Sequential Processing of ILRS Observations – Experiences over the last 5 years

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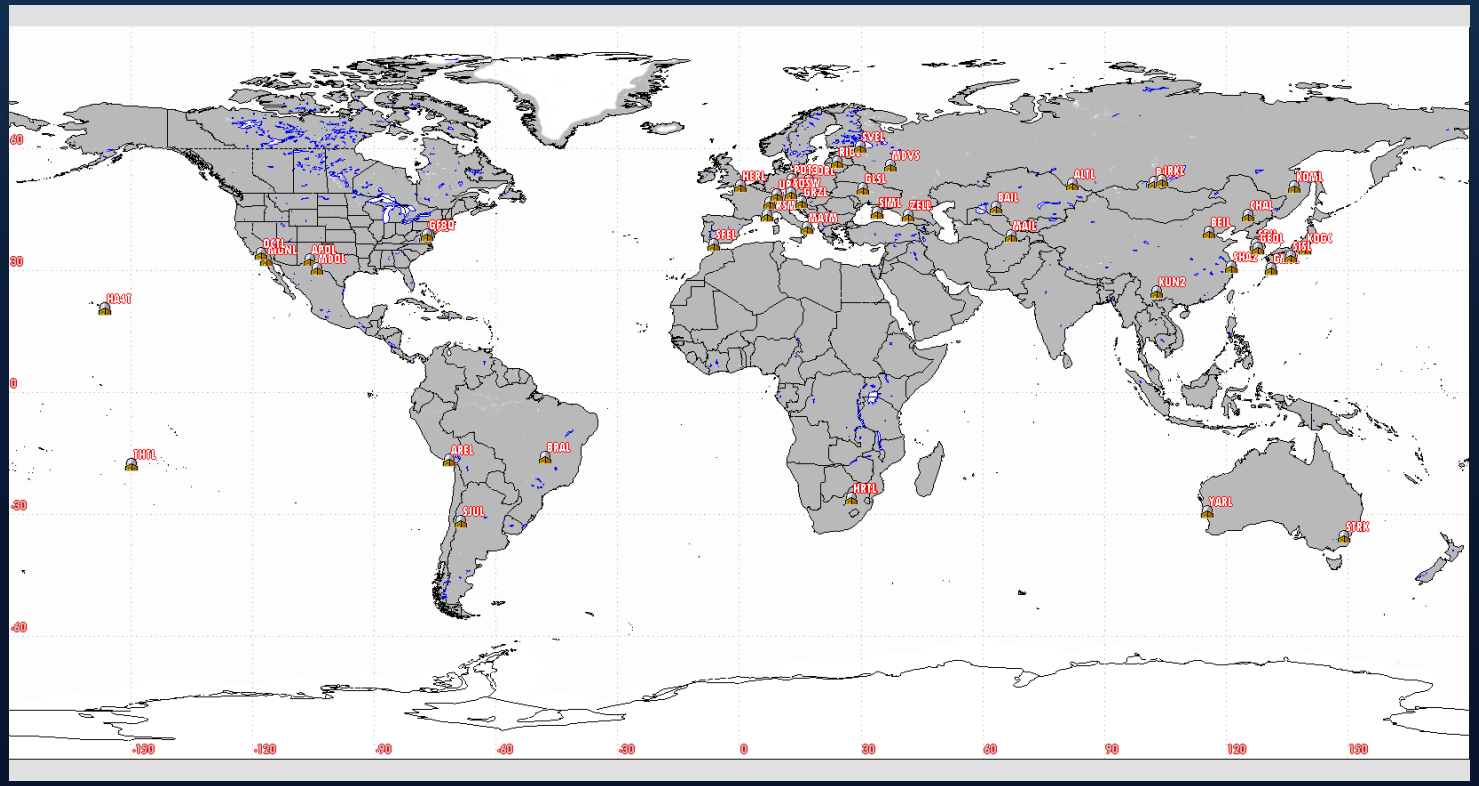
Outline

- International Laser Ranging Service (ILRS) Setup
- Satellite Characteristics
- Sensor system modeling
- Old and New Configuration Result comparisons
  - Res Ratios
  - Position Uncertainty
  - Filter Smoother Consistency (FSC)
- Comparisons
  - Old and new ephemerides
  - CPF ephemerides
  - TLE-derived ephemerides
- Conclusions

ILRS Network



ILRS Sensor Location Setup

- Active sensors
  - https://ilrs.cddis.eosdis.nasa.gov/network/stations/index.html
    - Active, engineering, inactive, and future stations
- Sensor locations
  - ftp://cddis.nasa.gov/slr/products/resource/SLRF2014_POS+VEL_2030.0_180504.snx
    - SLR 2014 frame
  - Instrument location (eccentricities)
    - ftp://cddis.gsfc.nasa.gov/slr/slrocc/ecc_xyz.snx
  - Historical sensors
    - https://ilrs.cddis.eosdis.nasa.gov/network/stations/pre-ILRS_Stations/index.html

New Sensors

- Difference from previous setup

New Sensors			Old Sensors		
STAL	7865		LVIL	1831	
OCTL	7040		MAIN	1863	
GF8Q	7125		MDVL	1870	
GEOL	7395		WUHL	7231	
HRTL	7503		KOGL	7328	
UROL	7816		DAEK	7359	Jun 15
KUN2	7819		CONL	7405	
STRK	7826		METL	7806	Nov 17
			KUNL	7820	Jun 14
			HLWL	7831	Jul 16
			RIYL	7832	

Orbit Determination

- **Sequential Orbit Determination**
  - Extended Kalman Filter / fixed interval smoother
  - Process noise
  - Stochastic sequences
    - Vasicek parameter modeling
      - Two time periods

$$V_{k+1} = P_{k+1,k}V_k + (1 - P_{k+1,k})m + \sqrt{1 - P_{k+1,k}^2}\,\frac{j\,Z_{k+1}}{\sqrt{2a}}$$

- Half-life → $a = -\dfrac{\ln 0.5}{t_{1/2}}$
- Exponential Correlation function → $P_{k+1} = \exp(-a(t_{k+1} - t_k))$
- Long-term mean → $m = \lim_{(t_{k+1} - t_k)\to\infty} E\{V_k\}$
- Short-term sigma → $\dfrac{j^2}{2a} = \lim_{(t_{k+1} - t_k)\to\infty} E\{(V_k - E\{V_{k+1}\})^2\}$

Satellite Physical Characteristics

- Study satellites

Satellite	NORAD #	ILRS #	Diameter (m)	Area (m^2)	Mass (kg)	Apogee Alt (km)	Perigee Alt (km)	*e*	*i* (°)	Retroreflector COM Offset (m)		
Larets	27944	304206	0.200	0.12570	23.280	691.0	675.0	0.001	98.00	0.000	0.000	0.000
Stella	22824	9306102	0.240	0.04524	48.000	806.0	795.0	0.001	98.90	0.000	0.000	0.000
STARLETTE	7646	7501001		0.04524	47.295	1107.0	805.0	0.021	49.80	0.000	0.000	0.000
LARES	38077	1200601	0.364	0.41620	386.800	1452.0	1436.0	0.001	69.50	0.000	0.000	0.000
Ajisai	16908	8606101	2.140	3.63000	685.000	1496.0	1479.0	0.001	50.00	0.000	0.000	0.000
LAGEOS 2	22195	9207002	0.600	0.28270	405.380	5952.0	5616.0	0.014	52.60	0.000	0.000	0.000
LAGEOS 1	8820	7603901	0.600	0.28270	406.965	5948.0	5838.0	0.004	109.90	0.000	0.000	0.000
Etalon 2	20026	8903903	1.294	1.31500	1415.000	19166.0	19078.0	0.002	65.30	0.000	0.000	0.000
Etalon 1	17951	8900103	1.294	1.31500	1415.000	19181.0	19070.0	0.002	64.20	0.000	0.000	0.000

- Additional information
  - http://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/index.html
  - http://ilrs.gsfc.nasa.gov/missions/spacecraft_parameters/center_of_mass.html

Satellite Force Model Configuration

Force Models									
Parameter	**Larets**	**Stella**	**STARLETTE**	**LARES**	**Ajisai**	**LAGEOS 2**	**LAGEOS 1**	**Etalon2**	**Etalon1**
Gravity									
field size	70x70	70x70	70x70	70x70	70x70	70x70	70x70	40x40	40x40
Solid	yes	yes	yes	yes	yes	yes	yes	yes	yes
Time Dep	yes	yes	yes	yes	yes	yes	yes	yes	yes
Ocean	yes 4x0	yes 4x0	yes 4x0	yes 4x0	yes 4x4	yes 4x0	yes 4x4	yes 4x0	yes 4x0
Variational	8x8	8x8	8x8	12x12	8x8	6x2	6x2	12x12	12x12
Gen Rel	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Atmospheric Drag	yes	yes	yes	yes	yes	no	no	no	no
Third Body	yes	yes	yes	yes	yes	yes	yes	yes	yes
SRP	yes	yes	yes	yes	yes	yes	yes	yes	yes
Albedo	no	no	no	no	no	no	no	no	no
Thermal	no	no	no	no	no	no	no	no	no
Process Noise									
R (cm/s^2)	0.0000000	0.0000000	0.0000000	0.0000000	0.0000067	0.0000000	0.0000000	0.0000000	0.0000083
I (cm/s^2)	0.0000833	0.0000083	0.0000083	0.0000833	0.0000000	0.0000002	0.0000002	0.0000000	0.0000000
C (cm/s^2)	0.0000333	0.0000167	0.0000167	0.0000167	0.0000167	0.0000058	0.0000058	0.0000003	0.0000083
time int (min)	1	2	2	1	1	1	1	1	1

