Transitioning the NASA SLR network from the Time Interval Mode to the Event Timing Mode for sustainability, improved Stability, Precision, Accuracy, and Data Quantity

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NASA code 453, Peraton, Cybioms, NASA's Global SLR Operations team <task responsibility>

UMBC <analysis>

NASA SGP, ILRS, KBRWyley <review team>

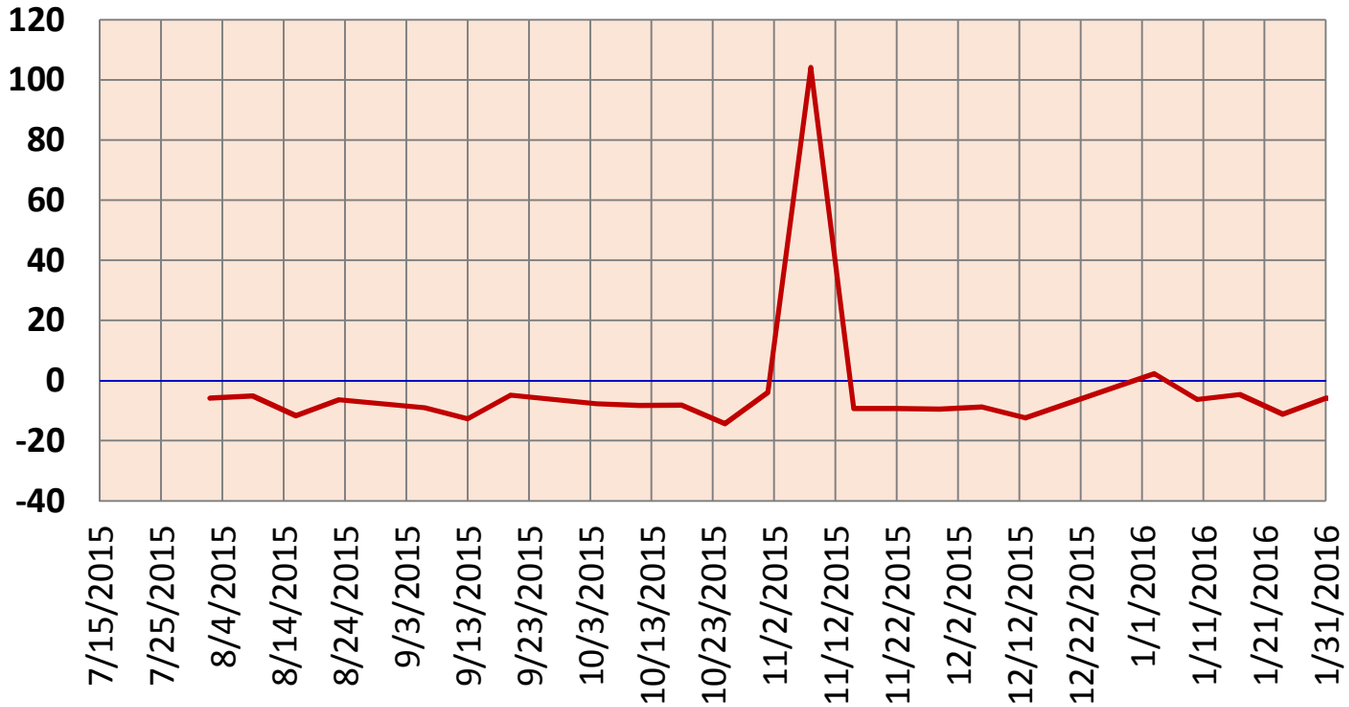
Background

1. NASA SLR has a Global distribution of SLR stations in key locations;
2. Locations include: Moblas7@Greenbelt, MD; Mobas4@Monument Peak, CA, TLRS4@Haleakala, HI; Moblas8@Tahiti, F. Polynesia; TLRS3@Arequipa, Peru; Moblas6@Hartebeesthoek, SA, and Moblas5@Yarragadee, Australia
3. NASA SLR sustaining engineering maintains the systems for best data quality and quantity;
4. TIU is a critical part of the range measurement scheme;
5. HP5370 has served the SLR program well during the 25+ years since its introduction;
6. HP support ceased in early 2000; unable to calibrate the TIU, get parts, to sustain ops;
7. Occasional problems, performance issues, and systematics;
8. High risk item for the SLR network maintenance;

Past TIU data issues - Examples

2015-2016 M7 Data RB analysis from JCET

(Y-axis, 1 divn =20 mm; X-axis - 1 divn = 10 days



1991-92 TIU intercomparison results

PORTABLE STANDARD PASSES

TAKEN AT MOBLAS 7

DATE	SATELLITE	OBS.	PS RMS (mm)	M7 RMS (mm)	Bias (mm)
19-OCT-91	LAGEOS	8098	7.8	10.7	-3.4
25-OCT-91	LAGEOS	3140	7.8	10.7	-3.4
29-OCT-91	LAGEOS	6478	7.8	10.2	-4.0
29-OCT-91	LAGEOS	989	8.7	11.6	-4.1
30-OCT-91	LAGEOS	2547	8.2	11.1	
31-OCT-91	LAGEOS	2626	7.6	10.7	-3.1
6-NOV-91	LAGEOS	4787	7.1	9.9	-2.6
6-NOV-91	LAGEOS	3591	7.7	10.5	-2.5
6-NOV-91	LAGEOS	829	7.6	10.8	-3.3
29-APR-92	LAGEOS	815	8.2	11.5	-5.4
19-OCT-91	STARLETTE	1343	6.1	7.1	-3.7
29-OCT-91	STARLETTE	443	5.1	5.8	-4.5
29-OCT-91	STARLETTE	598	5.4	6.5	
29-OCT-91	STARLETTE	1443	6.3	7.2	-4.3
30-OCT-91	STARLETTE	881	6.4	6.9	
30-OCT-91	STARLETTE	757	7.4	8.1	
6-NOV-91	STARLETTE	970	5.9	6.7	-7.8
30-OCT-91	ERS-1	463	5.7	6.8	-3.4
30-OCT-91	ERS-1	1062	6.4	6.9	
6-NOV-91	ERS-1	384	4.8	5.3	-1.9

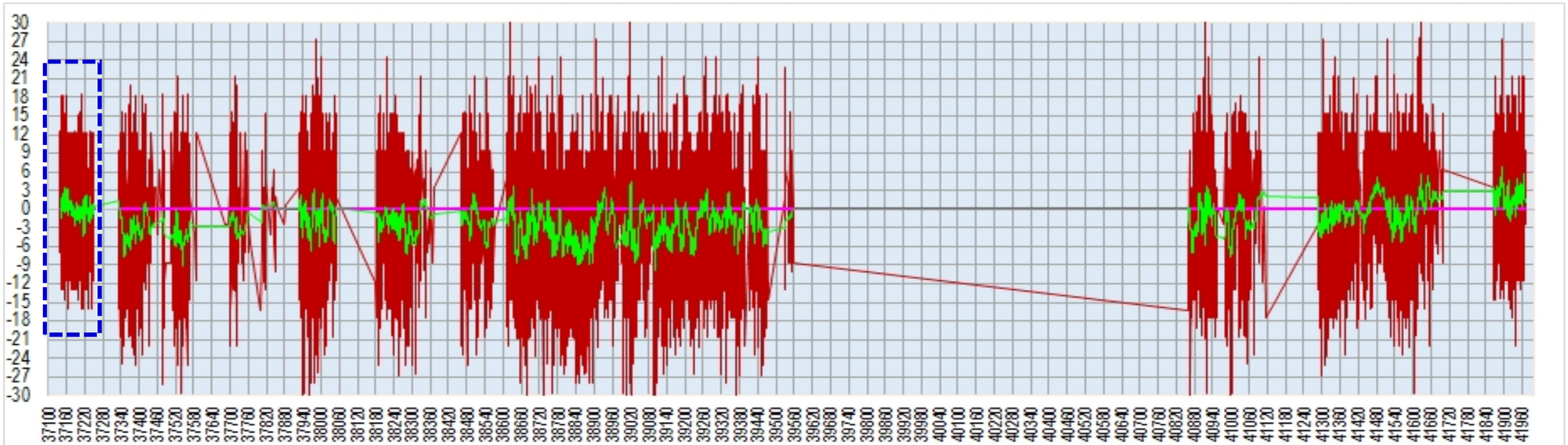
Table 1 Satellite Ranging Intercomparison Results

4-7

TIU1(M7) - TIU2(backup) Comparison on LEO satellites

(**LEO** data from the 2013 NGSLR collocation period); **Red plot = (3σ filtered)** shot by shot difference**;**

Green plot = **30 point MA**; **X-axis**: 1 divn = 60 seconds; **Y-axis**: **1 divn= 3 mm**

