The ILRS Analysis Centers' Report on the Evaluation of ITRF2020P

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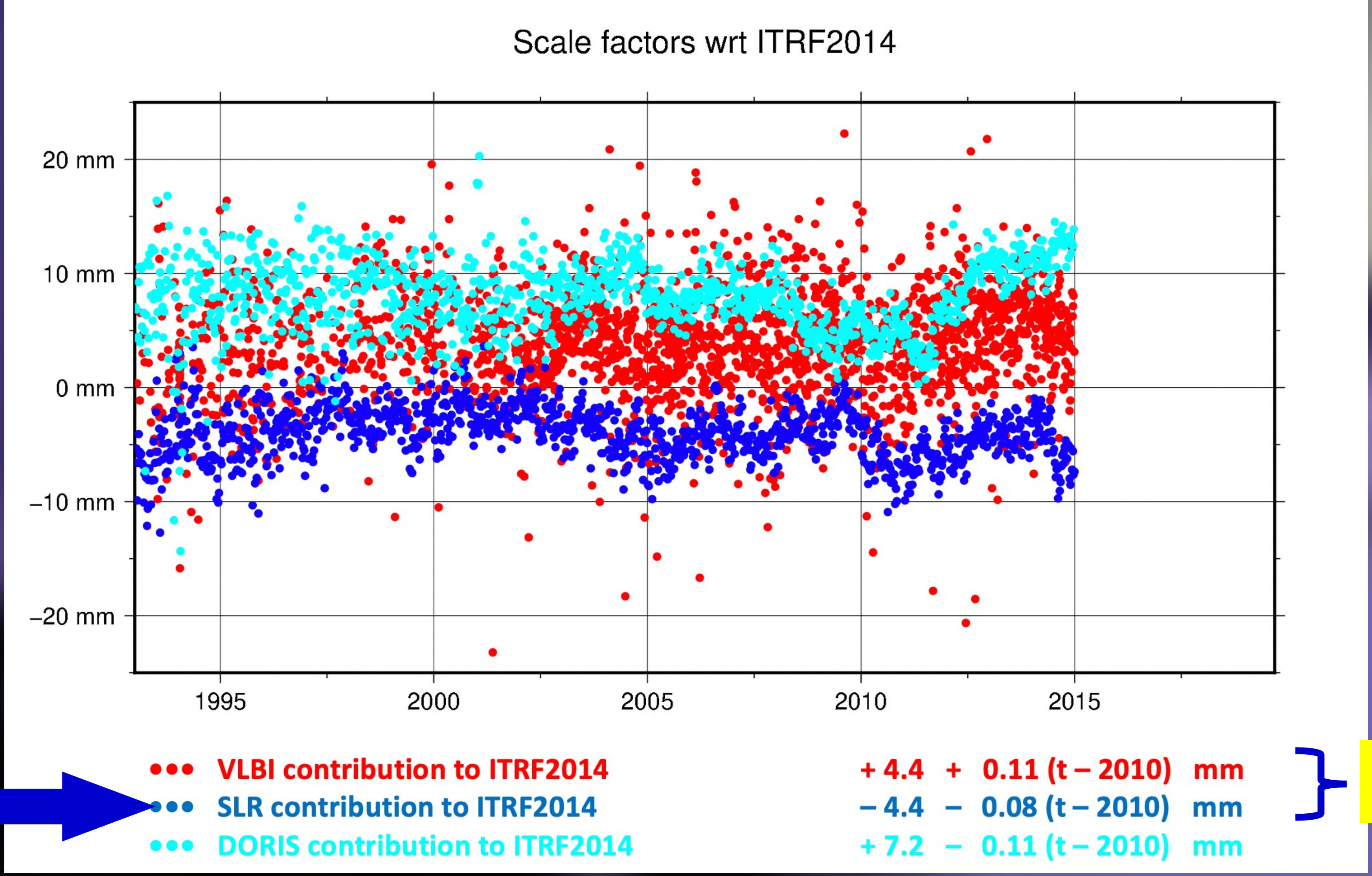
Overview of the ILRS ASC Evaluation

- Four of the Analysis Centers comprising the ILRS ASC submitted reports on evaluation tests performed on the preliminary version of ITRF2020—ITRF2020P. This summary provides an overview of the work performed and the key results as identified by the teams of the four ACs (ASI, DGFI, GFZ and NSGF). Additional evaluations are in progress, using now the FINAL version of ITRF2020, in preparation for its implementation.