Satellite Force Model Configuration

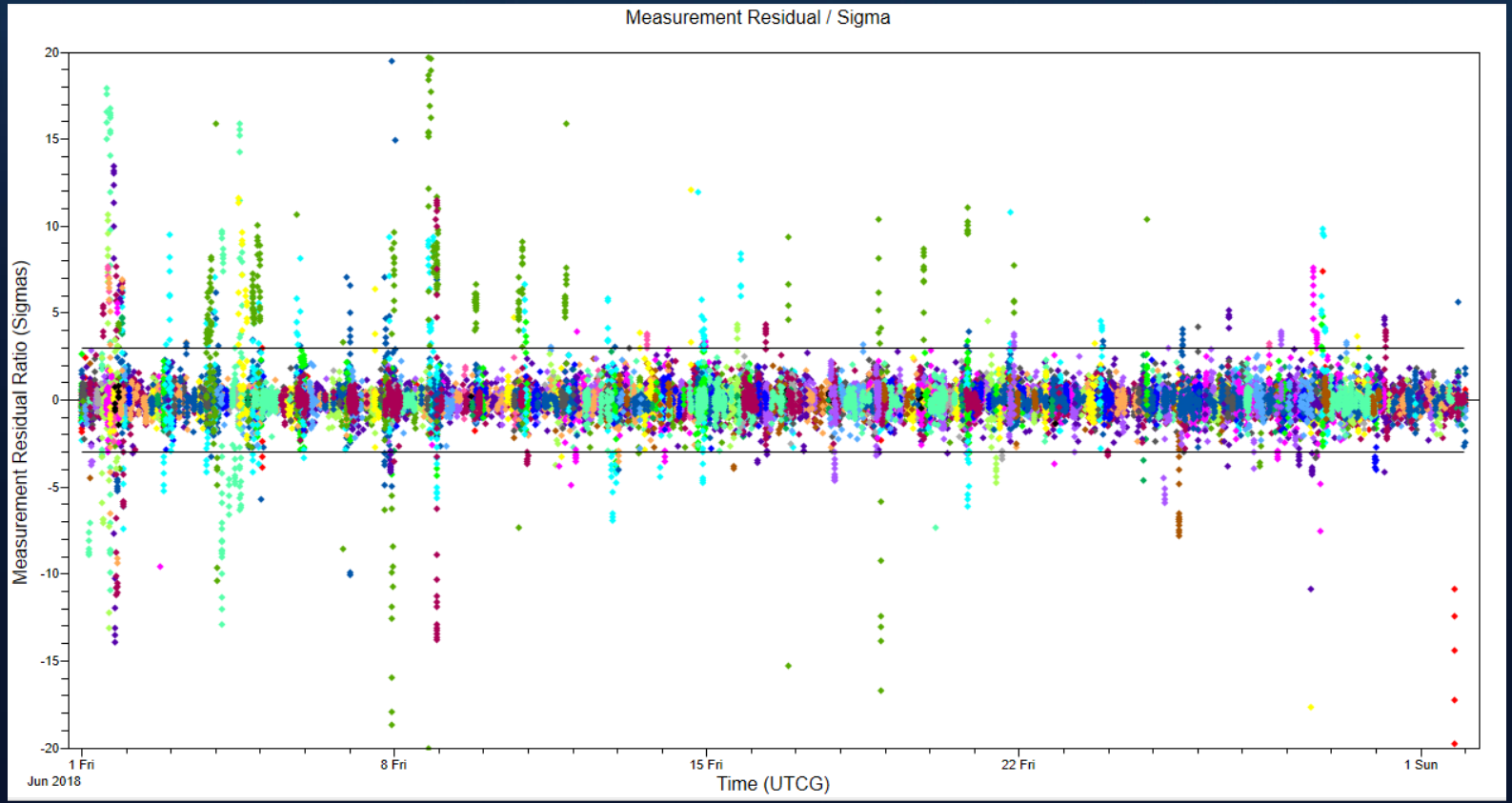
Parameter Settings									
Parameter	**Larets**	**Stella**	**STARLETTE**	**LARES**	**Ajisai**	**LAGEOS 2**	**LAGEOS 1**	**Etalon2**	**Etalon1**
Mass (kg)	23.28	48.000	47.295	386.80	685.00	405.380	406.985	1415.00	1415.00
Atmospheric Drag									
Model	Jacchia 71	NRLMSIS00E	NRLMSIS00E	Jacchia 71	Jacchia 71				
cd	3.06139	2.52738	2.5010	0.91782	2.6396				
area	0.0346	0.0452389	0.0452389	0.1450	3.6305				
LT Constant (BC	0.0045500	0.00238200	0.00239227	0.0003441	0.01348				
LT Sigma	0.05000	0.10000	0.10000	0.10000	0.10000				
LT Error Thresh	0.01000	0.01000	0.01000	0.01000	0.01000				
LT PNStep	0.00100	0.00100	0.00100	0.00100	0.00100				
ST Sigma	0.01500	0.10000	0.10000	0.10000	0.10000				
ST 1/2 life (min)	20	90	90	20	60				
Den 1/2 life	180	180	180	180	180				
Den Sigma Sc	1	1	1	1	1				
Use in Variationa	TRUE	TRUE	TRUE	TRUE	FALSE				
Addit PN	FALSE	FALSE	FALSE	FALSE	TRUE, .3/.3				
Solar Radiation Pressure									
area	0.035	0.0452389	0.0452389	0.145	3.6305	0.28274	0.28274	1.315	1.315
LT Constant (cr)	1.036700	1.01000	1.00000	0.570000	1.01514	1.10680	1.12000	1.29000	1.25000
LT Sigma	0.1000	0.0500	0.0500		0.1000	0.0200	0.0400	0.0500	0.0500
LT Error Thresh	0.0050	0.0100	0.0100		0.0100	0.0100	0.0100	0.0100	0.0100
LT PNStep	0.0050	0.0010	0.0010		0.0010	0.0010	0.0010	0.0010	0.0010
ST Sigma	0.0200	0.1000	0.1000	0.0200	0.1000	0.0500	0.1000	0.1000	0.1000
ST 1/2 life (min)	20	360	360	7200	360	3600	3600	720	720
Use in Variationa	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Addit PN	TRUE, 1/1	FALSE	FALSE	FALSE	TRUE, .3/.3	TRUE, .5/.5	TRUE, .5/.5	TRUE, .15/.15	TRUE, .15/.15
Retroreflector									
LT Constant (m)	-0.430	-0.160	-0.160	-0.908	-1.966	-0.481	-0.481	-1.124	-1.124
LT Sigma		0.005	0.005		0.0010	0.005	0.005	0.0020	0.0020
LT Error Thresh		0.00050	0.00050		0.0010	0.000000001	0.000000001	0.000000001	0.000000001
LT PNStep		0.00005	0.00005		0.0010	0.000000001	0.000000001	0.000000001	0.000000001
ST Sigma	0.0500	0.005	0.005	0.0500	0.0100	0.050	0.050	0.0050	0.0050
ST 1/2 life (min)	525600	525600	525600	525600	259200	525600	525600	259200	259200
PhaseCenterX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PhaseCenterY	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PhaseCenterZ	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Observation Numbers

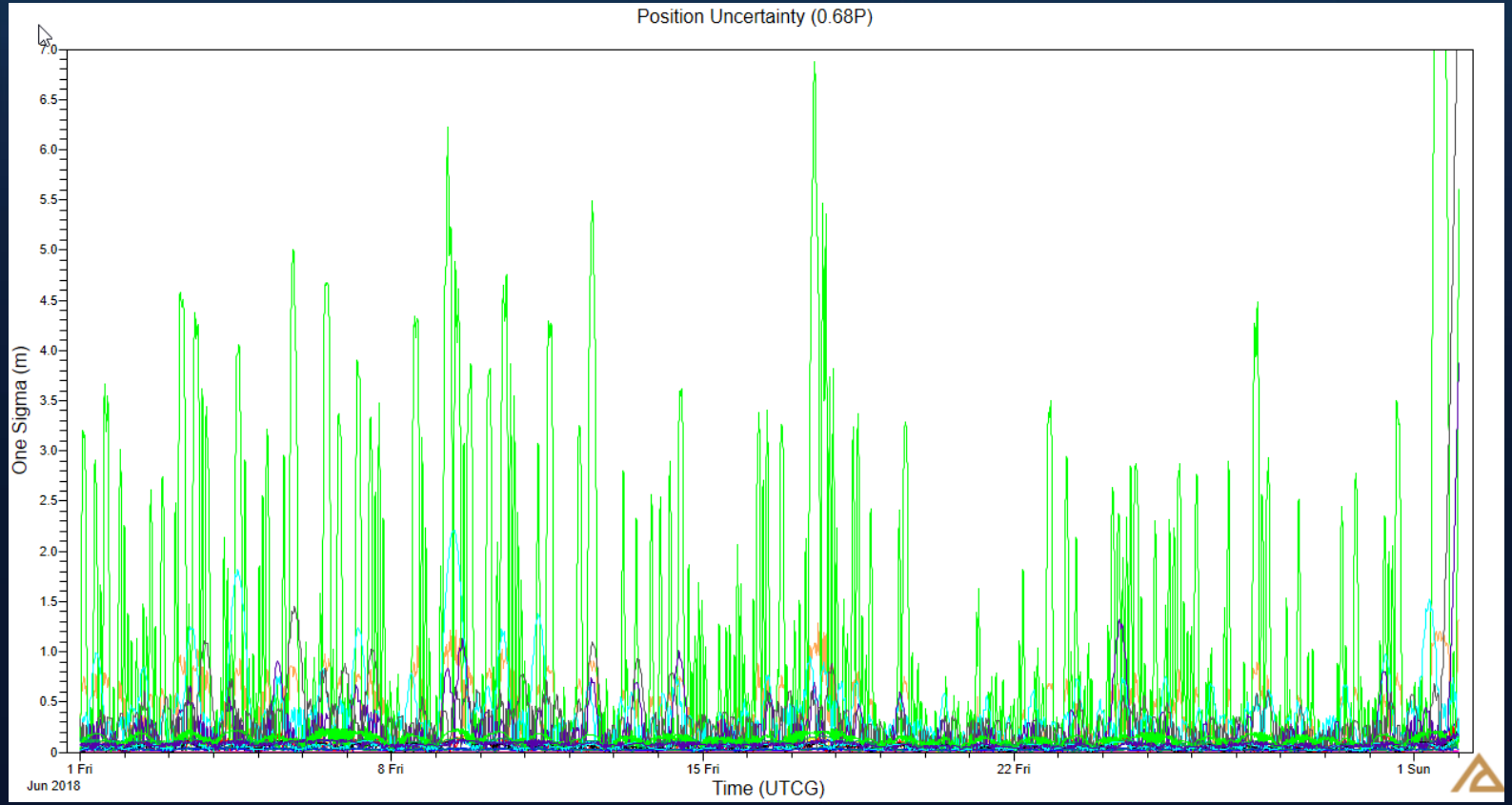
- Each satellite receives varying amounts of data (Jun – Aug 2018)