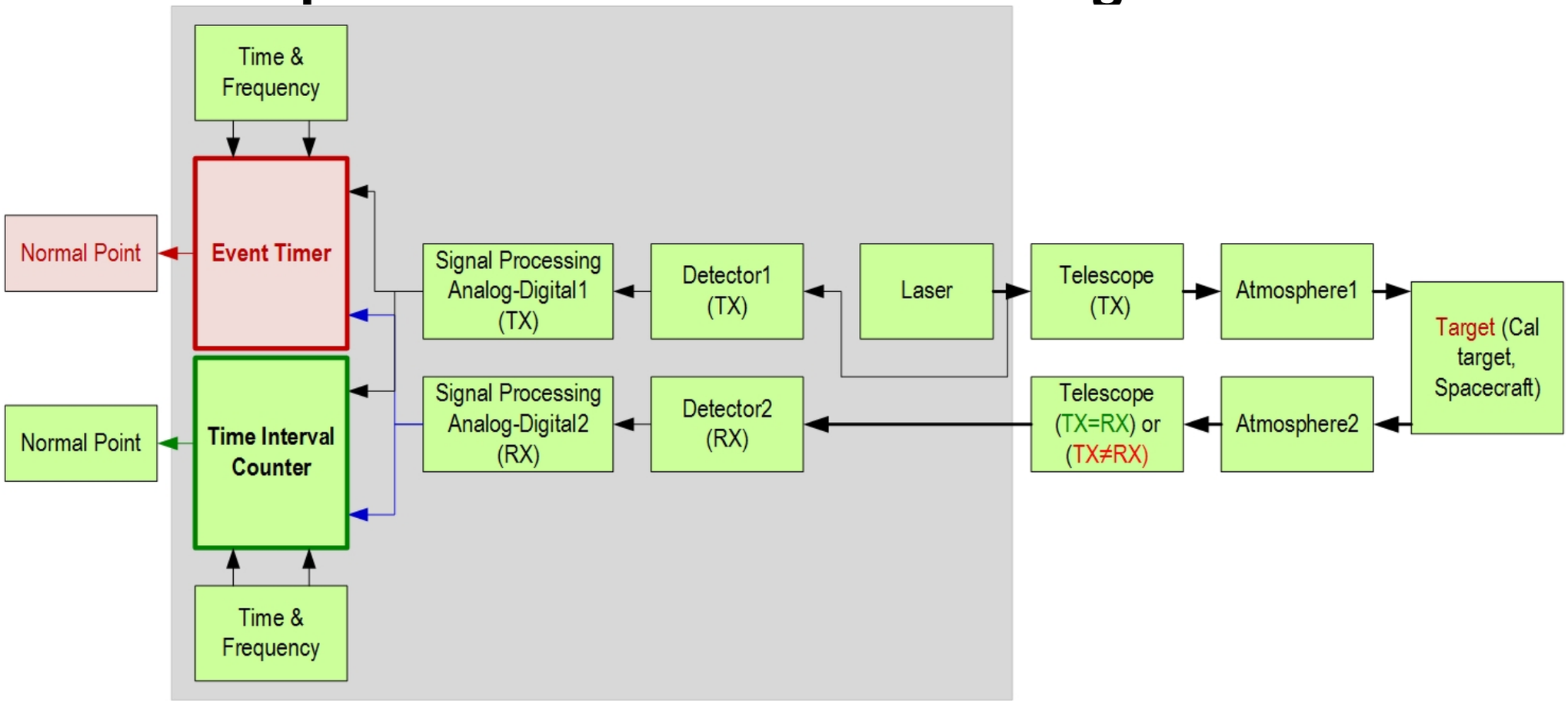


1. During NGSLR collocation, a spare TIU was integrated in M7(7105), in case the M7 TIU failed;
2. Above data shows simultaneous data taken on multiple LEO satellites;
3. 30 sec MA depicts the trend in the data.
4. BLUE dotted rectangle in the beginning is the cal data – small variations;
5. Larger (6+mm) fluctuations for satellite;

System changes require Performance Verification

1. Industry approach for qualifying a device is by comparing with a standard;
2. Intercomparison allows to characterize the inherent systematics;
3. SLR System needs "bias free cal"; Cal instability /drifts/jumps maps into the range; Ground Tests on multiple targets at surveyed ranges for range intercomparison;
4. At the multi-system level, collocations amongst the NASA stations and with international (non-NASA) stations; **|RB| <5 mm**
5. Intercomparison of Time of Flight devices (e.g., 1992, 2013); **|RB| <5 mm);**
6. Extensive testing in the lab with simulated ranges
7. **Tests performed in an operational system can be invasive or interrupting - How do we implement + test + baseline + validate a change without interrupting the operational data flow and causing any RB?**

Simplified Parallel TOF Test Configuration



1. **TIU based TOF: res: 20ps; SS RMS: ~22ps; Stability: ~10ps; Epoch time res= 0.2μs; PRF=10, 5, 4, 2Hz**
2. **ETM based TOF: res: 1ps; SS RMS: ~3ps; Stability: ~2ps; Epoch time res= 1ps; PRF =10Hz (max laser PRF)**
3. **Differential RB can be determined;**

Process steps performed for ETM validation

Real-time controller I/F issues

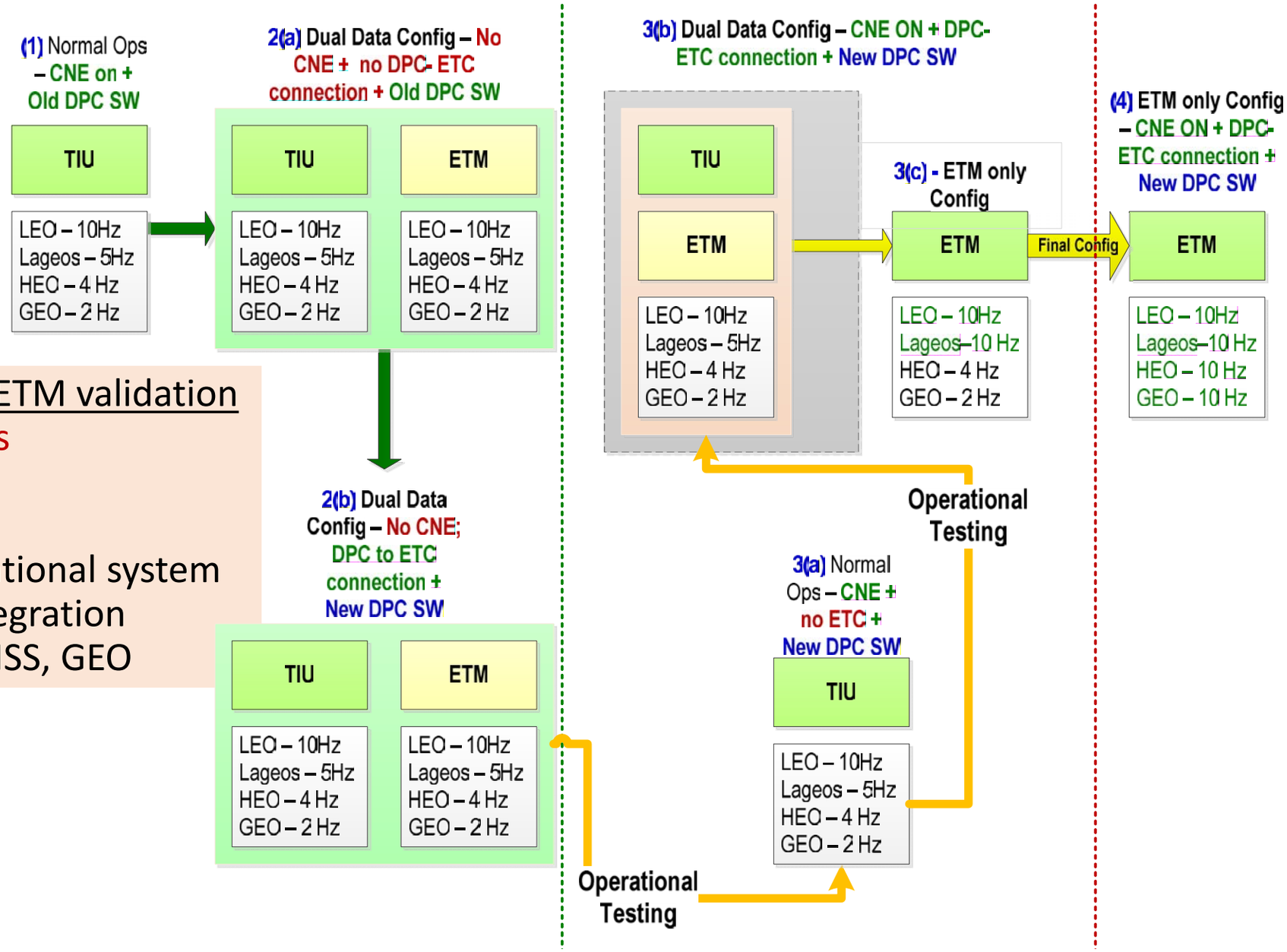
Stress test

(1) Standalone mode;

