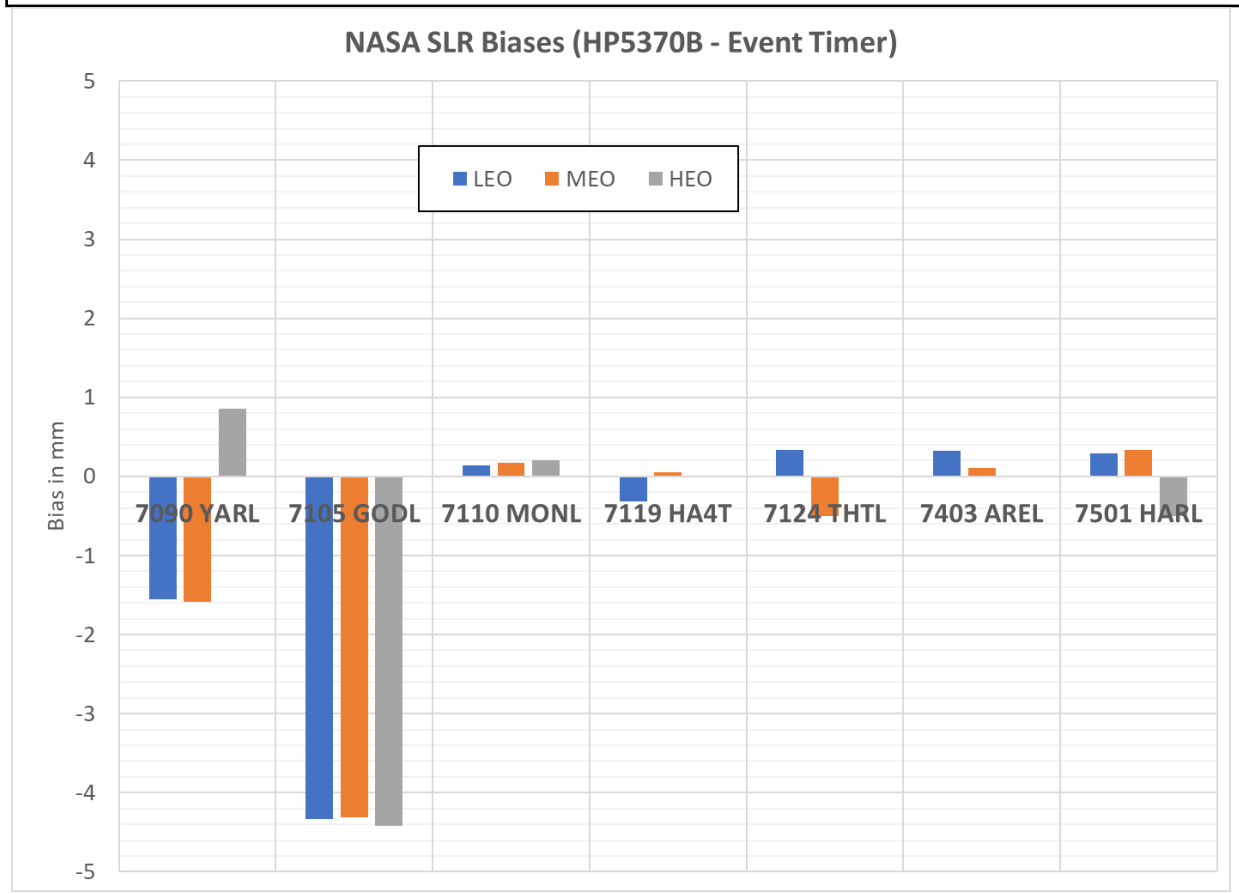

- **The laser beam divergence and transmit energy can only be optimized at one fire rate. These two charts are a time series of 7110 & 7090 system delays and laser transmit energies from a ground calibration. The 7110 & 7090 system delay differences between 5 and 10 Hz ranging were 2.5 and 1.4 mm; respectively.**