- In these evaluation efforts all four contributing ACs adopted ITRF2020P as the new a priori TRF for their work. They regenerated a new series of REPRO2020-like SINEX files, using exactly the same modeling as in REPRO2020 and replacing only the a priori TRF and PSD model with the ITRF2020P, in place of ITRF2014.

- We firstly review the main areas of modeling updates that resulted in the major improvement seen in the SLR contribution to ITRF2020.

SLR - VLBI Scales Systematically Different in ITRF2014



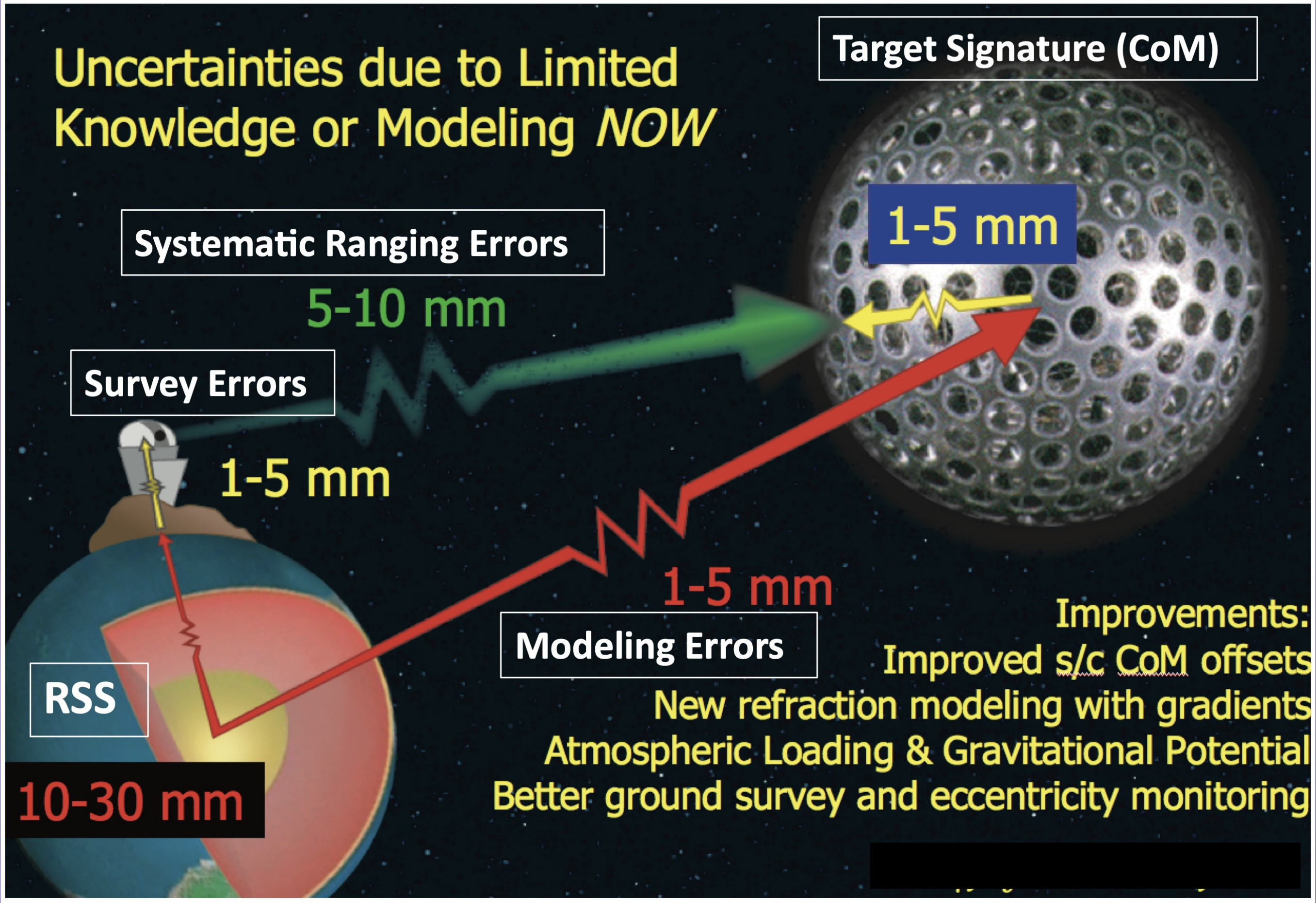
VLBI - SLR = 8.8 mm ≈ 1.375 ppb

In 2015 ILRS launched a multi-year effort to address and resolve the SLR scale issue: Station Systematic Error Modeling Pilot Project (**SSEM PP**).

Credits: ITRS Center, ILRS ASC Meeting, Oct. 1st, 2019, Observatoire de Paris

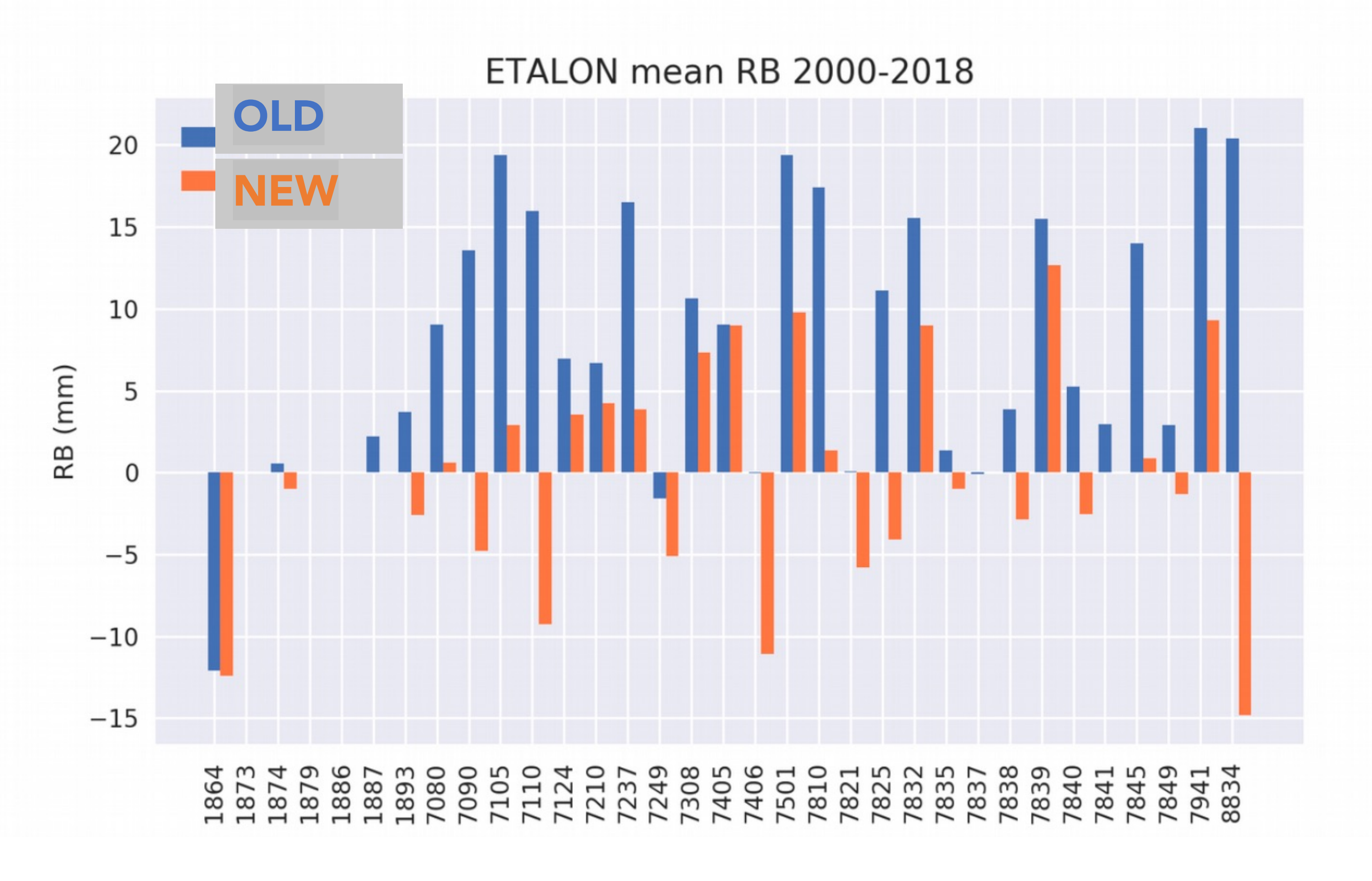
Pre-Analysis Investigations:

- Complete re-evaluation of stations' operating practices and recalculation of all station- and satellite-specific (time dependent) "target signature corrections"
- Simultaneous estimation of station positions and systematic errors (weekly resolution) adopted
- Review of station surveys and correction of eccentricity errors



Improved Target Signature Corrections

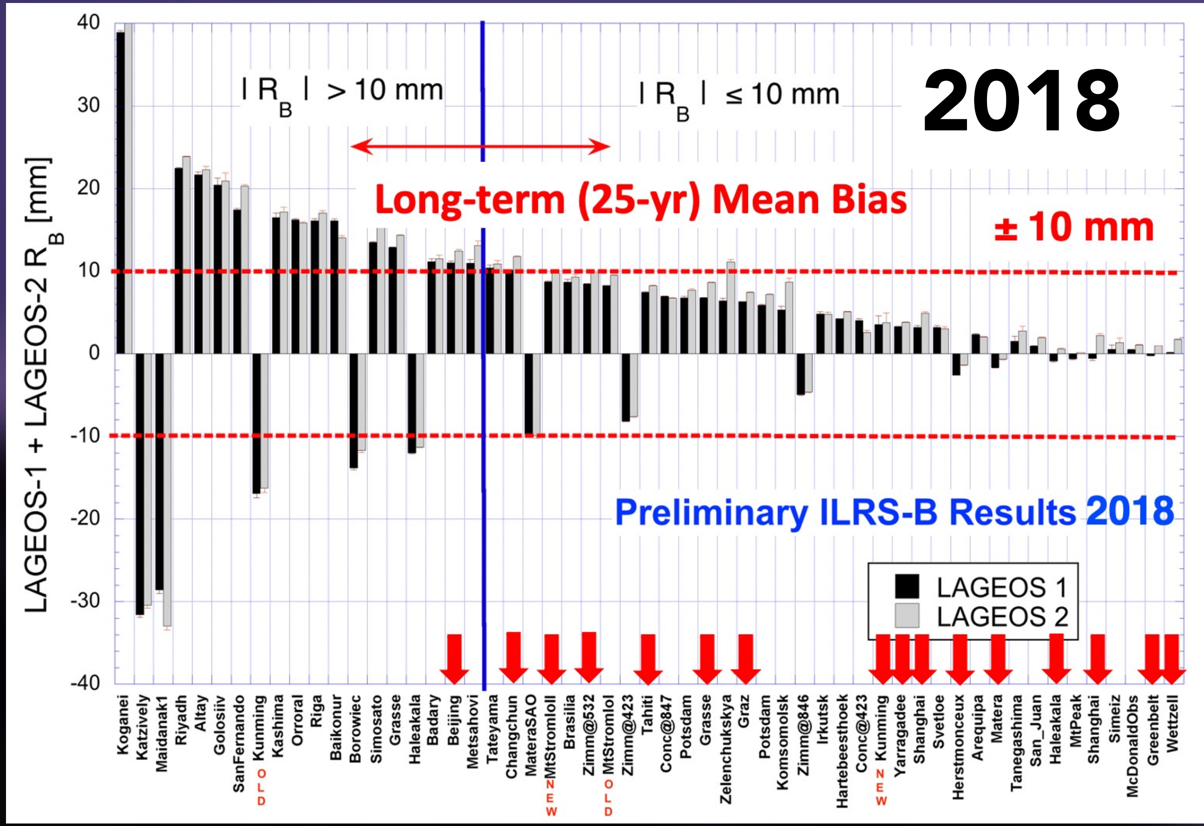
- These errors introduce a direct scale "bias"
- Most stations had inadequate modeling even at cm-level, e.g. for the Etalon satellites
- A non-random distribution in the network, resulted in significant distortion of the scale