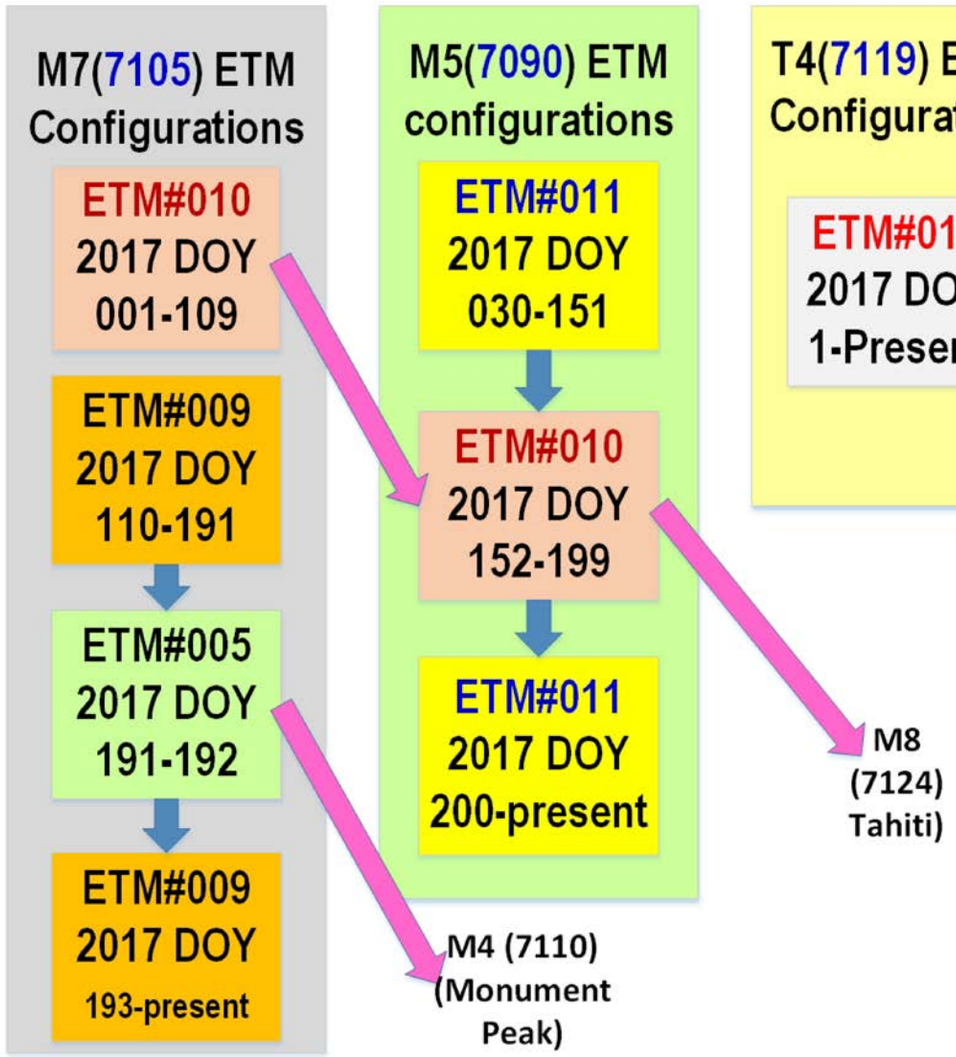
(2) Integrated with the Operational system

(3) Full-fledged Dual data integration

(4) Final Configuration for GNSS, GEO



ETM Test configurations in M5, M6, M7, and T4



1. All units tested in M7 in 2015;
2. More than 1 ETM going through the formal testing (M5, M7) in 2017;
3. RB evaluation from normal point and full rate data analysis
4. Untested stations to be equipped with previously tested ETMs (at M7 or M5) to effect a shortened test period;

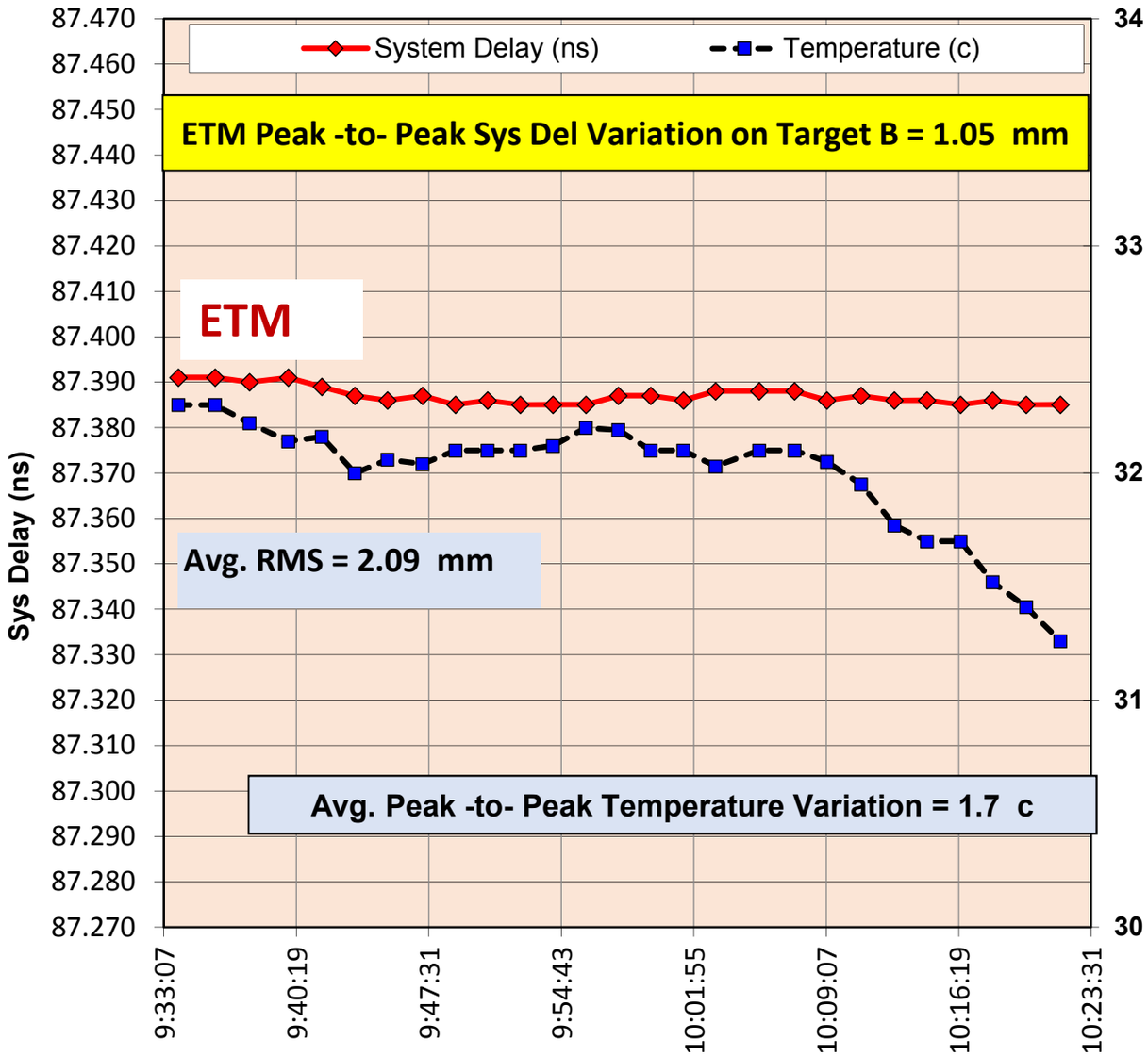
Note:

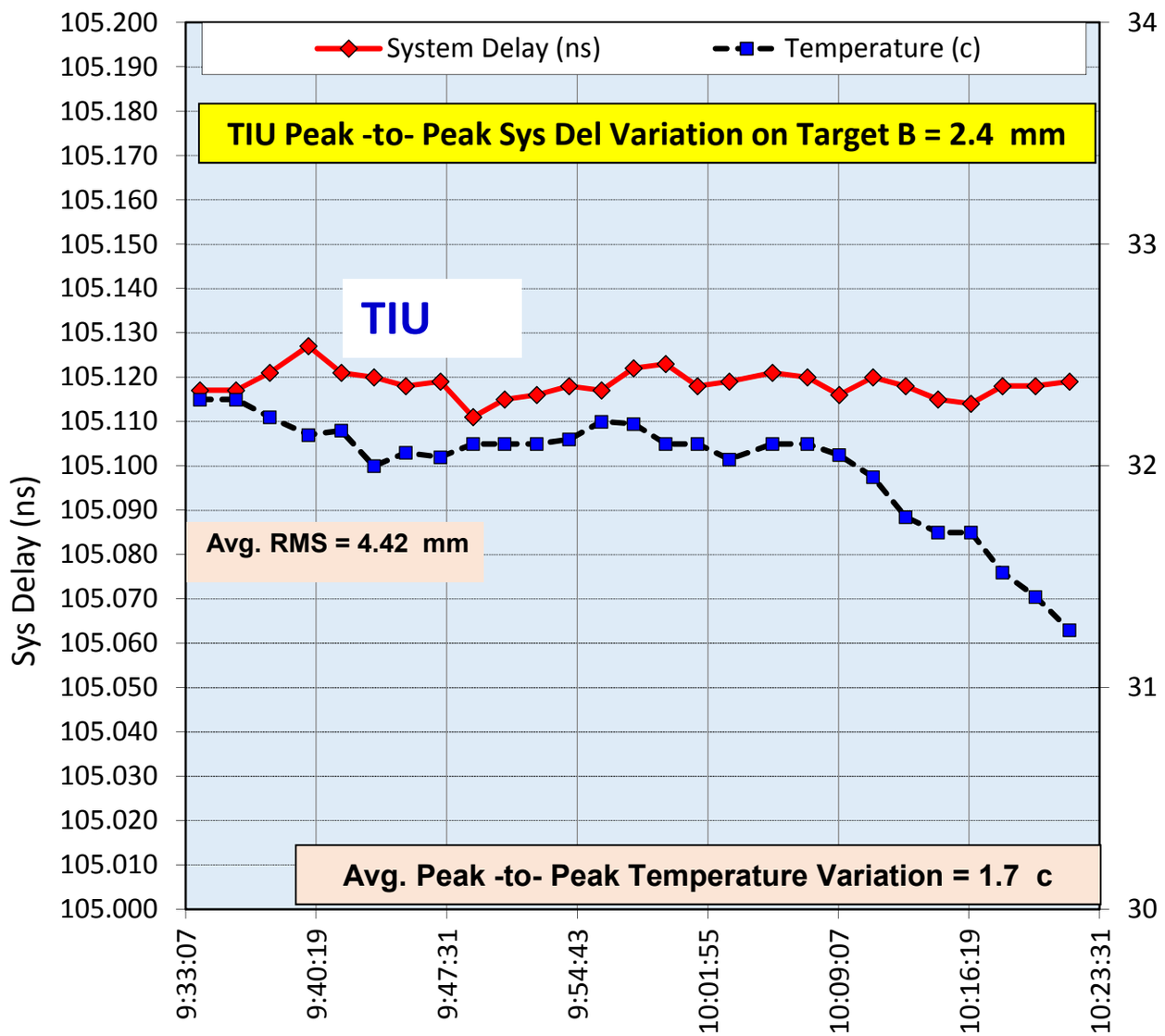
M5, 6, 7→ Moblas 5,6,7

T4 → TLRS4, Haleakala

M5 (7090) ETM#011 & TIU - Stability Test January 15, 2017 @ 09:33

UTC X-axis: Time UTC; 1 divn ~12 min ; Y-axis: SysDel: 1 divn=10ps

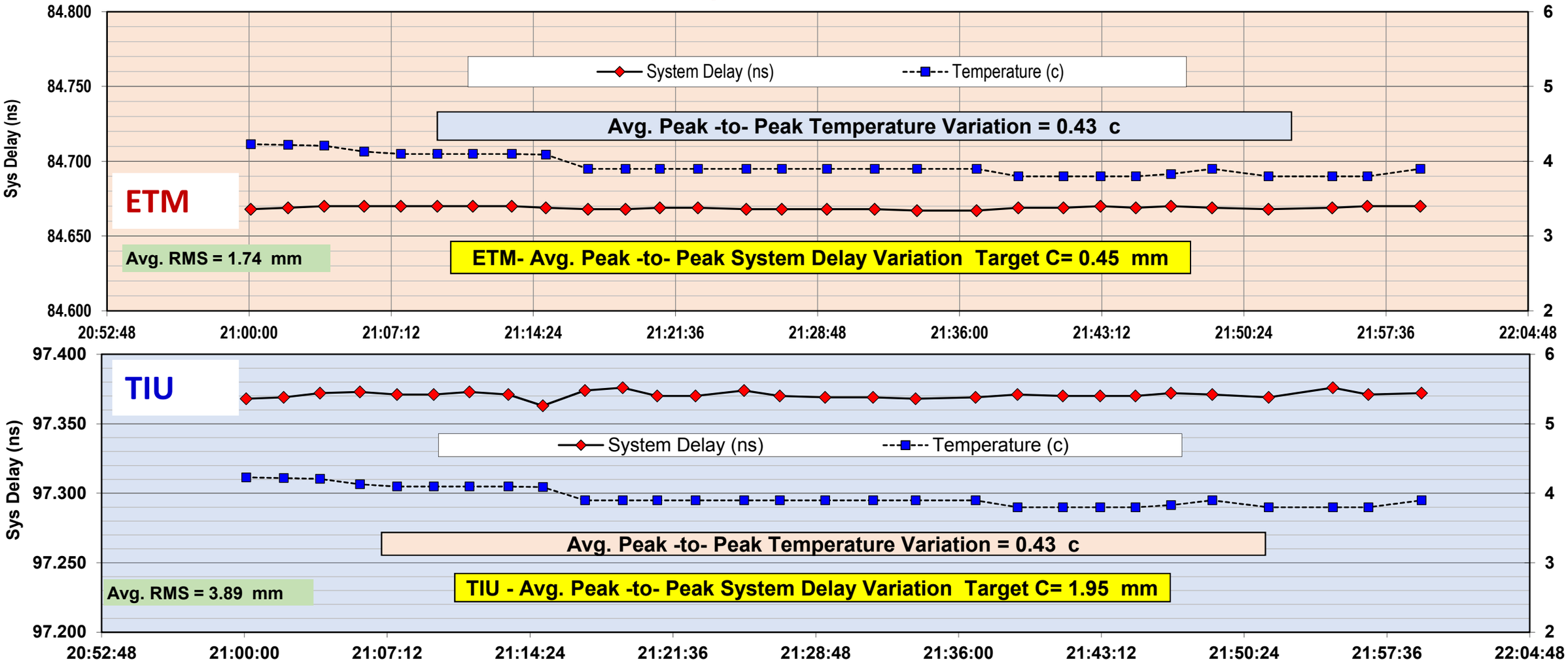


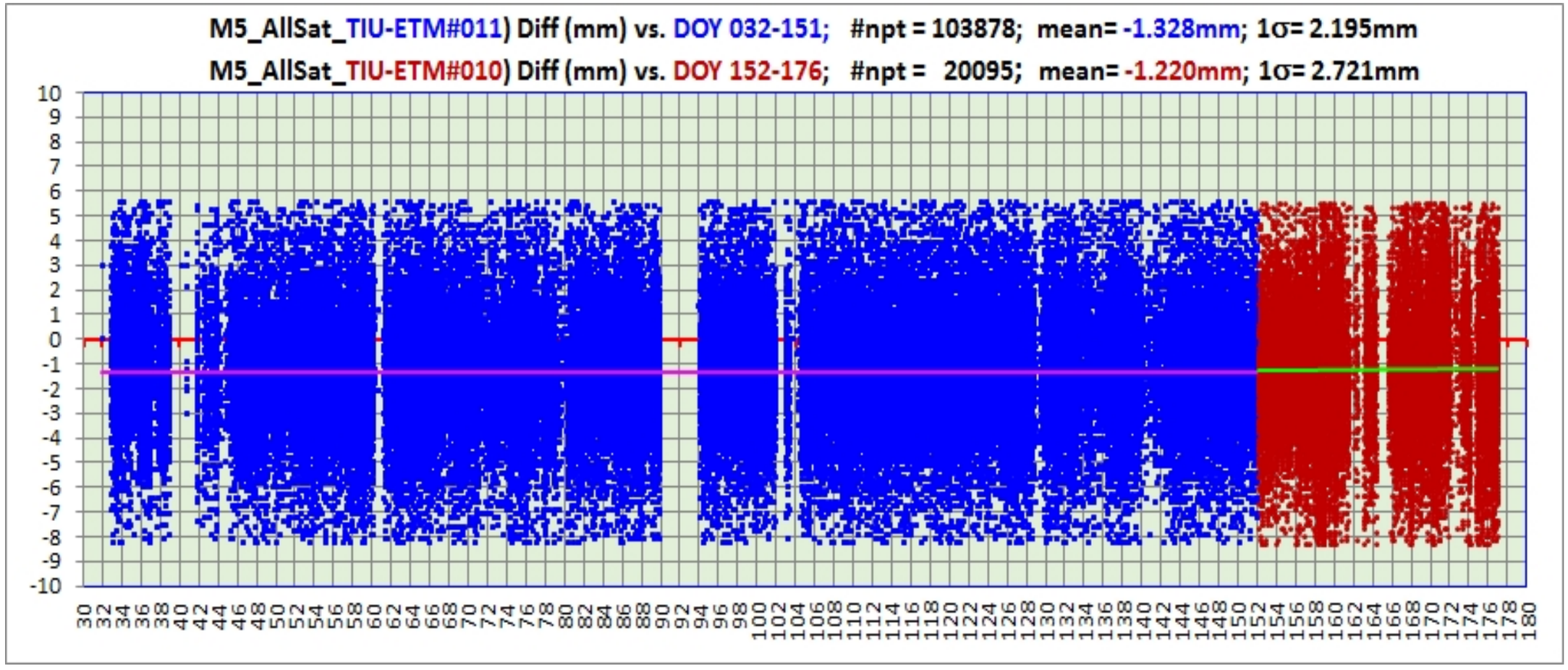


M7(7105) ETM #010 & TIU Stability Test

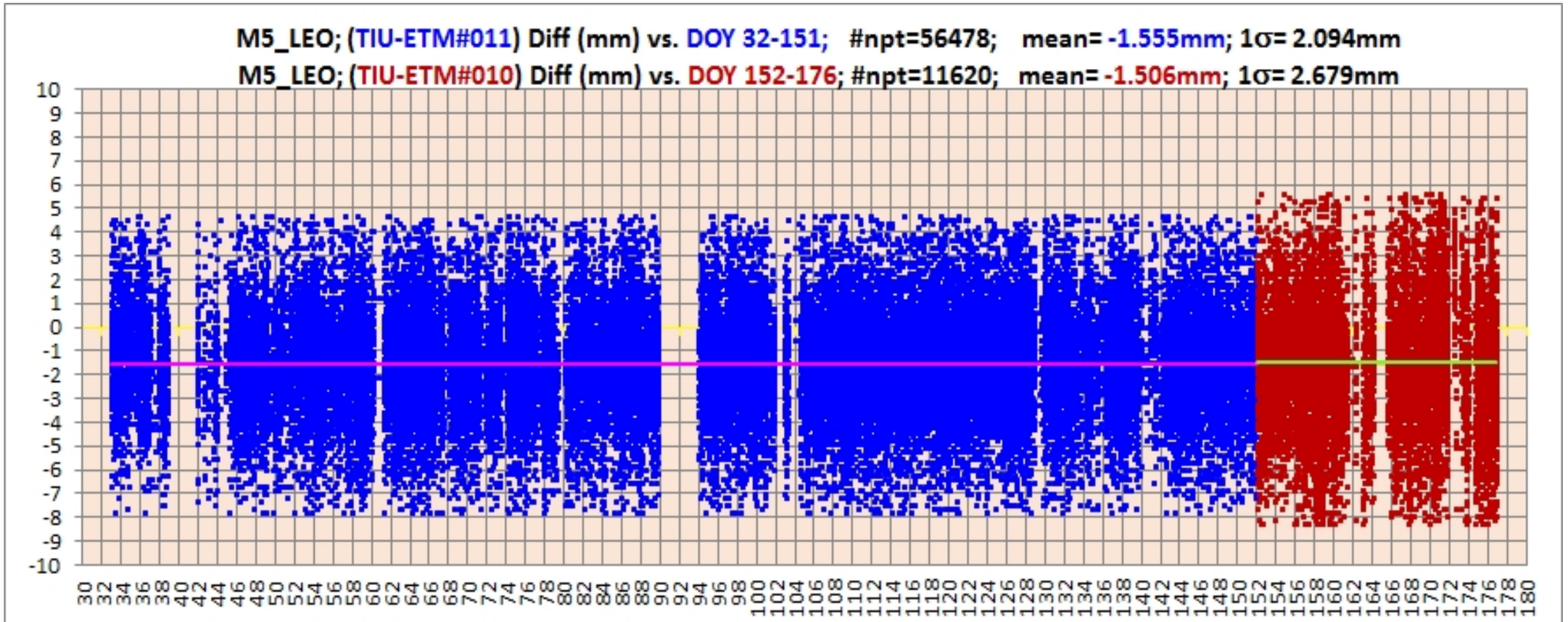
March 13, 2017 @ 21:00 GMT