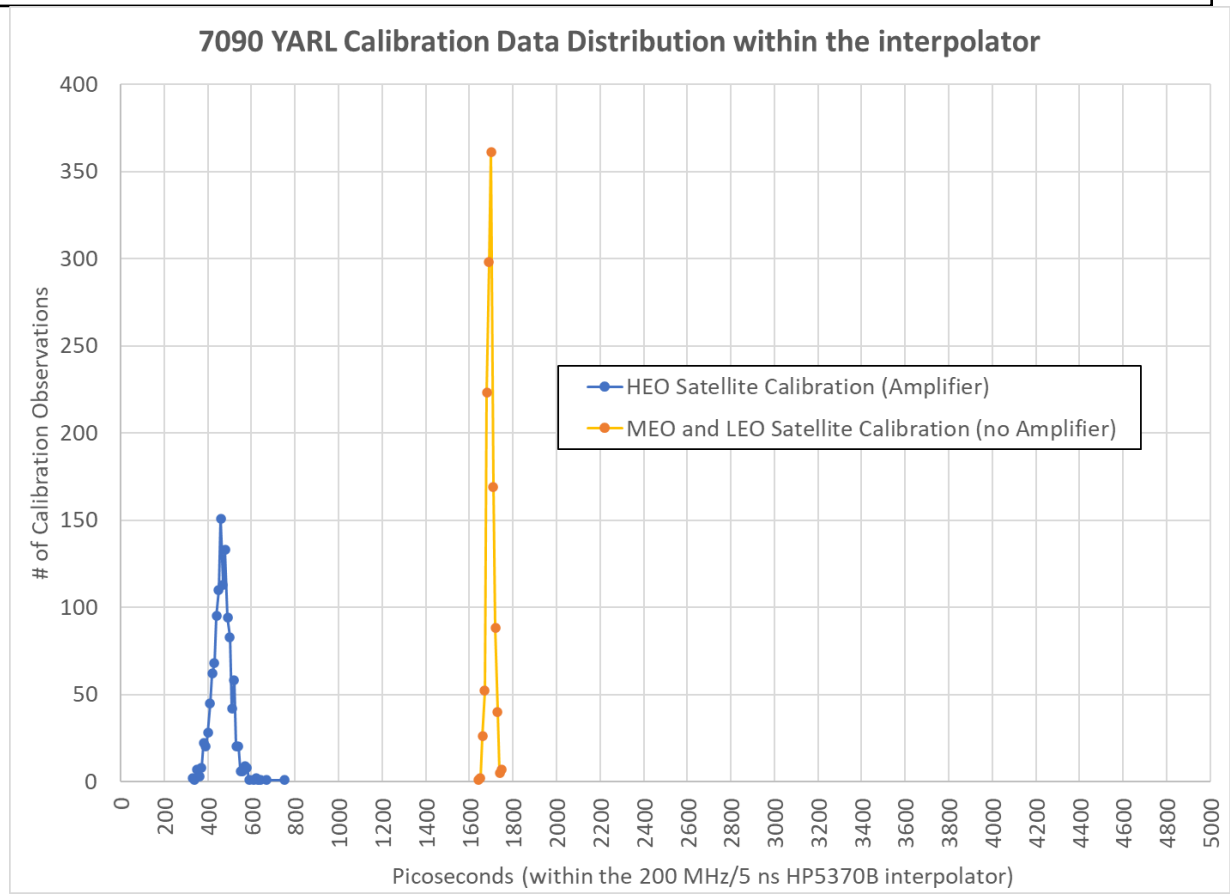
# Detector Package Systematics (Receive Signal Strength)




- In the MOBLAS, receive energy is measured by a quad integrator and is the area under a curve.
- Discriminator tests are designed to sample receive energies across the full dynamic range of the receive Constant Fraction Discriminator (CFD).
- The CFD triggers on the centroid of the received pulse.
- The 'linear' portion of the CFD is where the receive energy is < 1500.
- 7110 MONL LAGEOS returns are less than 900.