Larets			Stella			STARLETTE			LARES			Ajisai			LAGEOS 2			LAGEOS 1			Etalon1			Etalon2		
# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #	# obs	Site	Site #
1,208	ZIML	7810	1,948	YARL	7090	3,361	YARL	7090	3,695	ZIML	7810	4,528	YARL	7090	2,823	ZIML	7810	3,397	ZIML	7810	448	MATM	7941	481	YARL	7090
1,122	YARL	7090	1,787	ZIML	7810	2,821	ZIML	7810	2,283	YARL	7090	3,064	ZIML	7810	2,323	YARL	7090	2,536	YARL	7090	431	YARL	7090	305	MATM	7941
706	STL3	7825	1,146	STL3	7825	2,105	STL3	7825	1,895	HERL	7840	2,833	HARL	7501	1,921	MATM	7941	1,974	HERL	7840	199	WETL	8834	174	HARL	7501
660	GODL	7105	839	HARL	7501	1,855	MATM	7941	1,721	GRZL	7839	2,737	STL3	7825	1,543	HARL	7501	1,809	MATM	7941	179	HERL	7840	163	WETL	8834
538	GRZL	7839	684	GODL	7105	1,423	HARL	7501	1,547	POT3	7841	2,083	GRZL	7839	1,285	HERL	7840	1,251	HARL	7501	138	ZIML	7810	102	HERL	7840
476	HARL	7501	617	AREL	7403	1,416	GODL	7105	1,441	SOSW	7827	2,038	AREL	7403	1,046	GODL	7105	955	STL3	7825	109	GODL	7105	92	ZIML	7810
452	POT3	7841	497	GRZL	7839	1,376	GRZL	7839	1,381	MATM	7941	2,005	MONL	7110	922	STL3	7825	913	POT3	7841	91	HARL	7501	56	SOSW	7827
417	HERL	7840	487	MATM	7941	1,239	WETL	8834	1,176	HARL	7501	1,836	GODL	7105	662	WETL	8834	867	SISL	7838	87	SHA2	7821	33	THTL	7124
365	SIML	1873	483	WETL	8834	1,144	HERL	7840	1,171	GODL	7105	1,800	MATM	7941	600	SHA2	7821	805	GODL	7105	68	GRZL	7839	31	GRZL	7839
328	MATM	7941	369	POT3	7841	1,068	MONL	7110	1,066	STL3	7825	1,731	WETL	8834	458	SISL	7838	765	WETL	8834	63	SOSW	7827	25	SHA2	7821
320	CHAL	7237	325	HERL	7840	935	POT3	7841	821	WETL	8834	1,461	HERL	7840	424	HA4T	7119	733	SHA2	7821	45	CHAL	7237	24	STL3	7825
259	AREL	7403	318	CHAL	7237	839	CHAL	7237	810	SIML	1873	1,377	POT3	7841	394	GRZL	7839	576	GRZL	7839	36	BEIL	7249	14	KUN2	7819
224	WETL	8834	318	KTZL	1893	829	KTZL	1893	717	CHAL	7237	1,364	SISL	7838	376	CHAL	7237	539	MONL	7110	23	STL3	7825	11	GODL	7105
223	KTZL	1893	278	HA4T	7119	812	AREL	7403	639	MONL	7110	1,074	SHA2	7821	372	MONL	7110	527	HA4T	7119	21	SIML	1873	9	CHAL	7237
218	ALTL	1879	271	SIML	1873	698	SIML	1873	537	THTL	7124	985	KTZL	1893	310	THTL	7124	480	CHAL	7237	20	ALTL	1879	9	POT3	7841
218	HA4T	7119	253	HRTL	7503	662	SHA2	7821	463	SHA2	7821	893	CHAL	7237	307	BRAL	7407	458	THTL	7124	18	KUN2	7819	6	ALTL	1879
198	SISL	7838	242	SHA2	7821	535	SOSW	7827	461	HA4T	7119	851	HRTL	7503	287	POT3	7841	376	IRKL	1891	16	MDVS	1874	5	SIML	1873
177	HRTL	7503	230	SOSW	7827	518	HA4T	7119	446	BORL	7811	766	THTL	7124	243	SOSW	7827	346	GRSM	7845	15	MONL	7110	3	ARKL	1886
168	SHA2	7821	225	MONL	7110	509	SISL	7838	418	KTZL	1893	707	SOSW	7827	236	GRSM	7845	272	MDVS	1874	7	KOML	1868	3	BEIL	7249
142	SOSW	7827	191	SISL	7838	438	THTL	7124	355	SISL	7838	691	SIML	1873	211	SIML	1873	252	BEIL	7249	7	THTL	7124	3	IRKL	1891
141	BORL	7811	98	KUN2	7819	360	HRTL	7503	291	RIGL	1884	661	HA4T	7119	184	KTZL	1893	244	SOSW	7827	6	HRTL	7503	3	KOML	1868
135	RIGL	1884	81	IRKL	1891	336	BEIL	7249	253	ALTL	1879	541	BEIL	7249	180	BORL	7811	223	SIML	1873	6	IRKL	1891			
134	THTL	7124	71	BEIL	7249	219	GLSL	1824	232	BEIL	7249	362	KUN2	7819	179	BEIL	7249	212	BRAL	7407	6	POT3	7841			
125	MONL	7110	63	ZELL	1889	200	ZELL	1889	232	IRKL	1891	357	RIGL	1884	165	BAIL	1887	192	ALTL	1879	5	ARKL	1886			
92	BADL	1890	62	THTL	7124	180	BORL	7811	227	MDVS	1874	307	GLSL	1824	147	IRKL	1891	186	BAIL	1887	2	SEJL	7394			
72	KUN2	7819	48	SVEL	1888	179	KUN2	7819	225	AREL	7403	295	ZELL	1889	136	ALTL	1879	143	ARKL	1886						
58	SEJL	7394	27	SEJL	7394	122	SEJL	7394	204	BADL	1890	229	BORL	7811	135	MDVS	1874	135	KTZL	1893						
57	GLSL	1824	26	ARKL	1886	119	RIGL	1884	199	ZELL	1889	219	ARKL	1886	117	HRTL	7503	131	KUN2	7819						
56	BEIL	7249	9	BRAL	7407	116	ARKL	1886	186	ARKL	1886	207	IRKL	1891	98	AREL	7403	113	HRTL	7503						
53	KOML	1868	7	GRSM	7845	103	IRKL	1891	162	KUN2	7819	109	BRAL	7407	97	ZELL	1889	110	BORL	7811						
43	ZELL	1889	6	BORL	7811	54	MDVS	1874	145	HRTL	7503	108	SEJL	7394	89	ARKL	1886	88	KOML	1868						
28	SVEL	1888	6	RIGL	1884	43	BRAL	7407	112	KOML	1868	68	MDVS	1874	88	KUN2	7819	81	RIGL	1884						
20	IRKL	1891				28	SVEL	1888	98	GLSL	1824	52	SVEL	1888	74	SEJL	7394	72	AREL	7403						
16	BAIL	1887				21	MDOL	7080	89	SEJL	7394				55	KOML	1868	61	ZELL	1889						
10	BRAL	7407							69	GRSM	7845				55	SVEL	1888	42	SEJL	7394						
									63	SVEL	1888				31	RIGL	1884	37	BADL	1890						
									35	BRAL	7407				17	BADL	1890	13	SVEL	1888						
9459			12012			26663			25865			38339			18590			21914			2046			1552		

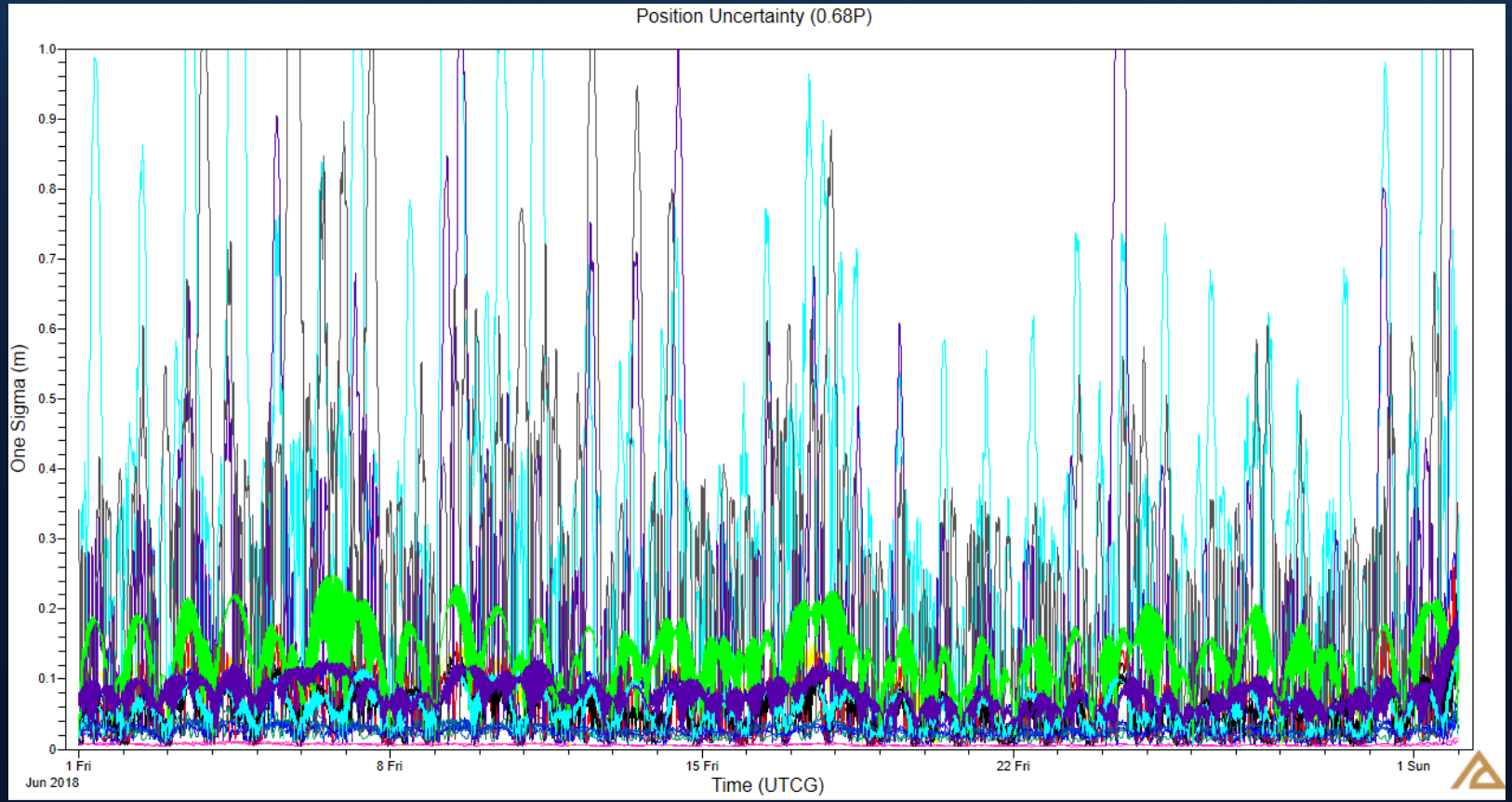
Original Configuration – Residual Ratios