Y-axis =10ps/divn; X-axis: UTC

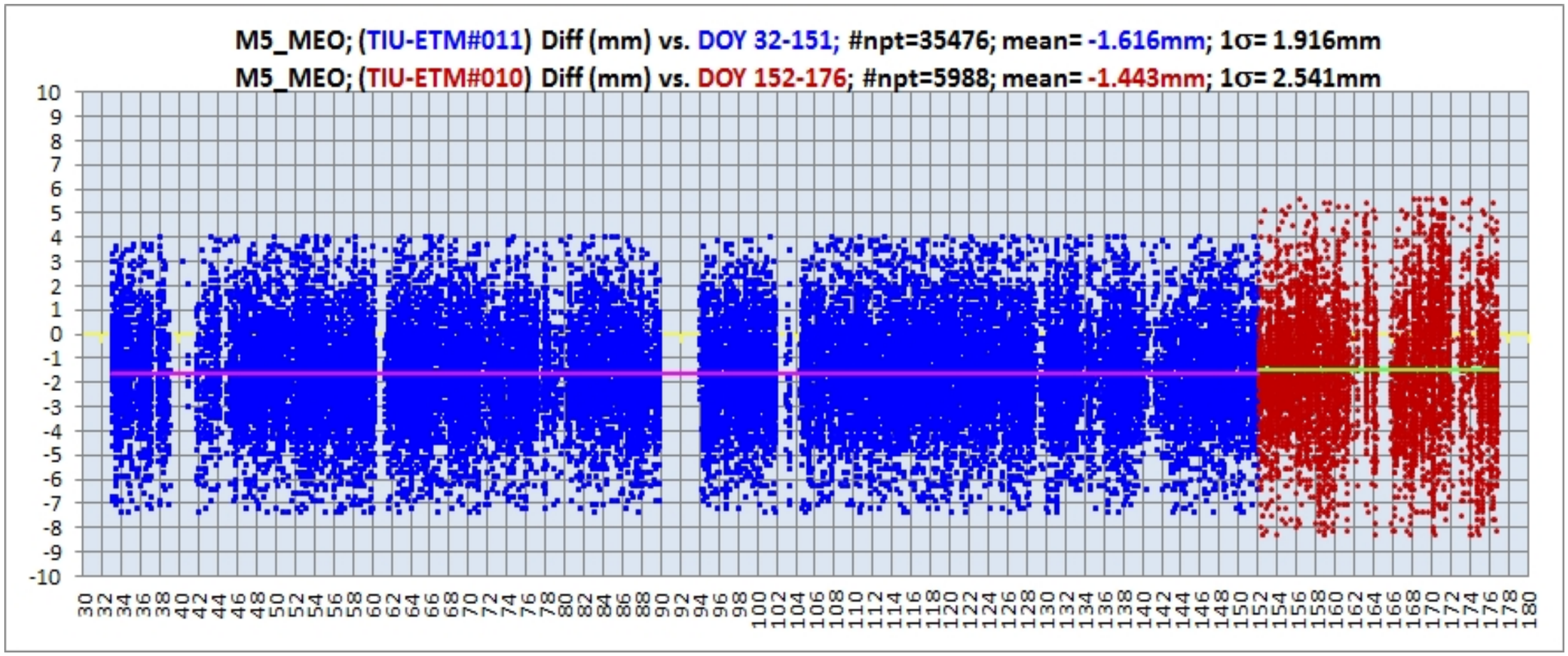




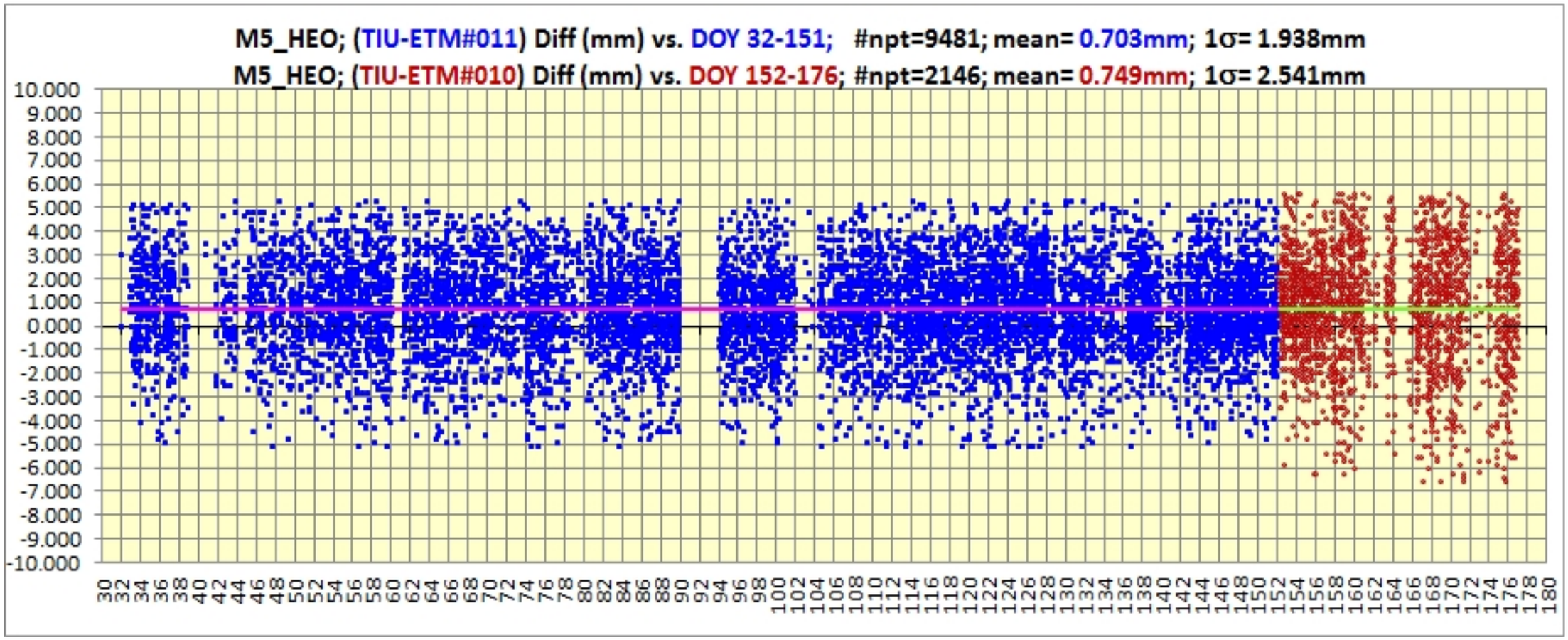
1. #NPT=103,878; AllSat Range Diff during DOY 32-151; Mean TIU-ETM#011 (DOY 32-151) = -1.328mm;
2. #NPT= 20,095; AllSat Range Diff during DOY152-176; Mean TIU-ETM#010 (DOY 152-176) = -1.220mm;
3. Mean of the 2 groups are shown by the magenta and green lines; mean computed after 3σ filtering