# Time of Flight (ToF) Device Systematics
# HP5370B & Event Timer Module (ETM) Comparisons



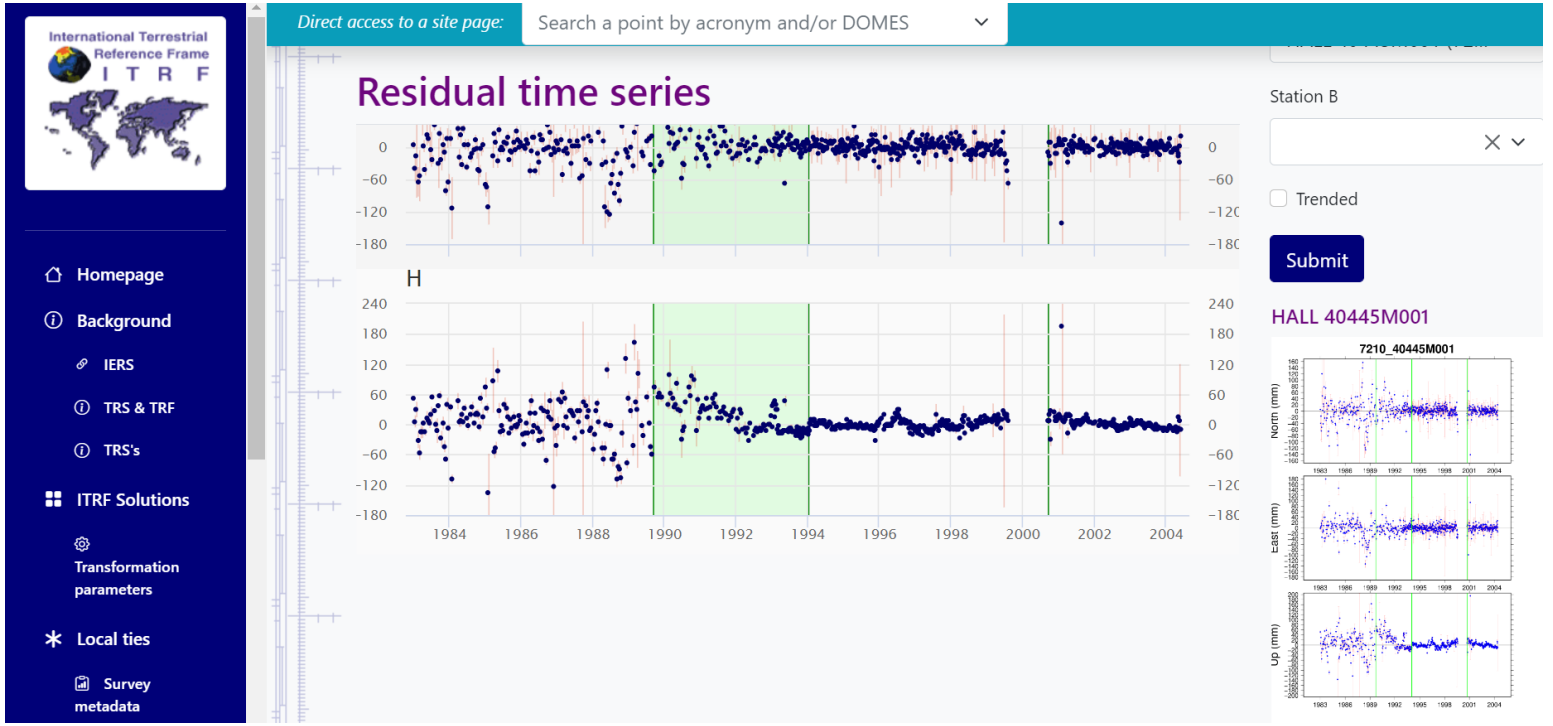




- ❑ **Millimeter level non-linearities exist within the HP5370B 200 MHz interpolator. ETM non-linearities are < 1 mm.**
- ❑ **Left chart: NASA SLR HP5370B versus ETM results [Varghese, 2020]; 7124 results [Pavlis, 2021; Husson, 2021]**
- ❑ **Right Chart: 7090 YARL HEO and LEO/MEO calibration returns within the 200 MHz HP5370B interpolator. Satellite returns are randomly distributed within the interpolator, but calibration returns are not.**
- ❑ **During these comparisons, Stations 7090, 7110 and 7501 used its second receiver chain to track HEOs, where 7105 did not.**

# Frequency Device Systematics
# SLR Frequency Error Analysis

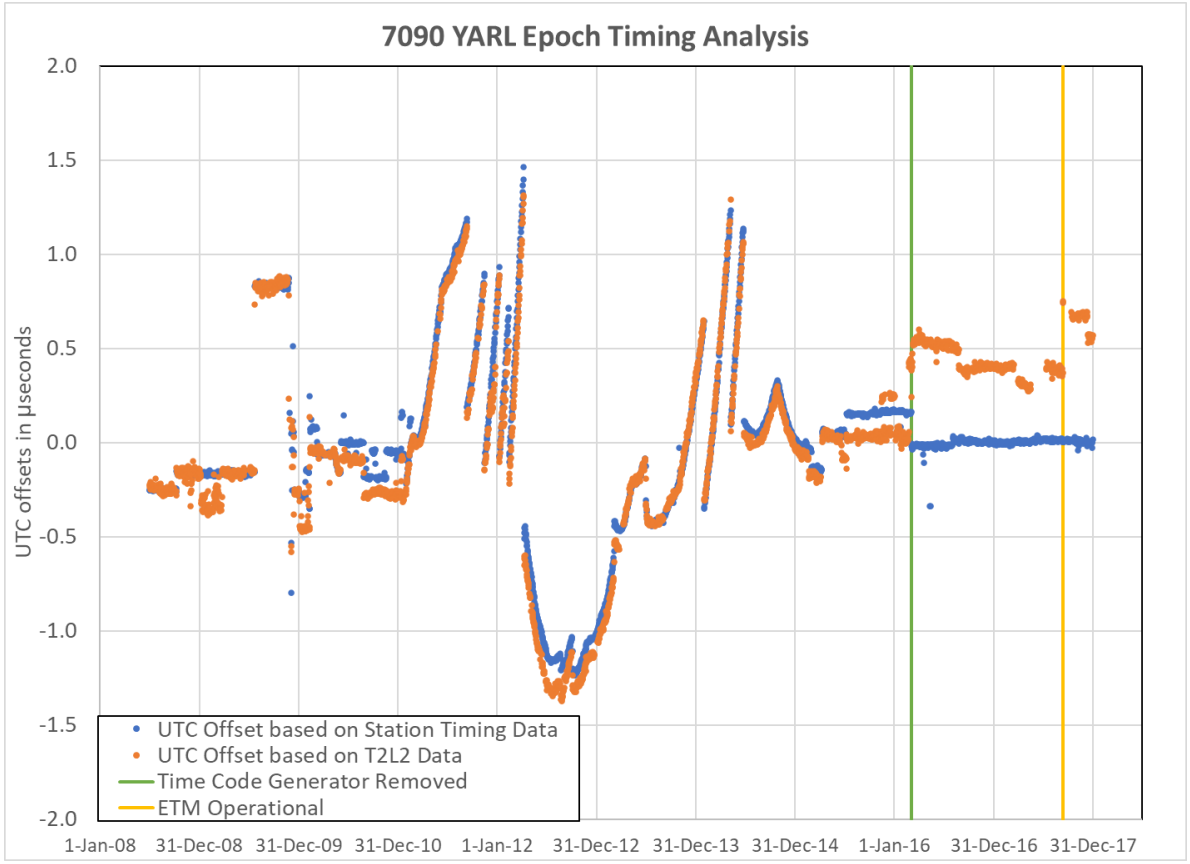
| Freqeuncy Error | LEO (26ms) | LAGEOS (65ms) | Etalon (155ms) |
|---|---|---|---|
| 1.00E-08 | 38.973 | 97.433 | 232.339 |
| 1.00E-09 | 3.897 | 9.743 | 23.234 |
| 1.00E-10 | 0.390 | 0.974 | 2.323 |
| 1.00E-11 | 0.039 | 0.097 | 0.232 |
| 1.00E-12 | 0.004 | 0.010 | 0.023 |
| 1.00E-13 | 0.000 | 0.001 | 0.002 |