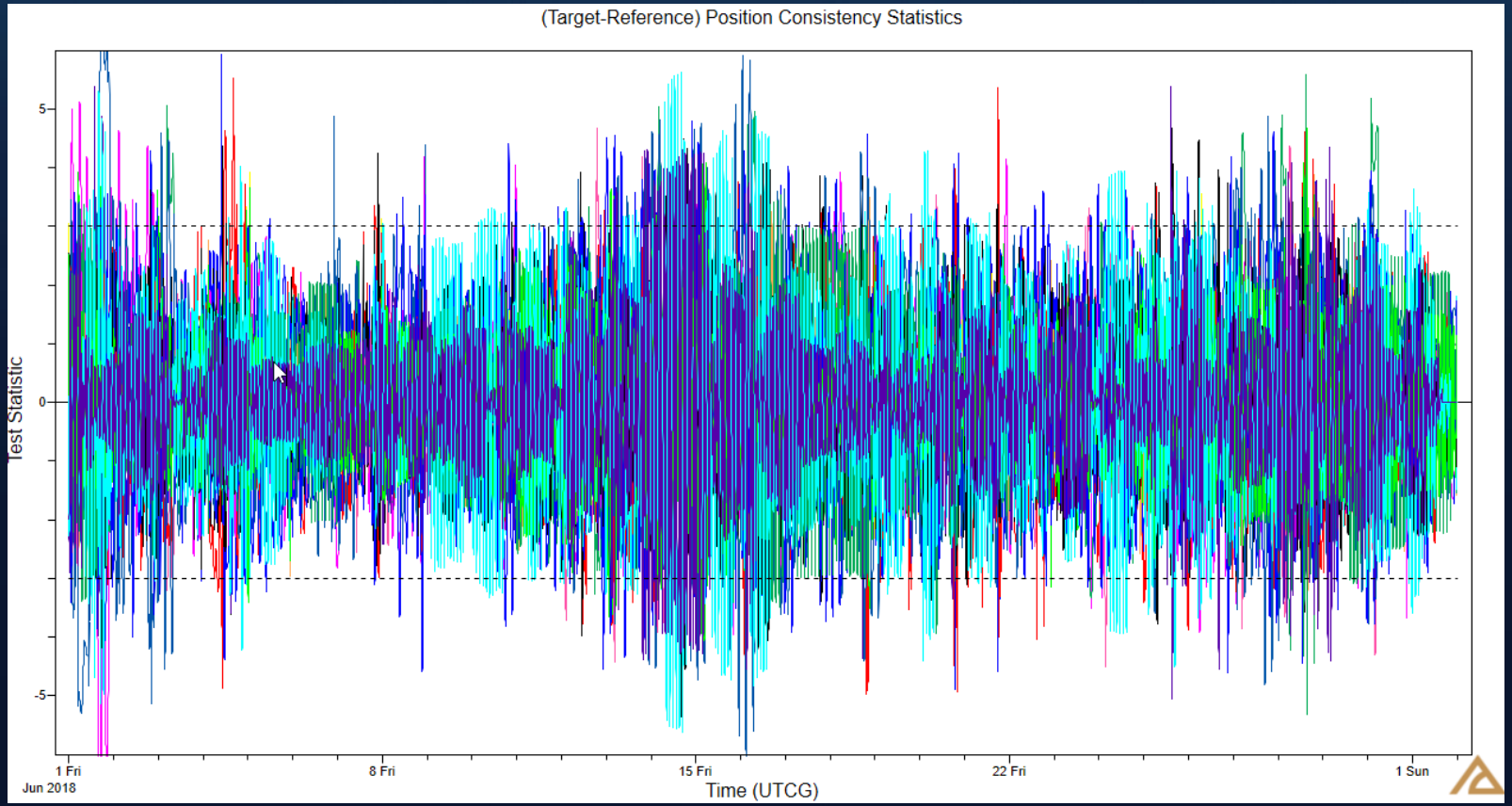
Original Configuration - Covariance



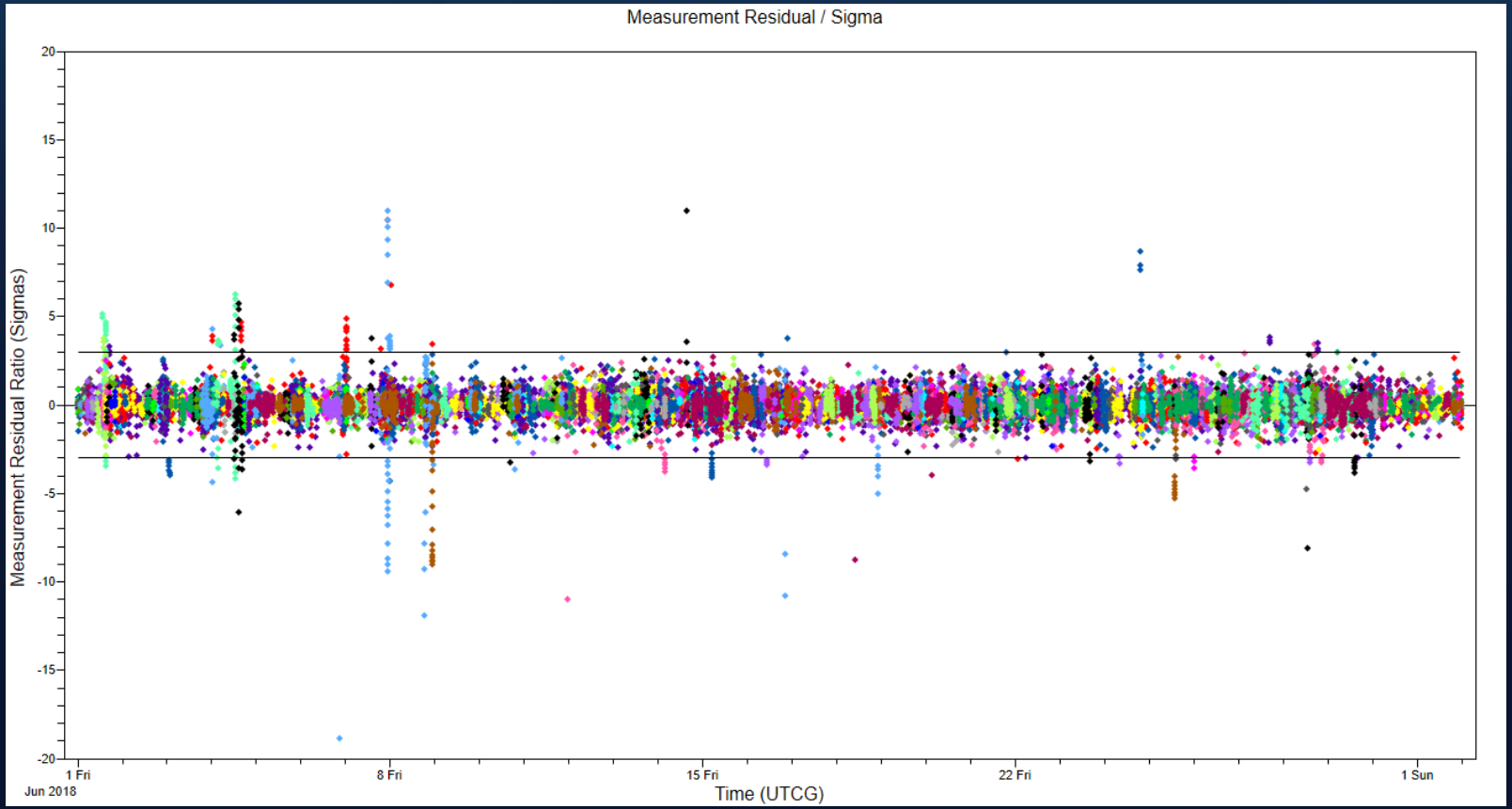
Original without LARES



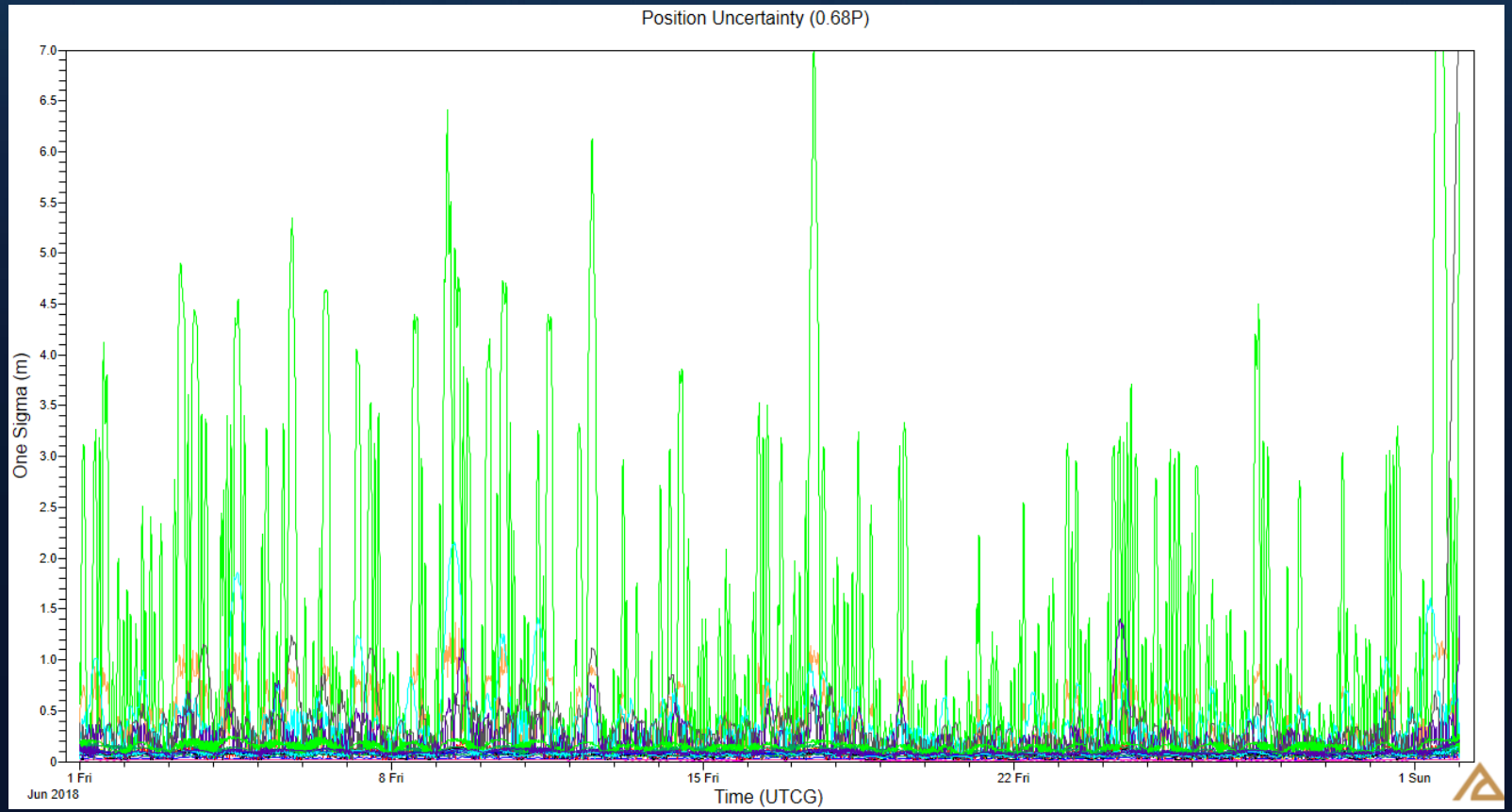
Original – Position Filter Smoother Consistency