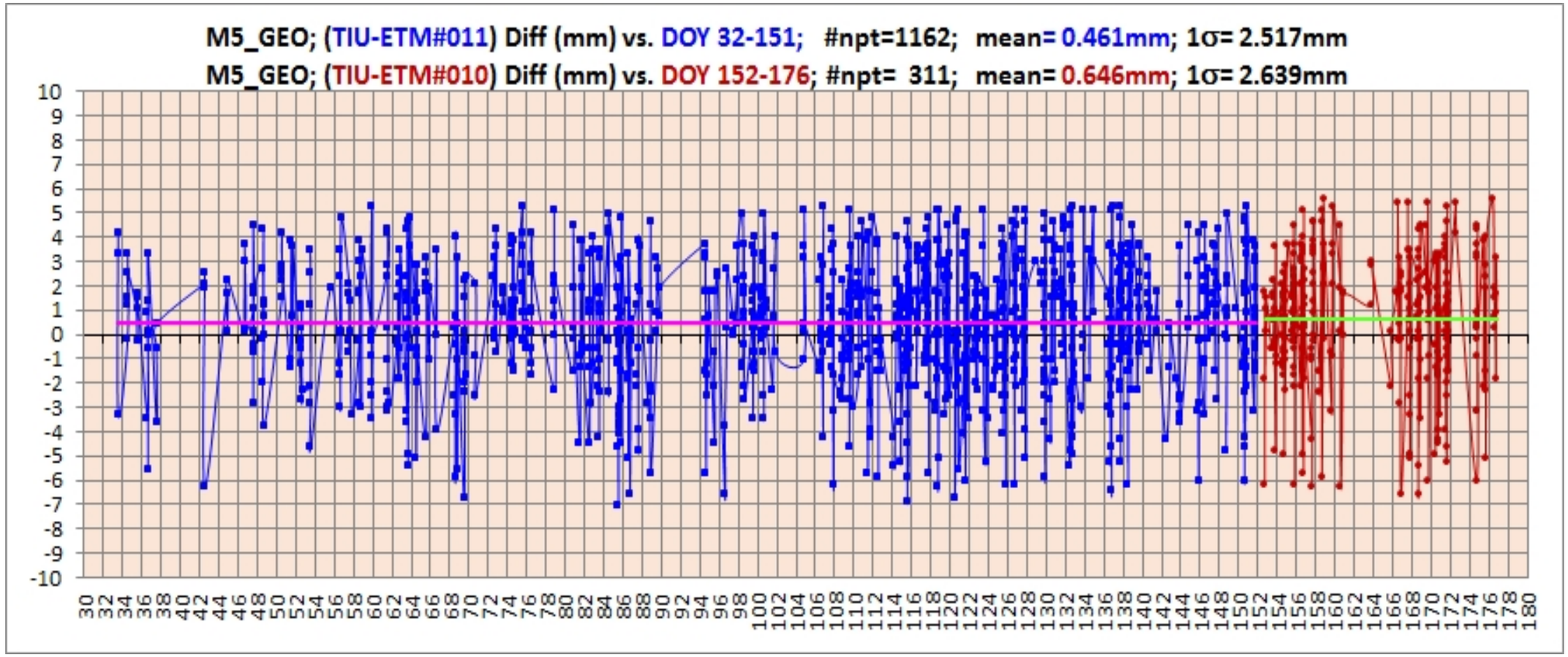
1. LEO Range Diff; #NPT=56478 Mean TIU-ETM#011 (DOY 32-151) = -1.555mm;
2. LEO Range Diff: #NPT=11620; Mean TIU-ETM#010 (DOY 152-176) = -1.506mm;
3. Mean of the 2 groups are shown by the magenta and green lines; mean computed after 3σ filtering



1. MEO Range Diff; #NPT=35476; Mean TIU-ETM#011 (DOY 32-151) = -1.616mm;
2. MEO Range Diff: #NPT=5988; Mean TIU-ETM#010 (DOY 152-176) = -1.443mm;
3. Mean of the 2 groups are shown by the magenta and green lines; mean computed after 3σ filtering



1. HEO Range Diff; #NPT=9481; Mean TIU-ETM#011 (DOY 32-151) = 0.703mm;
2. HEO Range Diff: #NPT=2146; Mean TIU-ETM#010 (DOY 152-176) = 0.749mm;
3. Mean of the 2 groups are shown by the magenta and green lines; mean computed after 3σ filtering



1. GEO Range Diff; #NPT=1162; Mean TIU-ETM#011 (DOY 32-151) = 0.461mm;
2. GEO Range Diff: #NPT=311; Mean TIU-ETM#010 (DOY 152-176) = 0.646mm;
3. Mean of the 2 groups are shown by the magenta and green lines; mean computed after 3σ filtering

M5 – TIU & ETMs(#011 and #010) comparison Summary1

M5 - 2017 SLR data	Mean (mm)	StDev (mm)
Grouping based on Orbit		
M5-2017_DOY 32-176_Allsat	-1.315	2.323
M5-2017_DOY 32-176_LEO	-1.553	2.242
M5-2017_DOY 32-176_MEO	-1.591	2.010
M5-2017_DOY 32-176_HEO	0.861	2.292
M5-2017_DOY 32-176_GEO	0.902	3.104
Grouping based on ETM#011 (DOY 32-151) and ETM#010 (DOY 152-176		
M5-2017_DOY 032-151_Allsat	-1.328	2.195
M5-2017_DOY 152-176_Allsat	-1.220	2.721

1. **ETM#011** in M5 during 2017 **DOY 32-151**; replaced with **ETM#010** from M7 for DOY 152-176
2. Normal point Comparison between TIU and ETM made using 2017 data by grouping it into AllSat, LEO, MEO, HEO, and GEO; data was also grouped into 2 groups based on above DOY
3. Iterative 3-sigma filtering was performed to remove outliers in each group;
4. Mean and StDev of the data statistics for the various groups are shown in millimeters;

M5 – TIU & ETMs(#011 and #010) comparison Summary2

M5 - Paired Data between ETM#011 and ETM#010	Mean (mm)	Delta between the pair (mm)	StDev (mm)	Data Points
M5-TIU-ETM-2017-npt-diff-DOY032-151 (GEO 1)	0.461	0.184	2.517	1162
M5-TIU-ETM-2017-npt-diff-DOY152-176 (GEO 2)	0.646		2.639	311
M5-TIU-ETM-2017-npt-diff-DOY032-151 (HEO 1)	0.703	0.046	1.938	9481
M5-TIU-ETM-2017-npt-diff-DOY152-176 (HEO 2)	0.749		2.451	2146
M5-TIU-ETM-2017-npt-diff-DOY032-151 (MEO 1)	-1.616	0.173	1.916	35476
M5-TIU-ETM-2017-npt-diff-DOY152-176 (MEO 2)	-1.443		2.541	5988
M5-TIU-ETM-2017-npt-diff-DOY032-151 (LEO 1)	-1.555	0.049	2.094	56478
M5-TIU-ETM-2017-npt-diff-DOY152-176 (LEO 2)	-1.506		2.679	11620

1. AllSat data grouped by DOY AND ETM# ; e.g., GEO 1→ GEO data for DOY 32-151 with ETM#011;
2. GEO2 → GEO data for period 152-176 using ETM#010;
3. Each group is iteratively 3 sigma filtered;