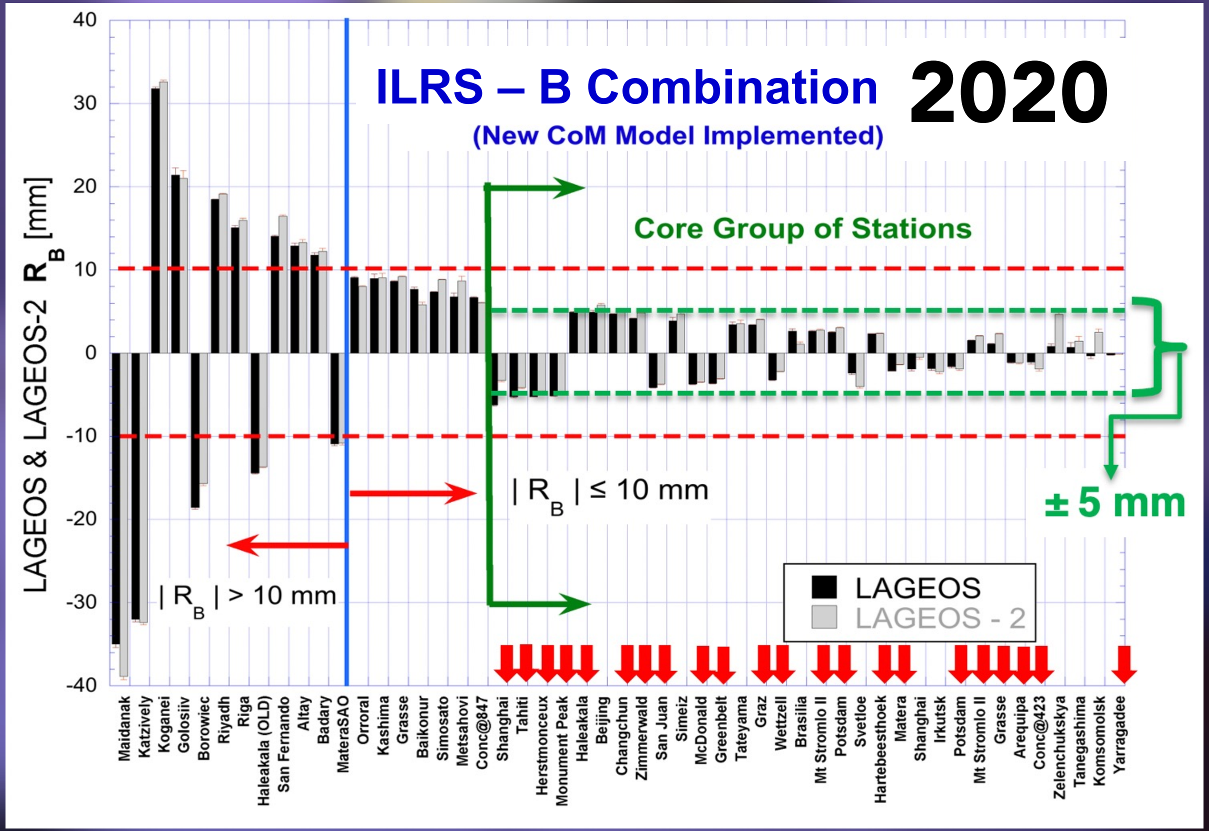


Rodríguez, J. et al., *J Geod* **93,** (2019). https://doi.org/10.1007/s00190-019-01315-0

New modeling vastly improved the solution:

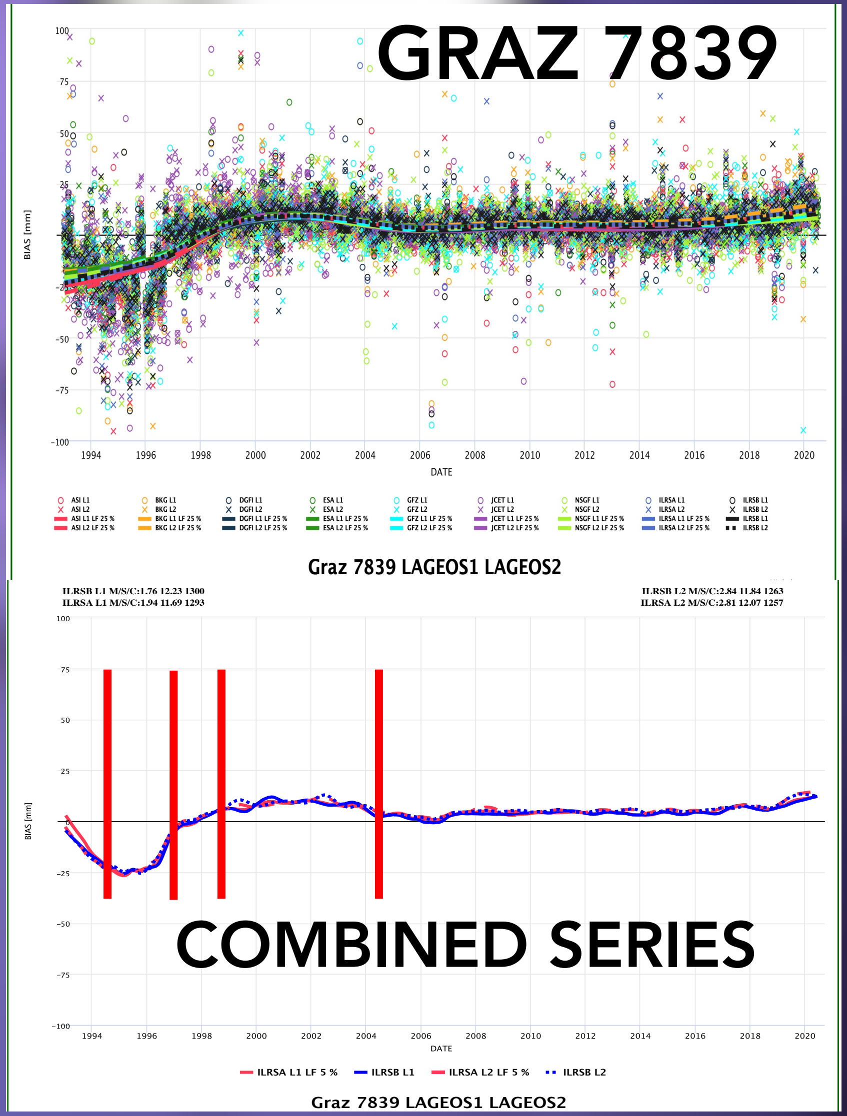
- Long-term mean biases for Core stations reduced by > 50% !!!
- Biases randomly distributed about zero ➠ net effect on scale ≈ 0