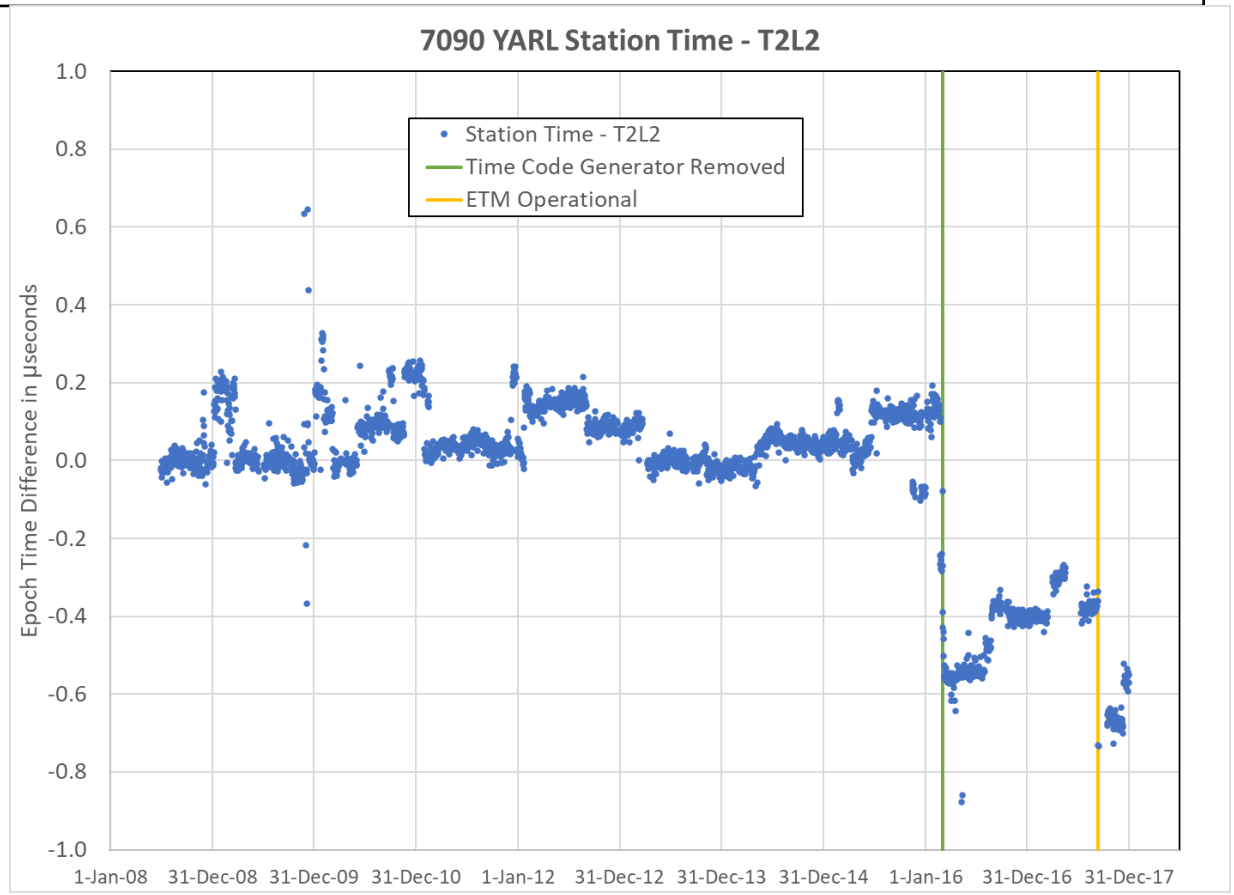
| Legend |
|---|
| >10 mm |
| >1 mm but < 10 mm |
| >0.1 mm but <1 mm |
| <=0.1 mm |




- The table on the left shows the impact in mm of a frequency error by satellite type
- Frequency accuracy of 1 part in 100 billion ($1x10^{-11}$) are needed to keep the systematic error below 1 mm on all geodetic satellites. The current NASA SLR rubidiums provide output frequencies to an accuracy of $1x10^{-12}$ exceeding our goal.
- Solving for **only** a range bias will **not** eliminate the systematic trends caused by a frequency error. On the right chart are the ITRF2020 7210 HALL height residuals for station 7210. The period shaded in light green is when there was a known frequency error.