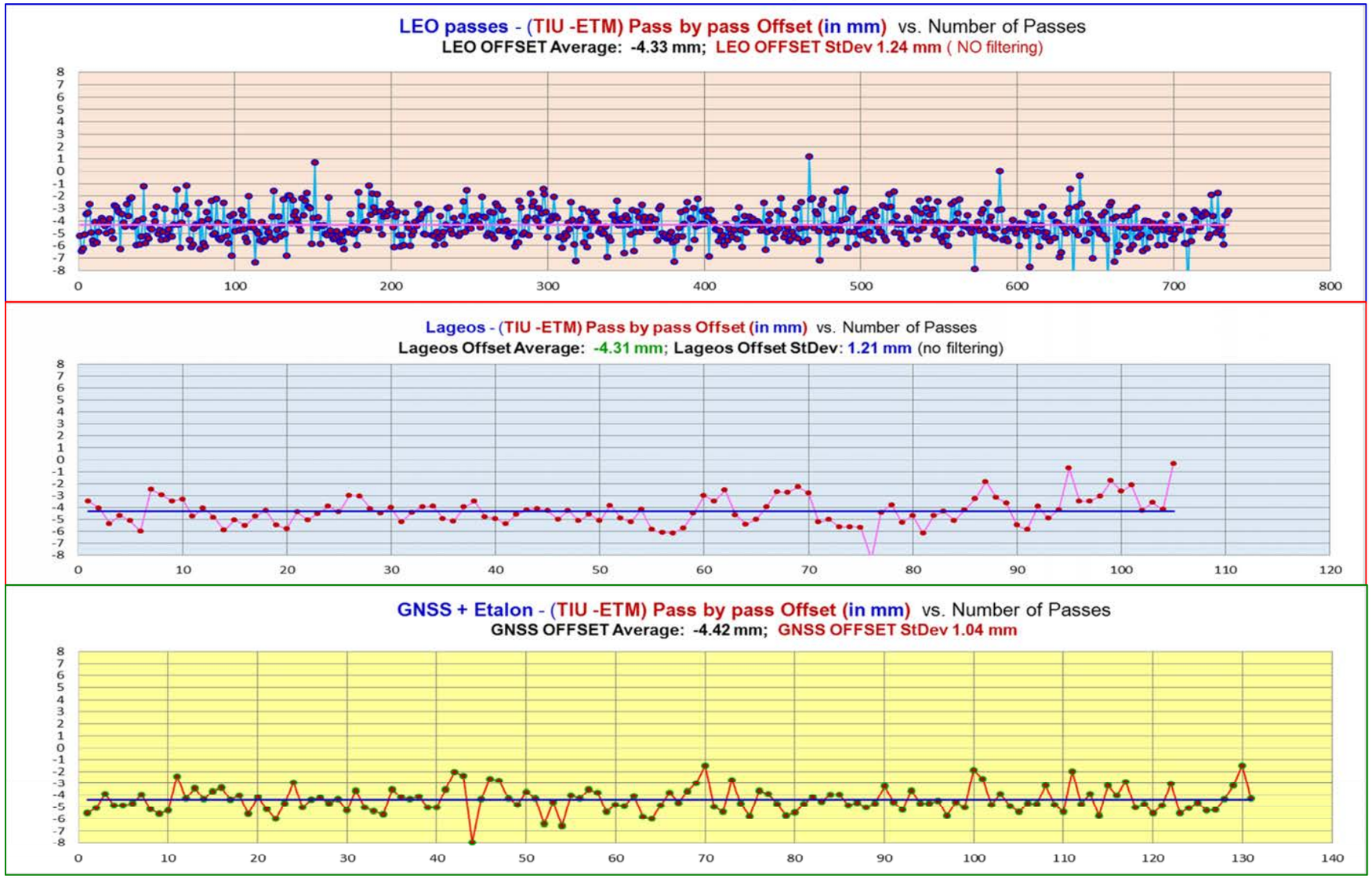
Summary – 7090 (Yarragadee) Results from Erricos & Magda, UMBC

TIME PERIOD	ORBITAL CLASS	GRANT AVG	STD. DEV.	COMMON NUMBER of RANGES
BEFORE DOY 152	LEO	-1.43	0.63	7582
ET011	MEO	-1.63	0.93	4992
	HEO	0.92	0.48	1415
	GEO	0.16	3.51	49
	GRANT AVG	-0.17	0.35	14038
AFTER DOY 152	LEO	-1.62	0.82	11837
ET010	MEO	-1.49	1.16	6163
	HEO	1.20	0.56	2409
	GEO	0.56	2.21	149
	GRANT AVG	0.08	0.42	20558

2015-16 (~3 months) M7 (7105) (TIU-ETM Range Offset) vs. Pass#; ~1000 passes from LEO to HEO

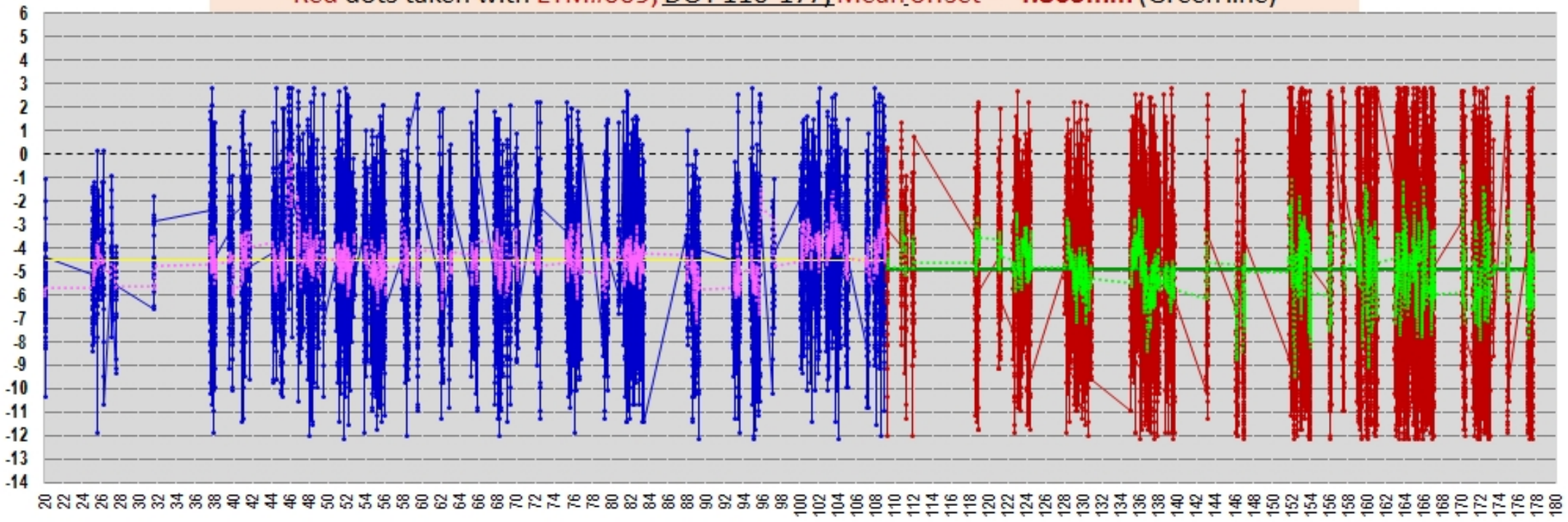
<NO 3 sigma FILTERING of the Pass Mean>; Mean Difference computed using FULL RATE data;

Mean offset : ~ -4mm; 1σ ~1mm; X-axis: Data sequence #; Y-axis: 1 divn = 1mm



M7_ ETM-TIU npt Offset (in mm) vs. 2017 DOY

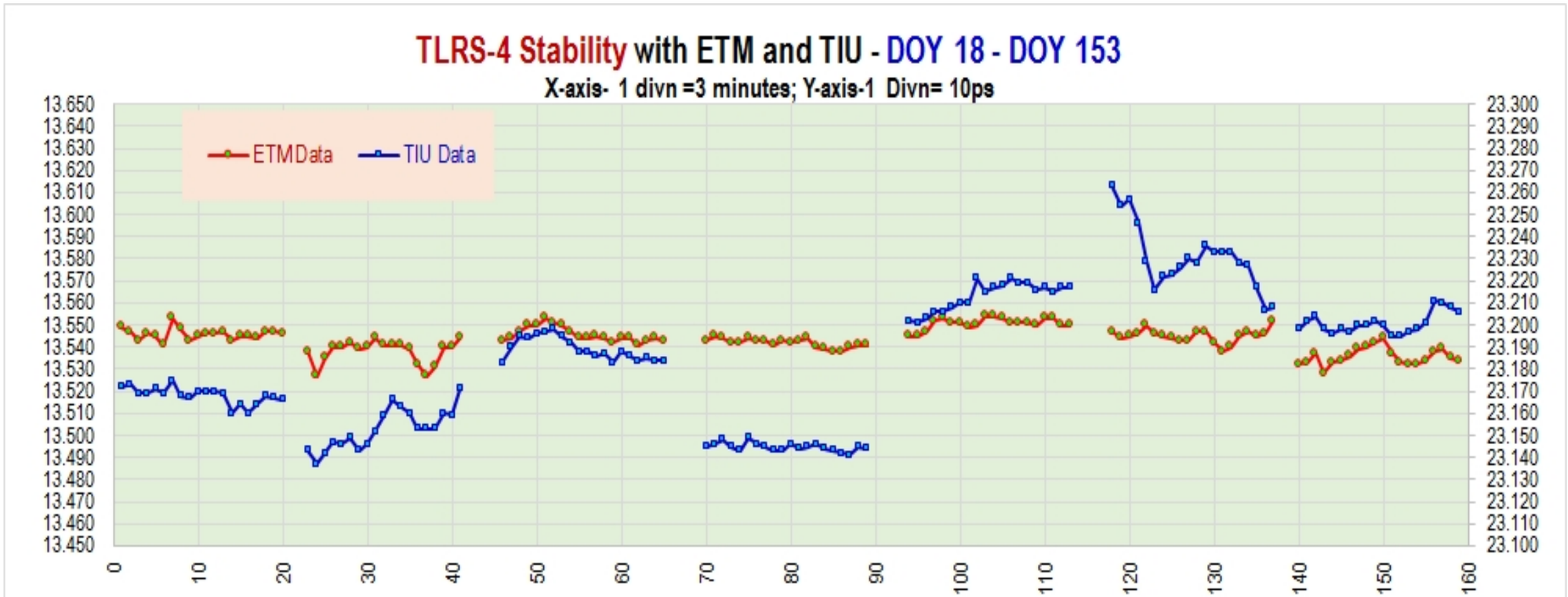
Blue dots taken with ETM #010 (now in M5); DOY 20-109 mean offset = **-4.512mm** (Yellow line);
Red dots taken with ETM#009; DOY 110-177; Mean offset = **-4.865mm** (Green line)