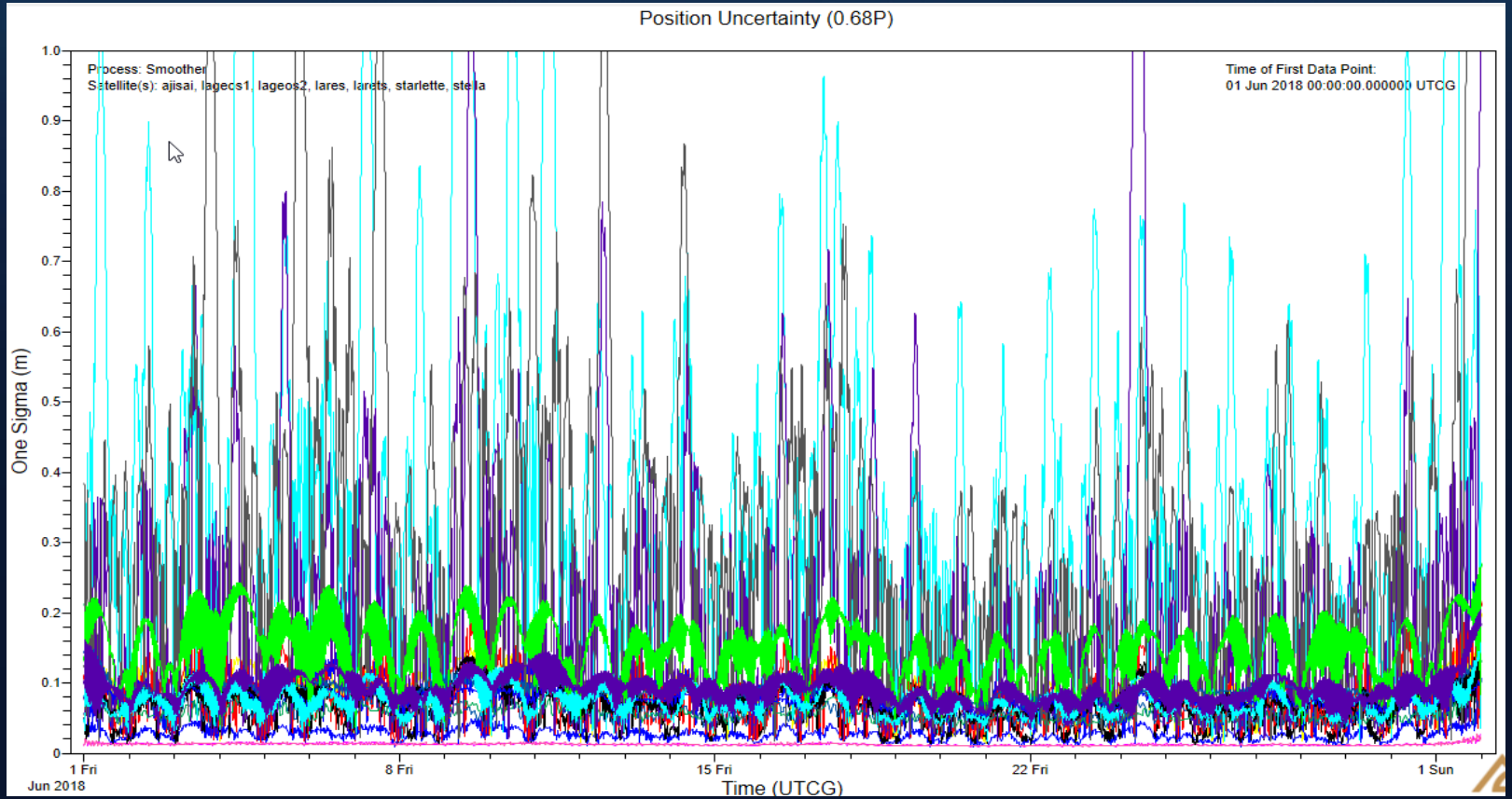
New Configuration



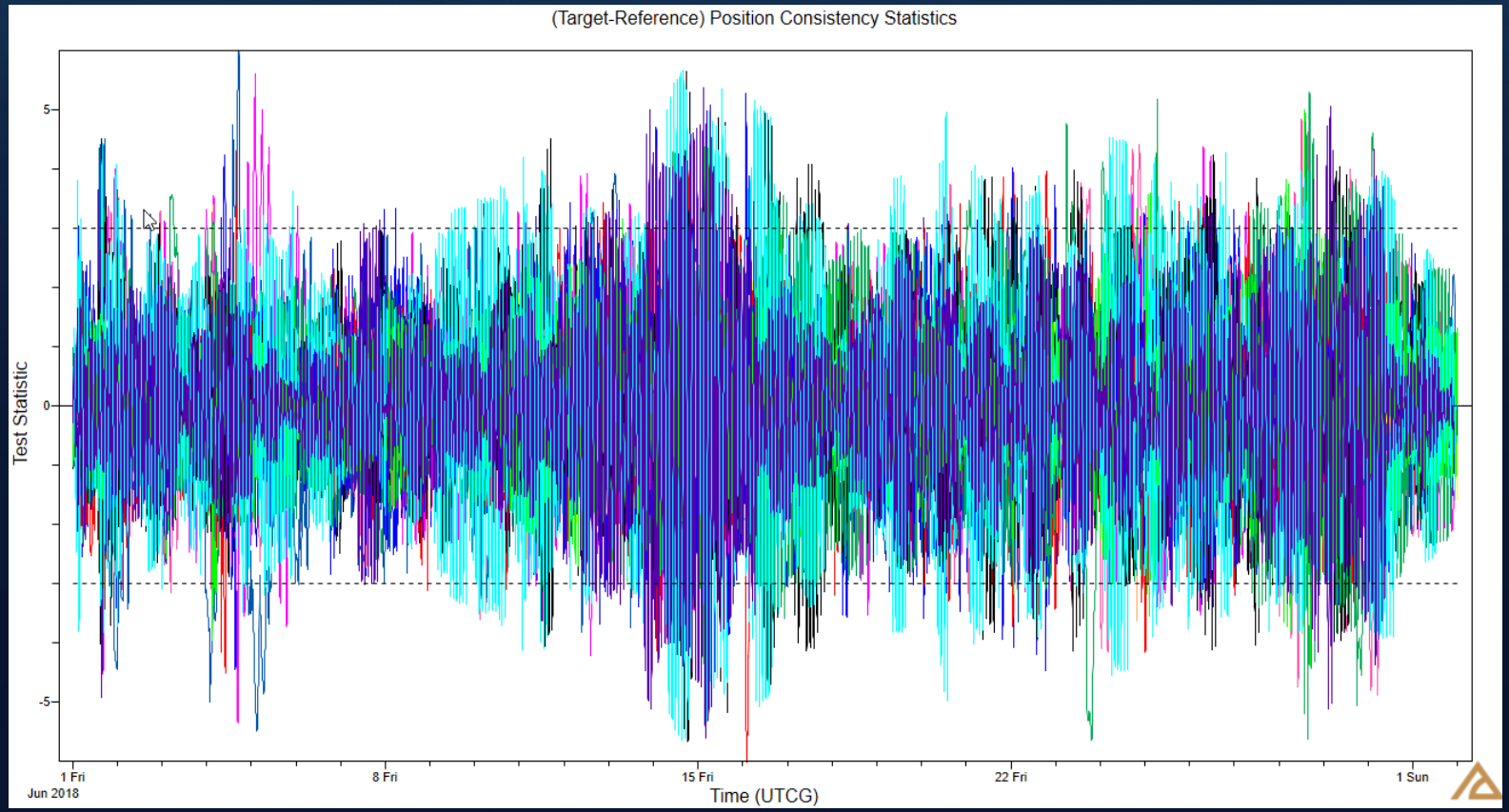
New Configuration



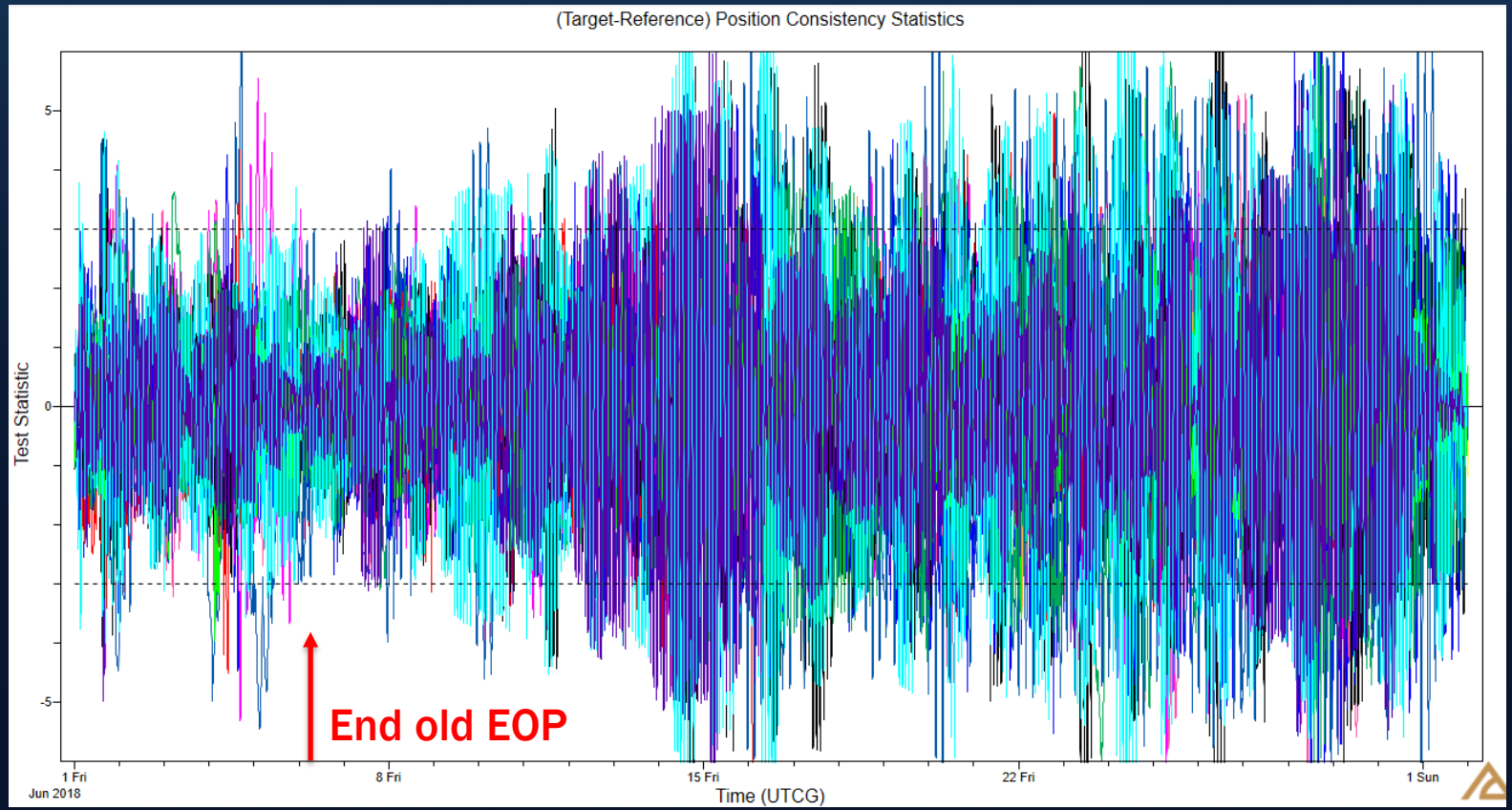
New without LARES



New – Position FSC

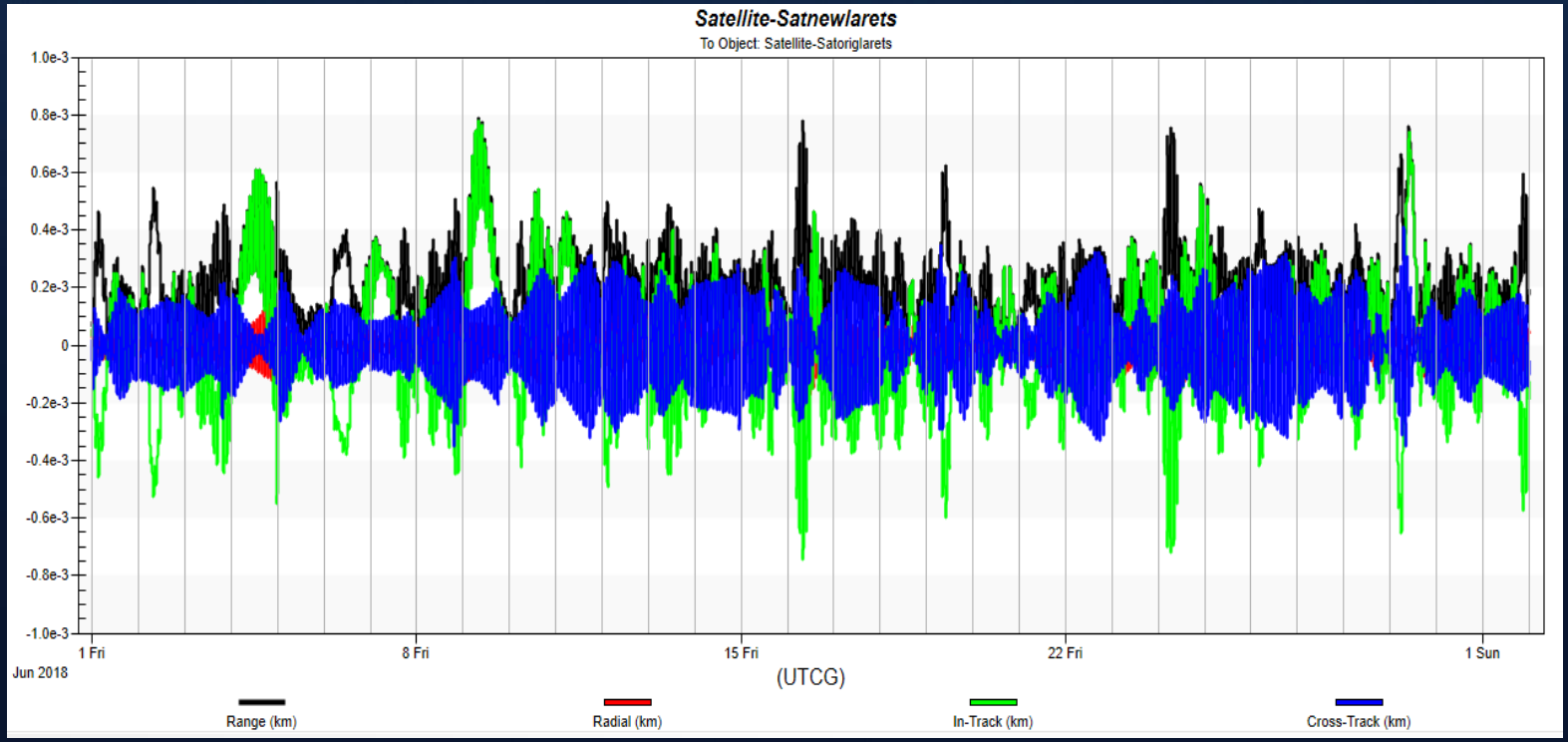


New – Position FSC – Old EOP



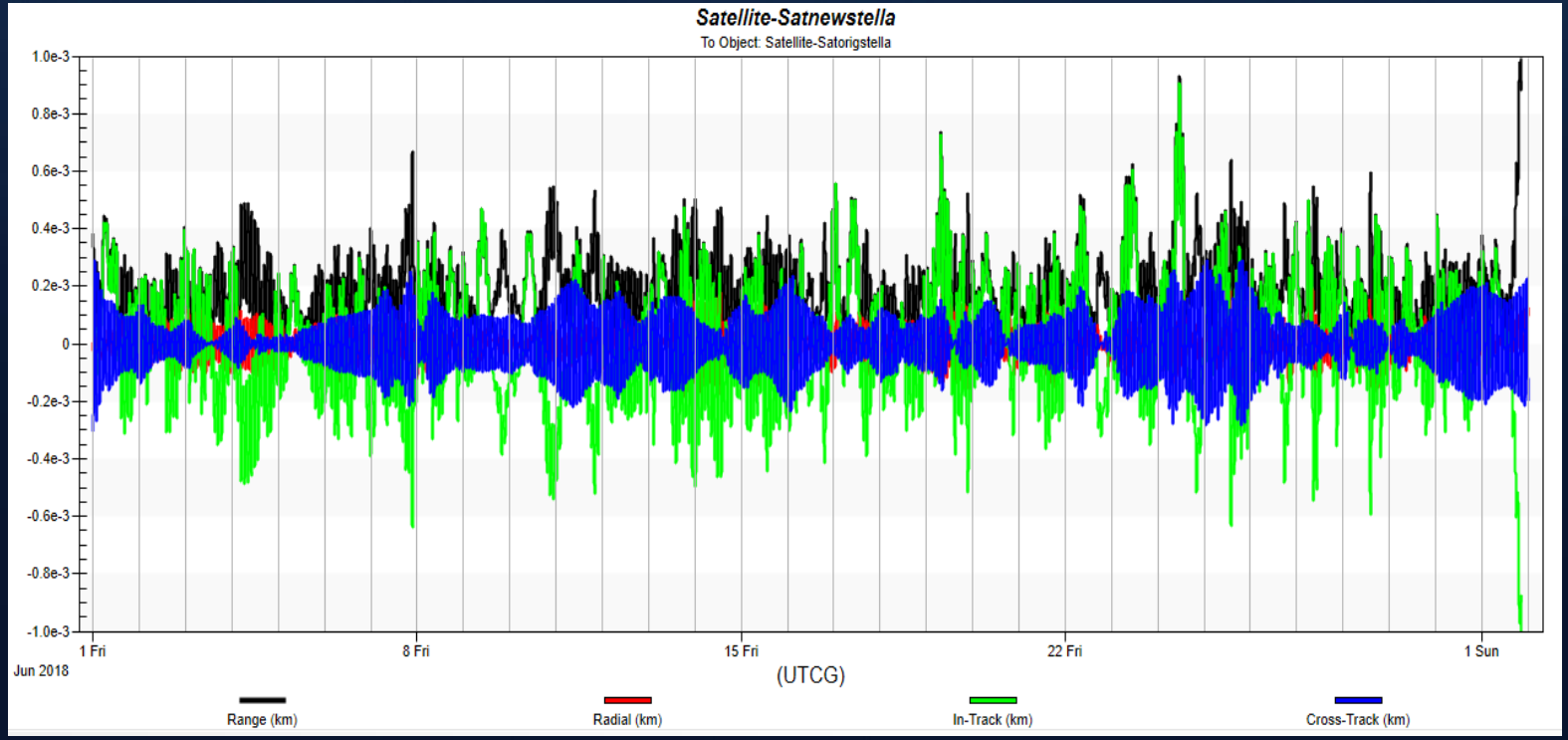