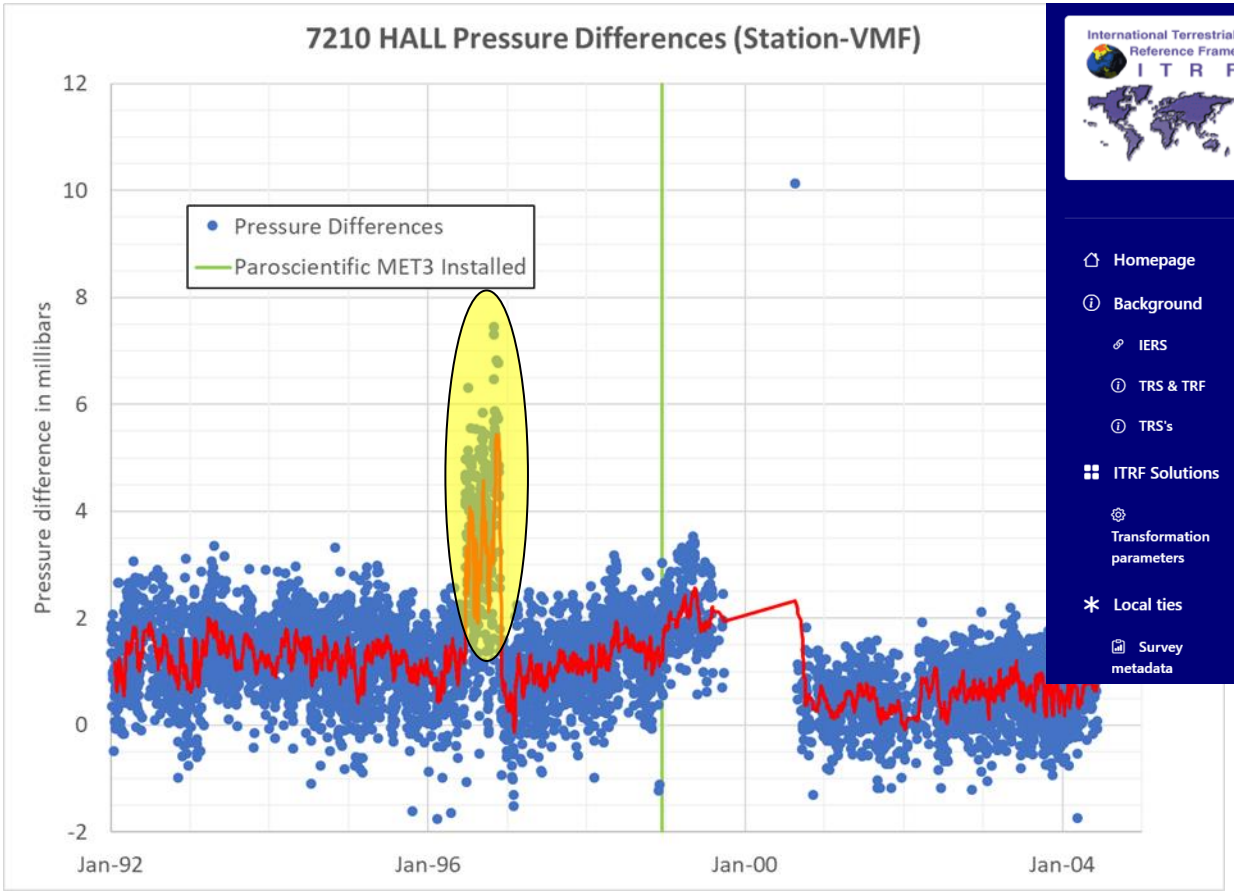
# Epoch Timing Systematics
# 7090 YARL Station Time relative to T2L2




- **The left chart are the 7090 UTC offsets based on Time Transfer by Laser Link (T2L2) [Belli, 2018] and the 7090 station's daily timing data. The chart on the right are the differences between the two datasets. Prior to the removal of the Time Code Generator (TCG) in March 2016, the two datasets agreed to within 200 ns.**

# Meteorological Sensor Systematics
# Impact of an Unmodeled Tropospheric Bias








- **Solving for only a range bias will remove some but NOT all the systematic trends due to a tropospheric bias [Drożdżewski, 2021]. The highlighted area on the left chart indicates a sudden jump in the 7210 (HALL) barometric pressures of few hPa based on comparisons with the Vienna Mapping Function (VMF) [Boisits, 2020] data. The highlighted area on the right chart indicates the HALL (7210) ITRF2020 height residuals [Altamimi, 2022] for this same period.**