1. 2 sets of ETM (Blue and Red dots) data taken sequentially in M7 with a common TIU ;
2. 30 point MA shown in **Magenta** and **Light Green** for the above respective data groups;
3. Blue dot ETM#010 from M7 was sent to M5 to replace M5's prior ETM#011 (see M5 charts);
4. Mean Offset between M7 TIU & ETM#010 = **-4.512 mm**;
5. Mean Offset between M7 TIU & ETM#009 = **-4.865mm**

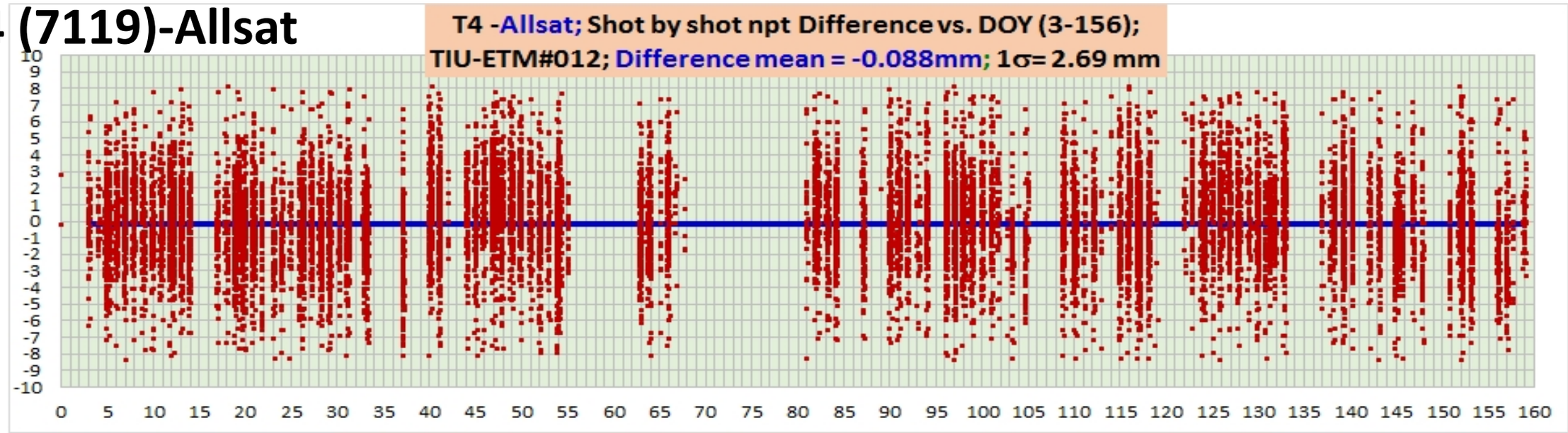
Moblas 7- Multi ETM NPT comparison summary

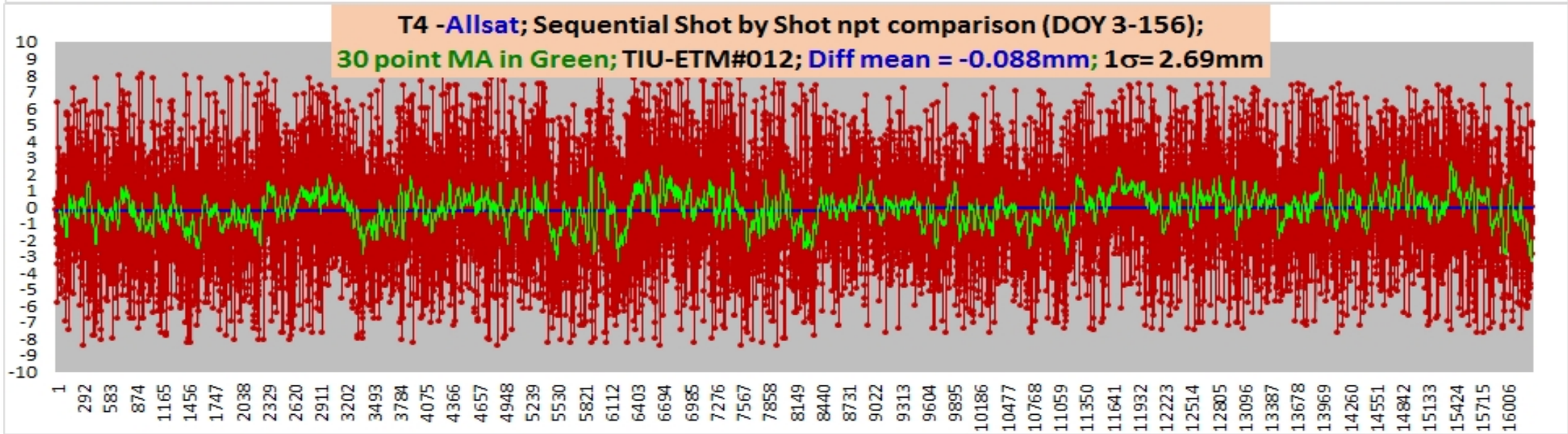
2017 M7 Data - Grouping based on Orbit	Mean (mm)	Sigma (mm)	Data Points
M7-2017- DOY 020-177_HEO	-4.991	1.970	1492
M7-2017- DOY 020-177_LEO	-4.670	2.458	22796
M7-2017- DOY 020-177_MEO	-4.596	2.153	11193
M7-2017- DOY 020-177_AllSat	-4.590	2.340	35712
2017 M7 data - Grouping based on ETM#010 (previously in M7) and ETM#009			
M7-2017- DOY 020-109 _AllSat	-4.512	1.808	19504
M7-2017- DOY 110-177_AllSat	-4.865	2.820	15828



1. **1 hour Stability Data sequence** taken during **DOY 18-153** is shown in sequence on the X-axis ;
2. **Primary Y-axis** shows **ETM Sys Delay**; secondary Y-axis shows TIU Sys Delay;
3. The individual behavior as well as externally (rest of the data loop) induced effects are clear in this plot from the pattern;

T4 (7119)-Allsat





T4(7119): (TIU-ETM#012) npt comparison Summary

1. Mean Allsat TIU-ETM offset = - 0.088mm; 1σ = 2.68mm;
2. Mean LEO TIU-ETM offset = - 0.242mm; 1σ = 2.77mm;
3. Mean MEO TIU-ETM offset = 0.081mm; 1σ = 2.44mm;
4. Sub-mm agreements in TLRS4 (7119)

M6: TIU-ETM Performance Summary

#Passes	2162	AllSat	Mean	0.369	mm
#Passes	2162	AllSat	1σ	2.038	mm

1. Sub-mm agreements in M6 (7501)

#passes	863	LEO	Mean	0.531	mm
#passes	863	LEO	1 σ	1.949	mm

#Passes	365	Lageos 1, 2	Mean	0.193	mm
#Passes	365	Lageos 1, 2	1σ	1.940	mm

# Passes	450	GNSS	Mean	-0.017	mm
# Passes	450	GNSS	1σ	2.045	mm

M5 (7090), M7 (7105), and T4 (7119): TIU-ETM Evaluation - Summary

1. **Most extensive test data** sets ever collected and analyzed for a NASA SLR engineering upgrade/replacement;
2. Test NPT Data include: **M5 (120000+); M7 (35000+); M6 (18000+); T4 (16000+);**
3. **Sub-mm level agreements** when averaged over a large data set in multiple ETM configurations;
4. In the case of M7, with no PMT amplifier for GNSS and thus a common HW configuration for all satellites, **sub-mm (<0.5mm)** agreements seen **amongst ALL satellite groups**.
5. Published NASA SLR work from 1992 on TIU showed variability (~ 5mm) in RB amongst the 5 HP5370B TIUs used in that study.
6. **Ops data unconstrained by the Test configuration**; **SMOOTH transition**
7. ETM data has better **Normal Point RB, Precision, and Stability** characteristics than TIU;