Comparison: Larets Old vs New

- Scale (1m max)



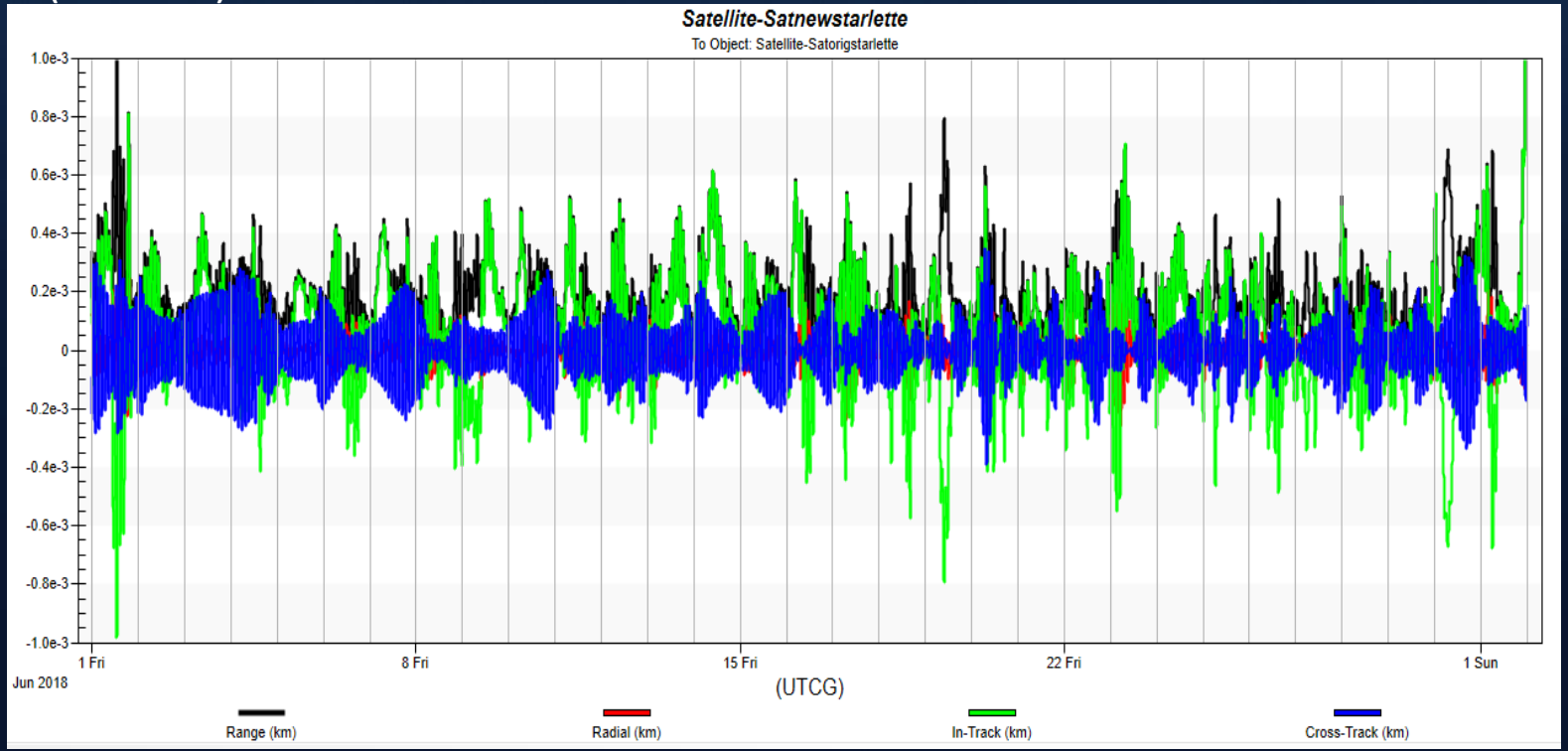
Comparison: Stella Old vs New

- Scale (1m max)



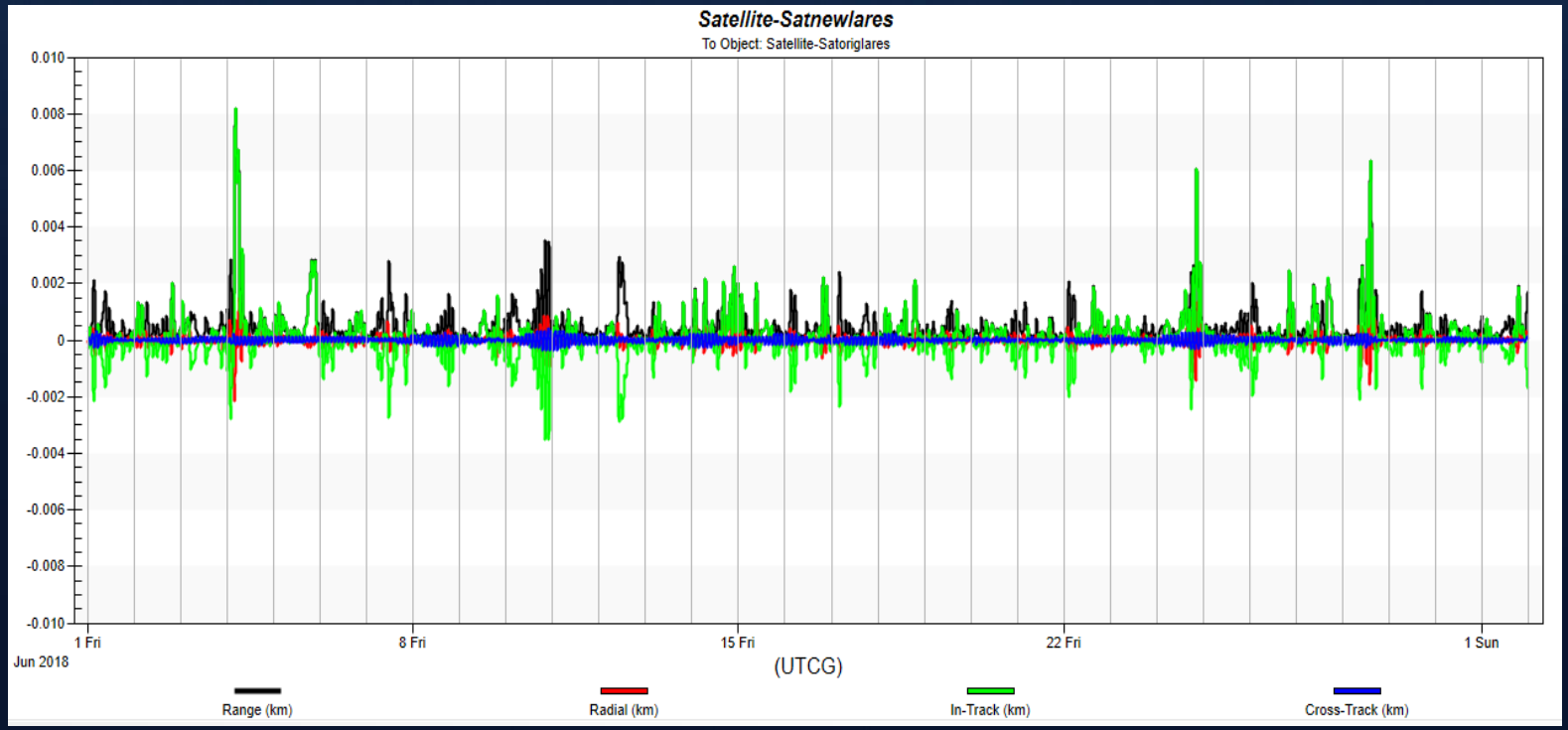
Comparison: Starlette Old vs New

- Scale (1m max)



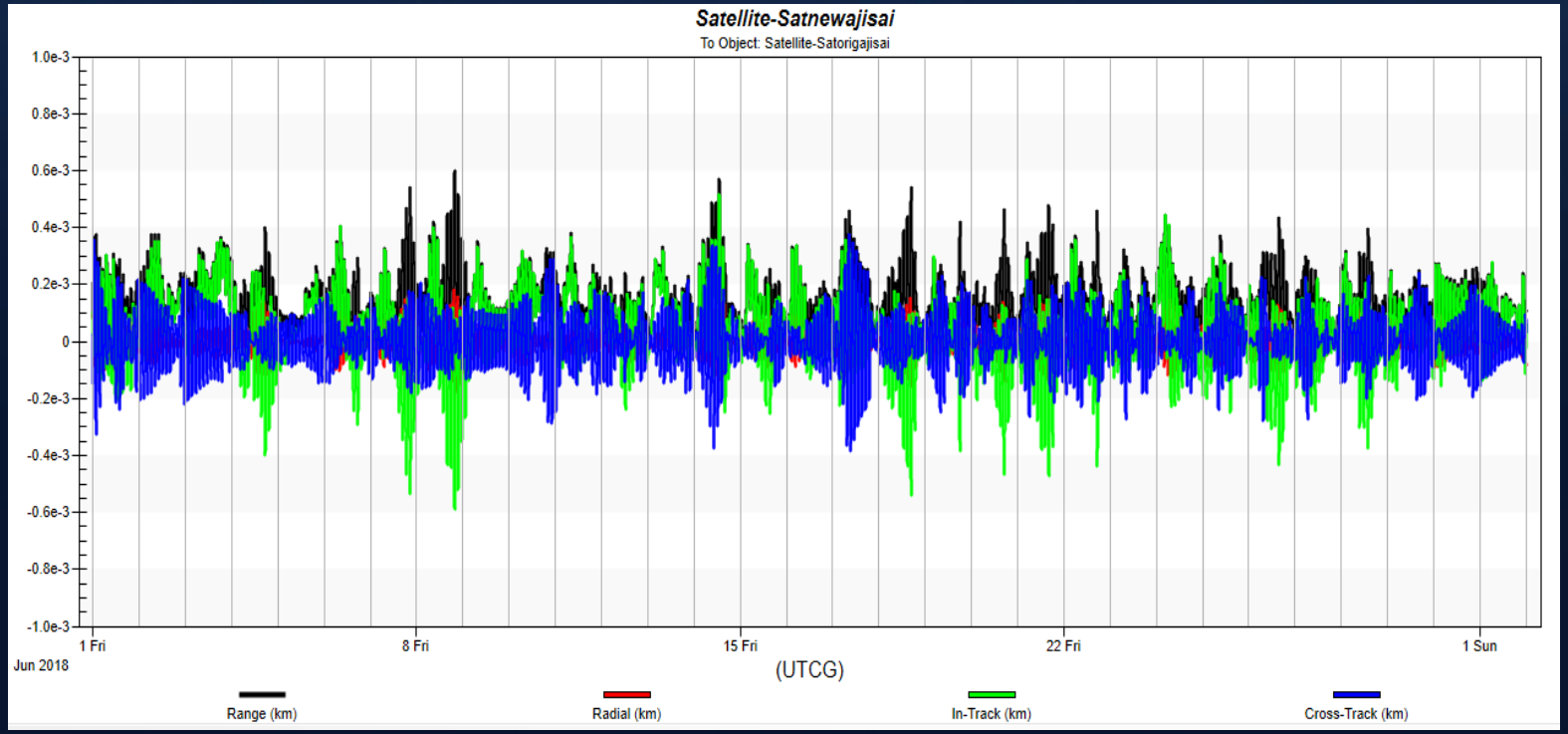
Comparison: Lares Old vs New

- Different scale (10m max)