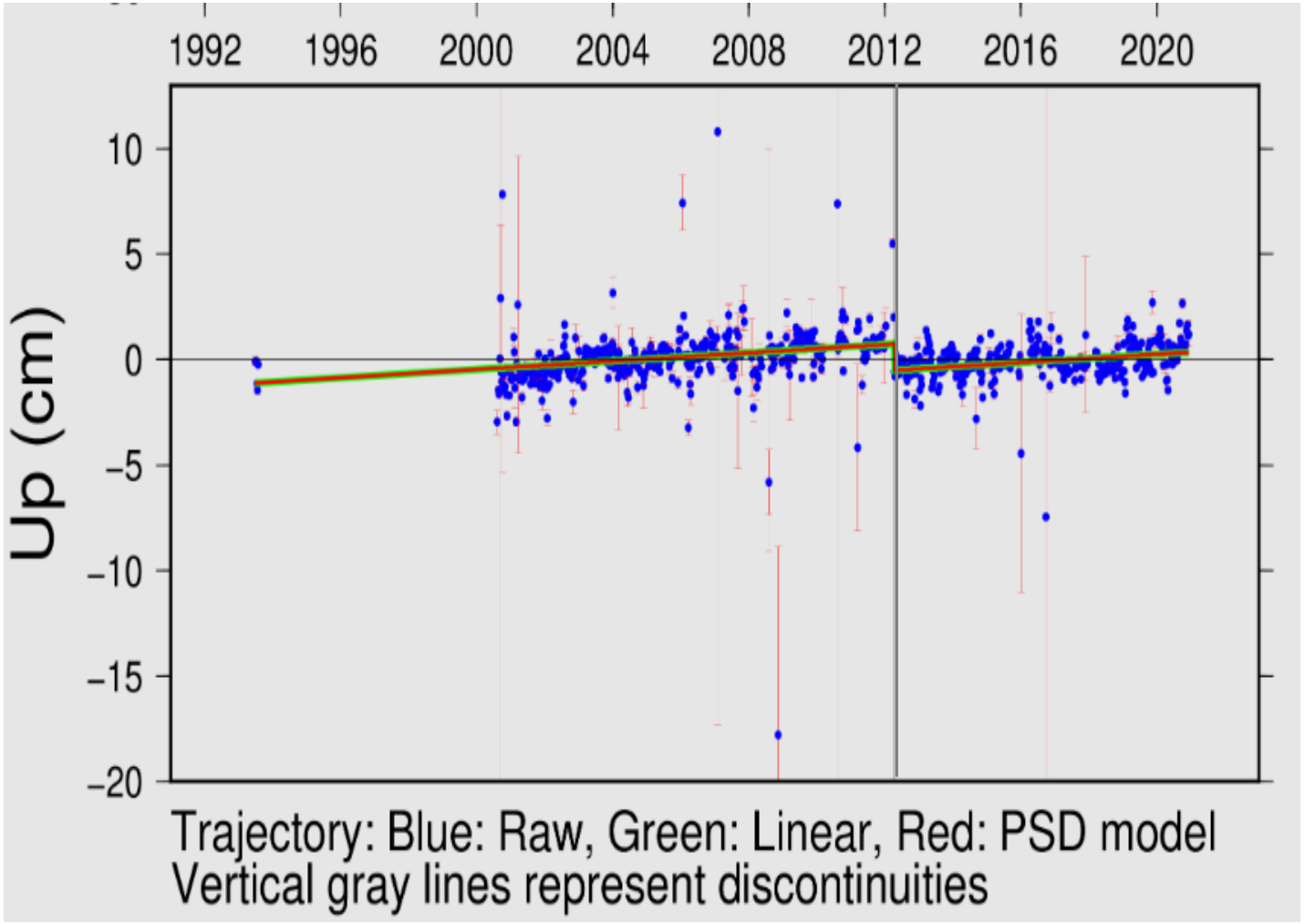
# Data Reduction Systematic
# NASA SLR Data Reduction Algorithms

- **System Delay (ps) = Cal ToF(ps) – Fn * (CalDis + Trans + ND)/(C/2)where**
  - Cal ToF is the measured round-trip Calibration Time of Flight based on constant fraction discrimination
  - Fn is the computed index of refraction based on the laser wavelength and local meteorological conditions
  - CalDis is the distance to the ground calibration target from the intersection of optical axes in mm based on the local survey
  - Trans is short for the Translator correction (distance divided by 2) for the MOBLAS systems in mm
  - ND is ¼ the thickness of the neutral density filters
  - C is the speed of light is mm/ps divided by two (0.299792458/2)

**Any errors in the CalDis, Trans or ND will induce a fixed range bias.**

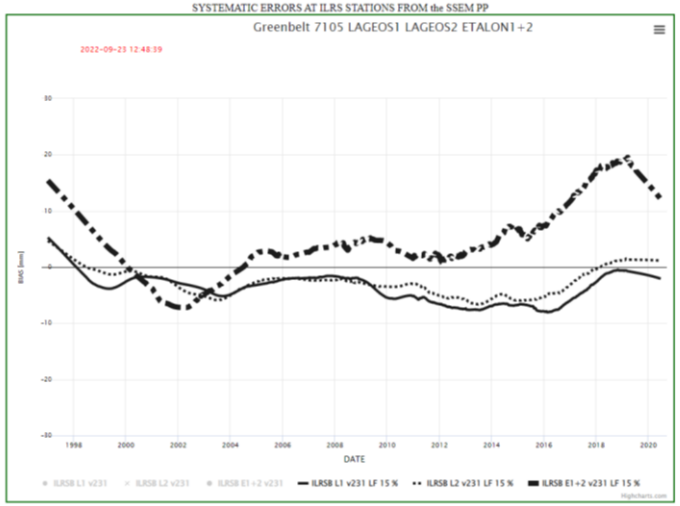
# Calibration Targets and Procedures Systematics
# MOBLAS-6 7501 HARL Changes in Calibration Targets

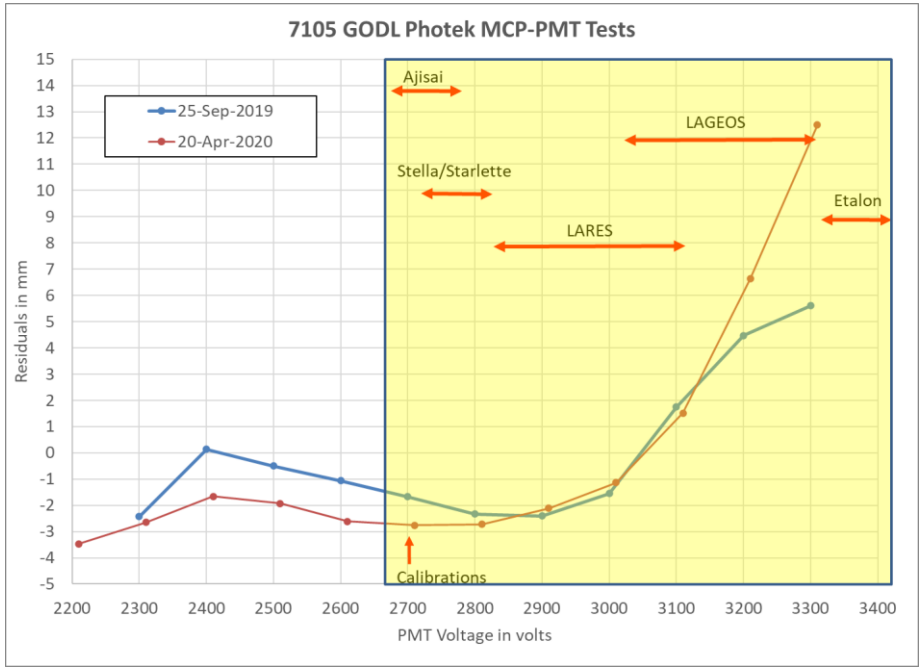
ITRF2020 7501 HARL Trended Station Height Residuals

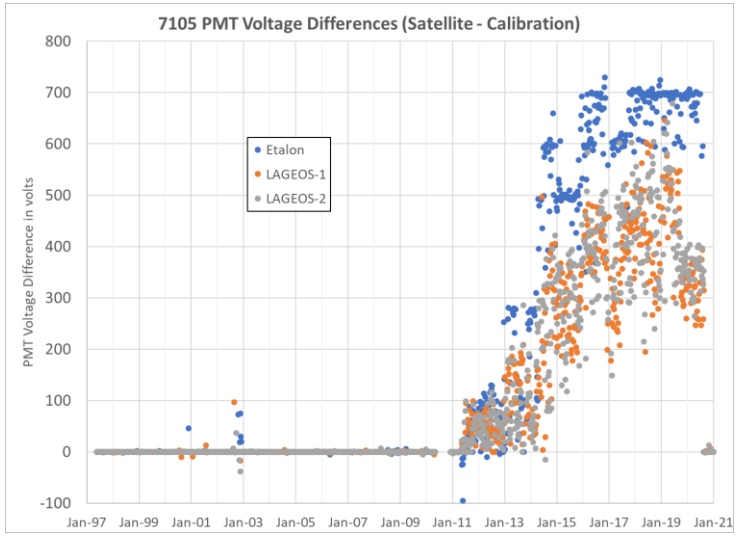



- **On 4-Apr-2012, 7501 HARL switched calibration targets which coincides with the unknown station height discontinuity shown here on this chart.**
- **Before the switch, a ground test was taken with a resultant 5.4 mm difference between these calibration targets.**
- *Note: The height residuals in 1993 were from the Dutch MTLRS-1, not MOBLAS-6.*