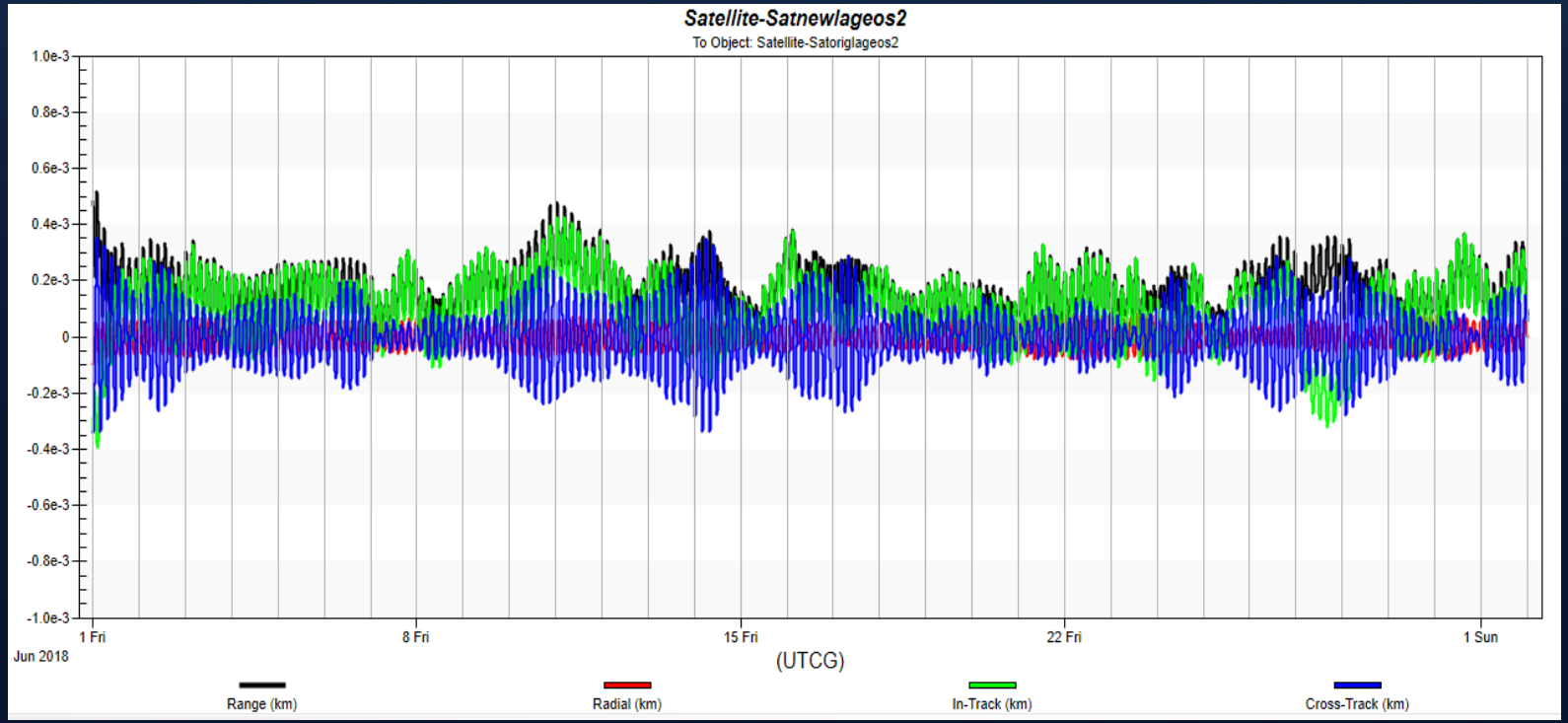
Comparison: Ajisai Old vs New

- Scale (1m max)



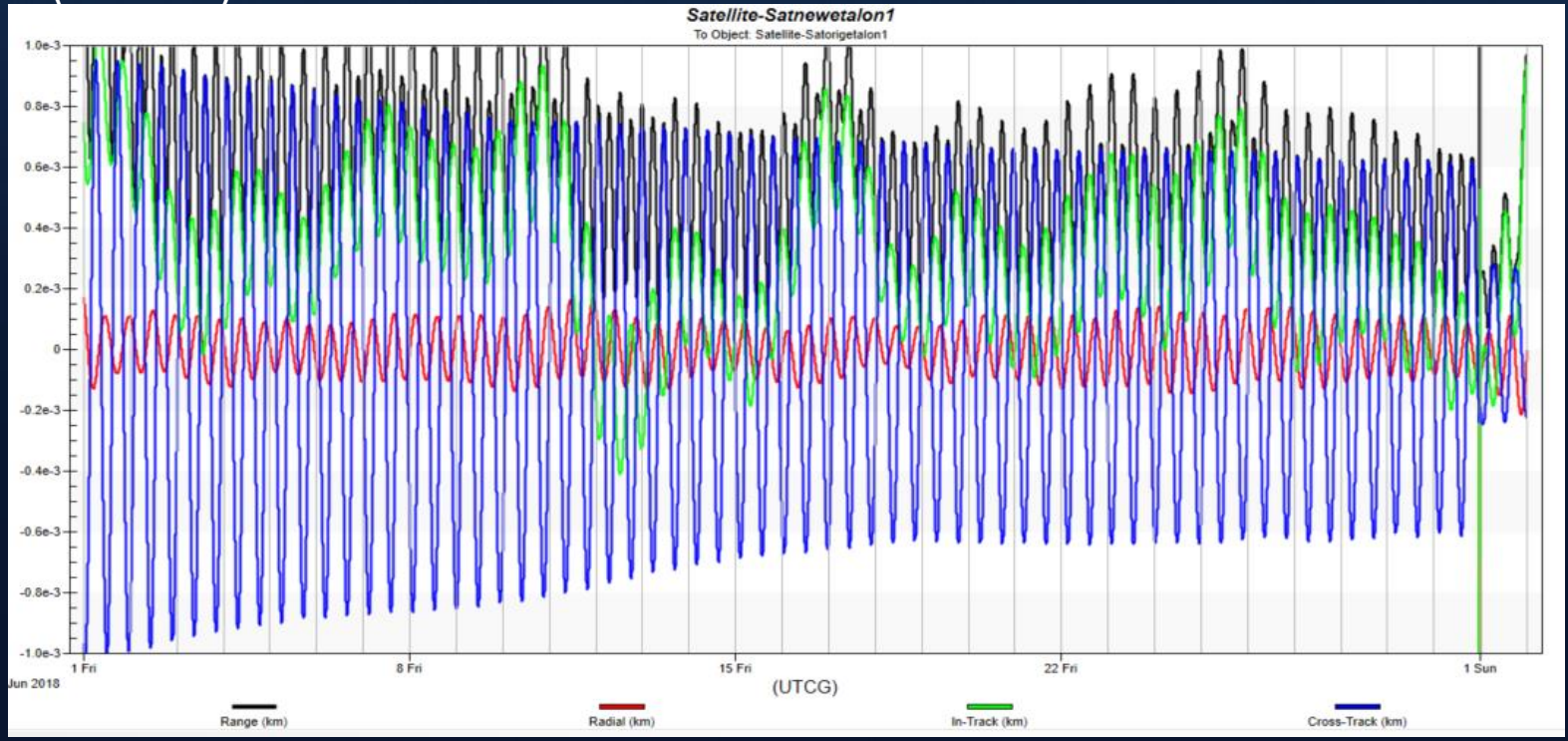
Comparison: Lageos II Old vs New

- Scale (1m max)



Comparison: Etalon-1 Old vs New

- Scale (1m max)

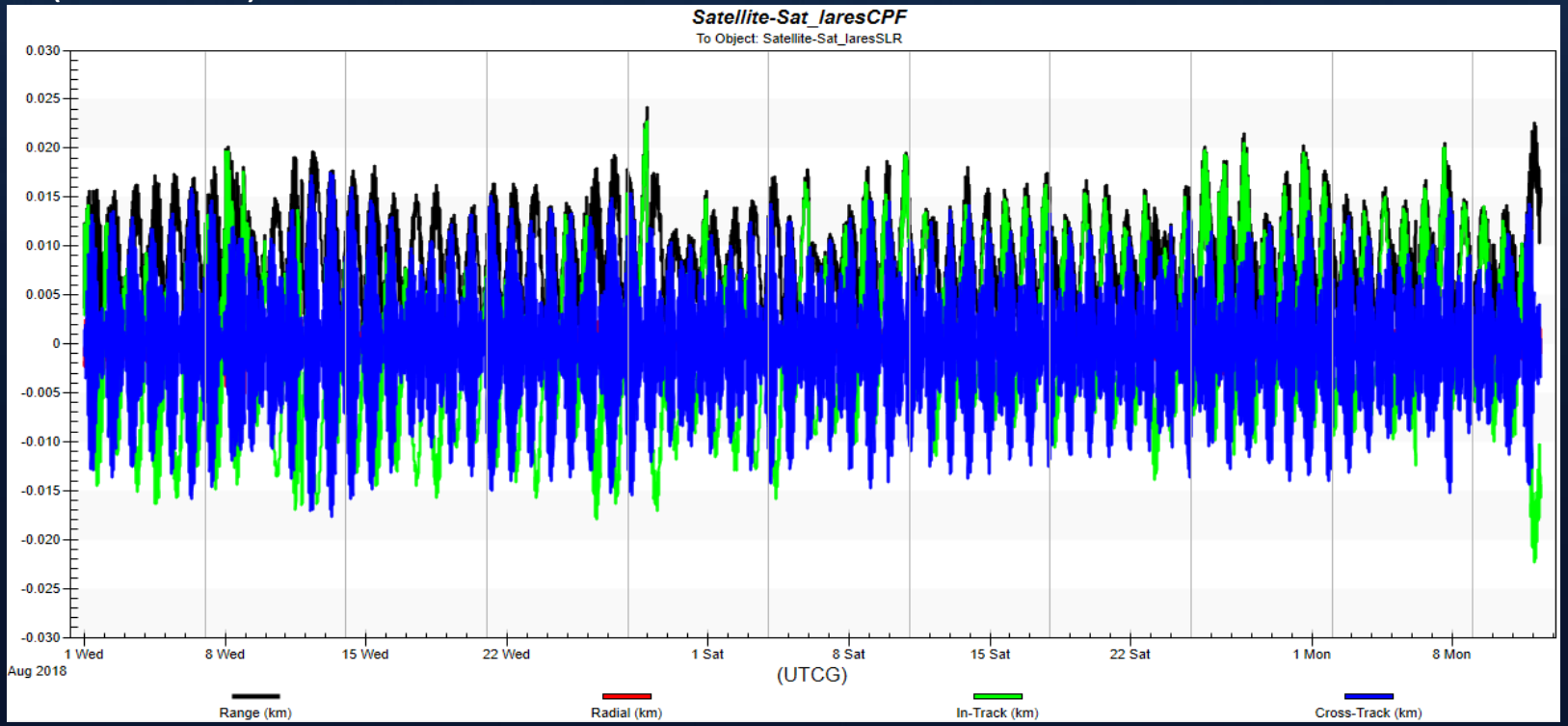


CPF file comparisons

- CPF files are a prediction, not an OD
  - Sometimes contain Maneuvers
- CPF files compared to new SLR processing
  - Comparisons in the meter range
  - Different centers produce different results?
- CPF files compared to Two-Line Element (TLE) sets
  - TLEs much less accurate, but very dense tracking produces reasonable results
  - Comparisons in the kilometer range

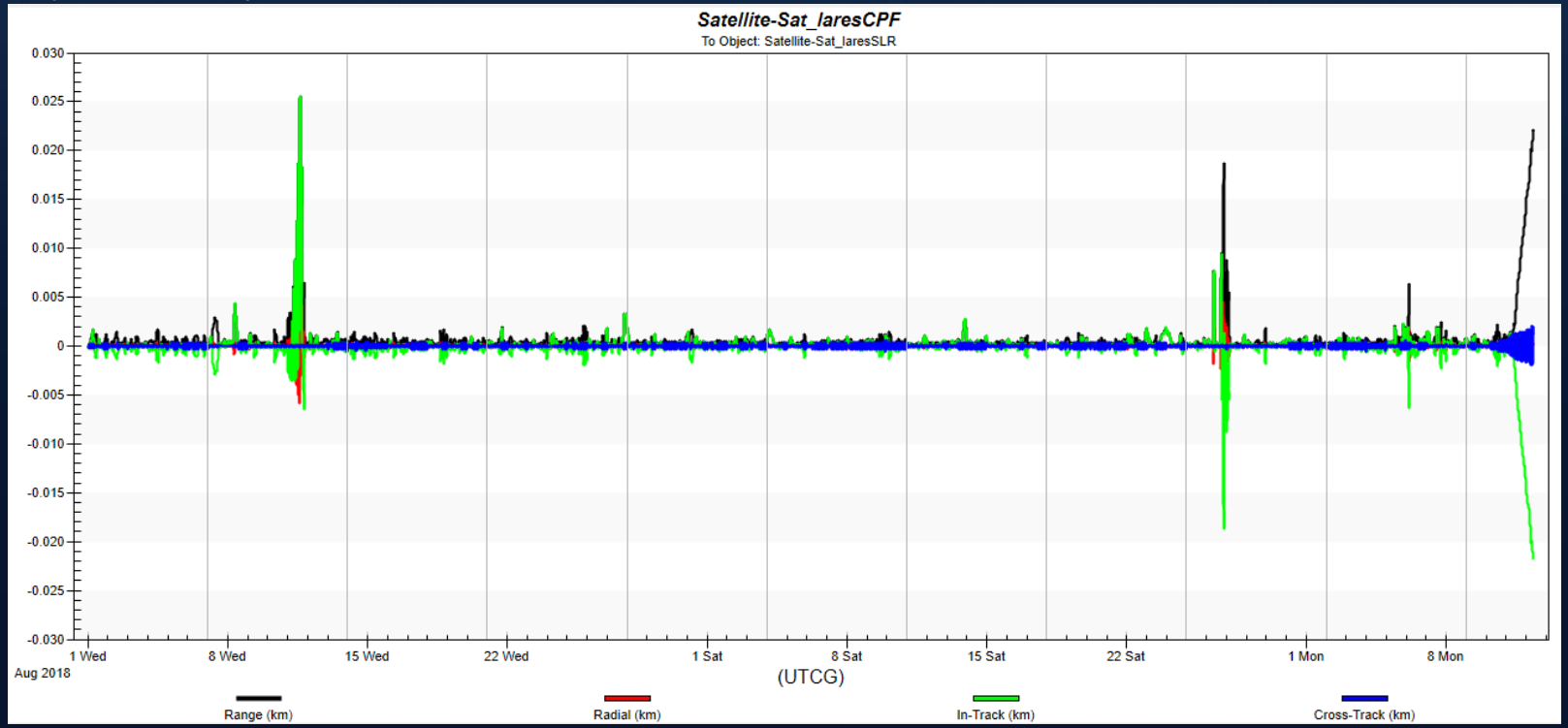
Comparison: LARES New vs CPF from HTS

- Scale (30 m max)



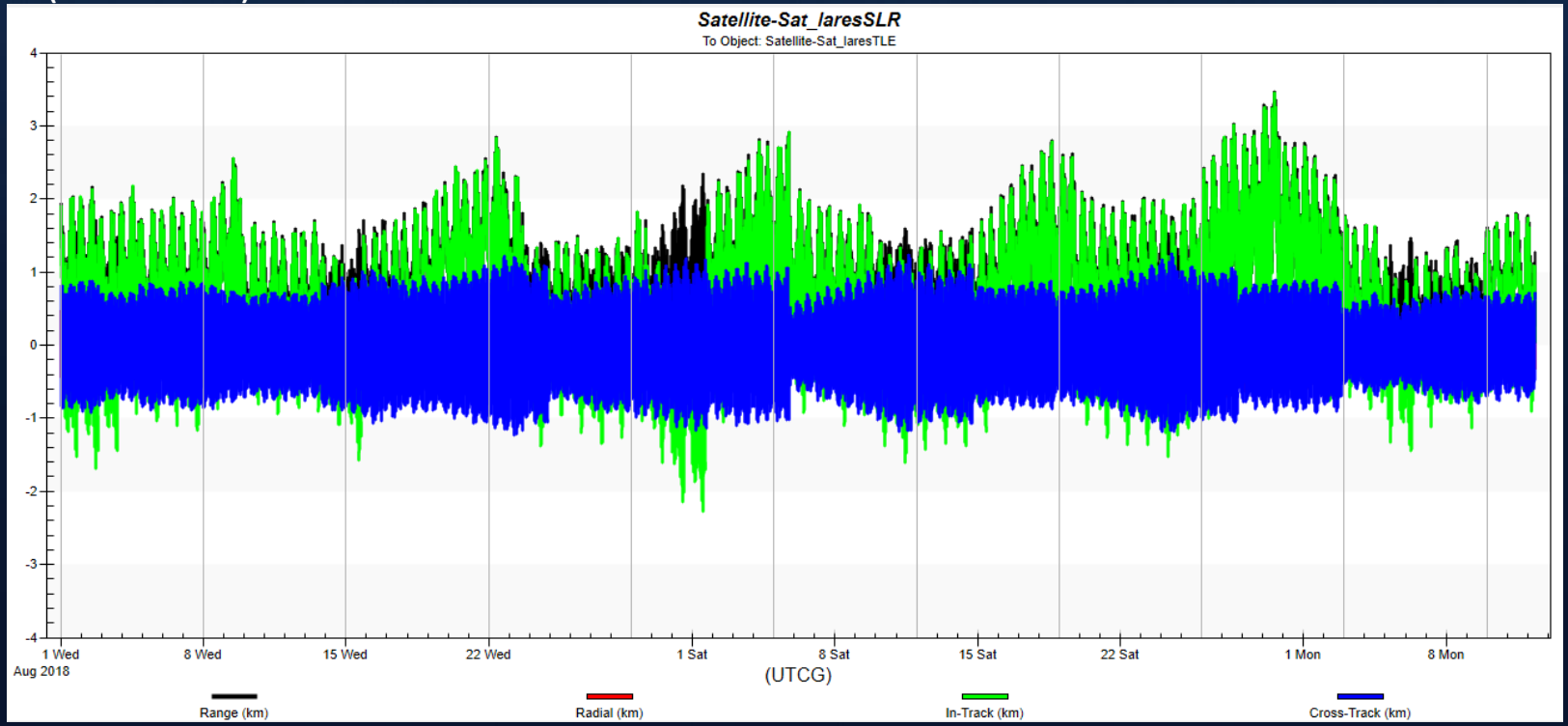
Comparison: LARES New vs CPF from SGF

- Scale (30 m max)



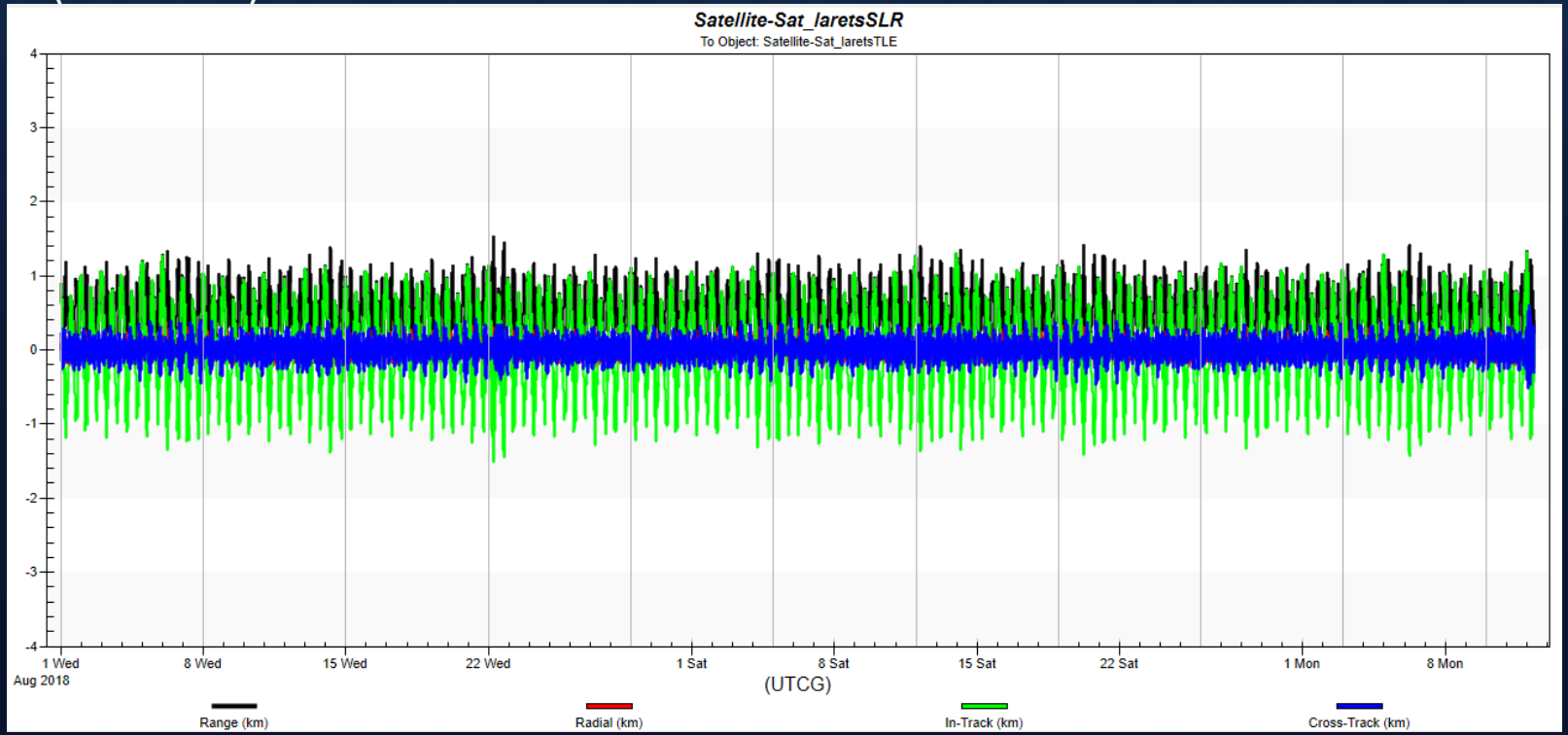
Comparison: LARES New vs TLE

- Scale (4 km max)



Comparison: Larets New vs TLE

- Scale (4 km max)



Conclusions

- Sequential OD using SLR Observations
  - Details to setup OD and initial calibration
    - Sensor system modeling
    - Satellite parameter modeling
- Changes from previous setup
  - New locations and sensor parameters
  - Etalon-1 un-modeled cross-track process noise
  - SEJL parameters to accept more observations
- Comparisons
  - Previous setup (sub meter)
  - CPF ephemerides (~10s meters)
  - TLE generated ephemerides (few kilometers)
  - Similarity of position uncertainty and independent comparisons
- Future
  - Understand LARES results better
  - Understand Prediction Centers processing better

Questions?