# Calibration Targets and Procedures Systematics (con't)
# Differences between Calibration & Satellite (PMT Voltage)



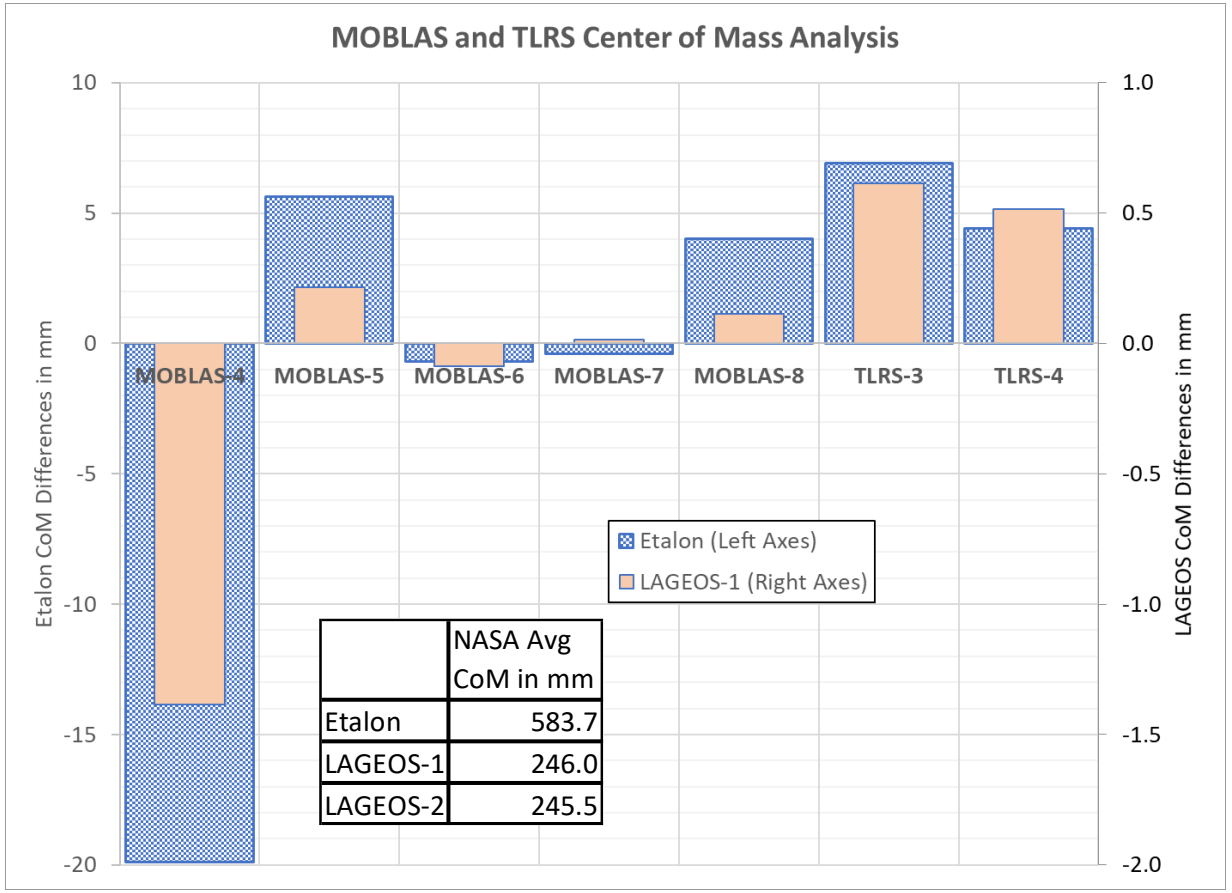




- Top Left Chart: Time Series of 7105 SSEM LAGEOS and Etalon Range Biases
- Bottom Left Chart: Time Series of Weekly 7105 PMT Differences (Satellite minus Calibration)
- Right Chart: 7105 PMT Voltage Characterization Tests.

- Since April 2011, 7105 PMT voltages were gradually increased on LAGEOS and Etalon to maximize data yield
- Since 2016, the positive drift in the 7105 LAGEOS and Etalon ranges biases can be attributed to PMT voltages variations coupled with the Event Timer installation in July 2016.
- On 14-Aug-2020, a single PMT voltage was used for both satellite and calibration data, eliminating PMT voltage variations as a systematic error source.

# DATA ANALYSIS SUB-SYSTEM (RRA/COM CORRECTIONS)

# RRA/CoM Correction Analysis




| | NASA Avg CoM in mm |
|---|---|
| Etalon | 583.7 |
| LAGEOS-1 | 246.0 |
| LAGEOS-2 | 245.5 |

- **The bar chart are the deviations from the mean MOBLAS and TLRS CoM corrections (see embedded table). Etalon and LAGEOS deviations are on the left and right axes; respectively.**
- **MOBLAS-4 (7110 MONL) Etalon and LAGEOS CoM corrections appear as 20 and 1 mm potential outliers; respectively.**
- *Reference: CoM Corrections [Rodriguez, 2019]*

# NASA SLR Systematics Summary/Recommendations

- Reducing NASA SLR systematic errors below 1 mm in each major component/sub-component is challenging
- T2L2 analysis; VMF analysis; system characterization tests; and CoM analysis are useful tools in investigating; detecting; and recovering past systematic errors

| Sub-System | Major Component | Sub-Component | Contributes to: NP Jitter | Contributes to: Bias | Bias Characteristic | Recommendation |
|---|---|---|---|---|---|---|
| Local Survey | Calibration Range, System Eccentricities | | No | Yes | Fixed | Implement new calibration target, a prism on the telescope (in progress) |
| Ranging Machine | Laser (Transmitter) | | Yes | Yes | Fixed | Implement 10 Hz ranging on all targets |
| | Receiver | Detector Package | Yes | Yes | Fixed | Investigate modeling receive amplitude variations (in progress) |
| | | Time of Flight Device | Yes | Yes | Fixed | None. ETM systematics < 1 mm |
| | Time and Frequency | Frequency Device | No | Yes | Range | Monitor rubidium frequency readings in daily LORS (ongoing) |
| | | Epoch Timing | No | Yes | Range-Rate | Investigate onsite time keeping procedures post ETM |
| | Meteorological System | Sensors | No | Yes | Elevation | Implement yearly barometric calibrations (in progress) |
| | Mount/Telescope | Optics/Filters | No | Yes | Fixed | Remeasure translator distances and ND filter thicknesses (in progress) |
| | Controller Computer | | N/A | N/A | N/A | N/A |
| | Data Reduction | Data Smoothing, Outlier Rejection, NP Creation | Yes | Yes | Fixed | Re-evaluate all data processing constants (target ranges, optical path corrections, epoch timing corrections) |
| | Calibration Target/ Procedures | | No | Yes | Fixed | Use the same PMT Voltage for satellite and calibration (completed) |
| | Aircraft Detection | | N/A | N/A | N/A | N/A |
| Geodetic Satellites | Retro-Reflector Array (RRA) | | Yes | Yes | Fixed | Investigate NASA SLR satellite signatures (in progress) |
| Data Analysis | Precise Orbit Determination Software | RRA Correction | N/A | Yes | Fixed | Re-evaluate MOBLAS-4 (7110 MONL) CoM corrections (completed) |