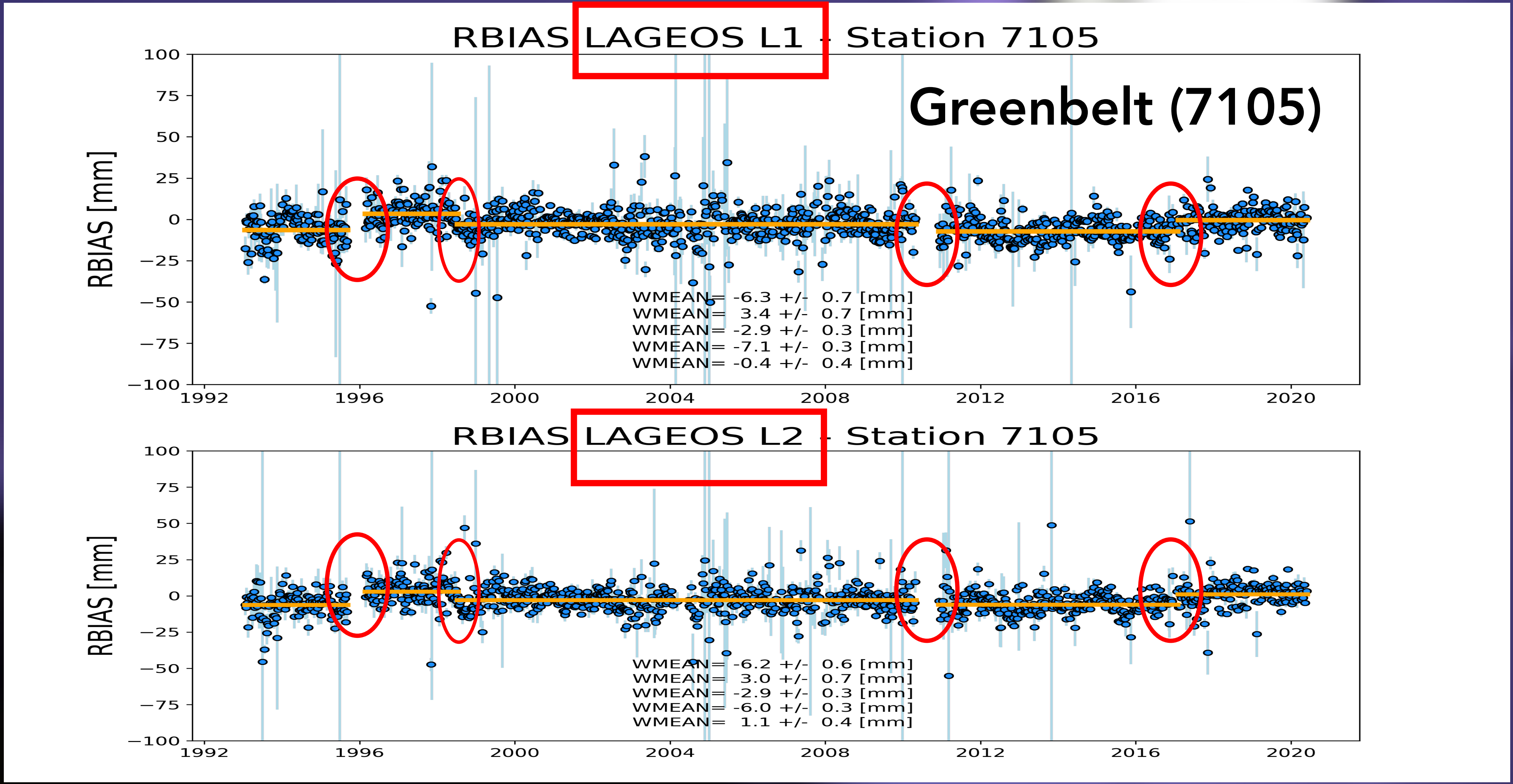


Identifying changes in station systematic behavior:

- The 7 AC weekly series were combined for each satellite:
  - LAGEOS, LAGEOS 2 and
  - Etalon 1 & 2 (combined, common bias)
- Statistically good agreement, with the combined series showing even better agreement
- Periods of different station behavior were identified in the combined series and in consultation with available station logs
- The next step developed a set of mean estimates for each period identified, to be used *a priori* in the reanalysis for ITRF2020, resulting in a stronger and cleaner solution



Each station series were examined to identify all breaks:



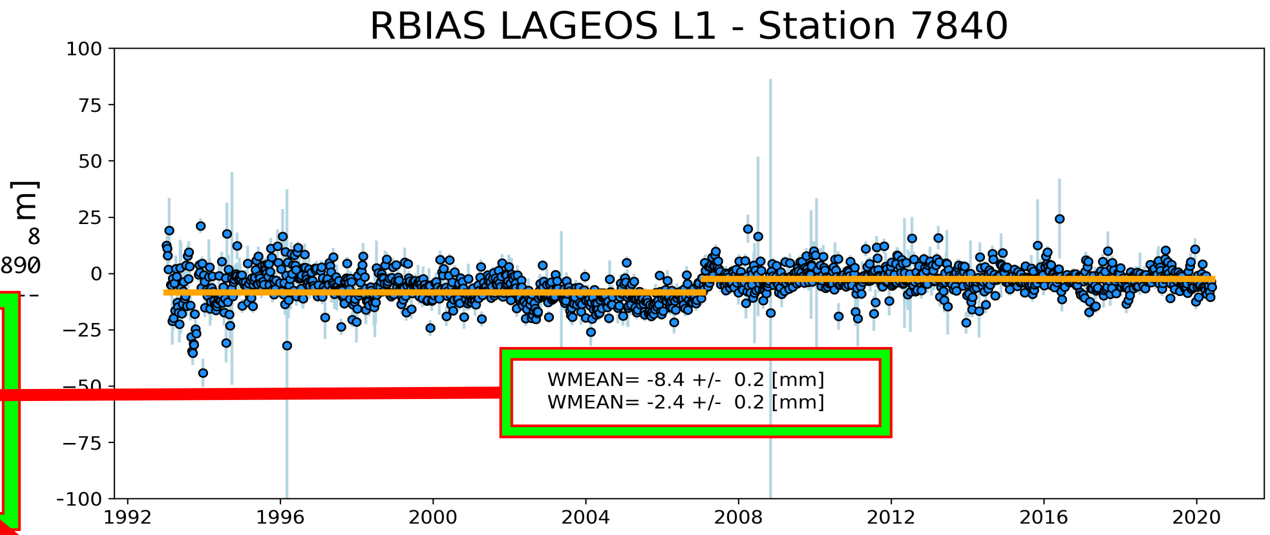
A priori range bias documentation:

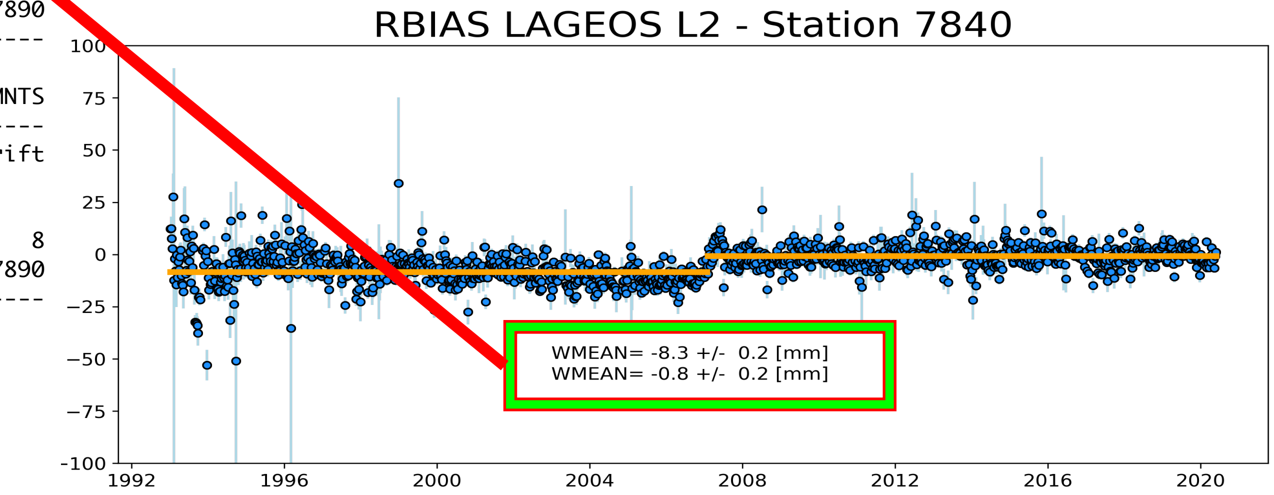
Weekly SINEXs now contain the systematics applied *a priori:*

```
*         1         2         3         4         5         6         7         8
*23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
*---------------------------------------------------------------------------------------
+MODEL/RANGE_BIAS
*SITE PT SOLN T START_DATE__ END_DATE____ M RANGE_BIAS STD_DEV UNIT
 1873 51  501 L 08:288:00000 08:295:00000 R    -0.0193   0.002    m
 7810 51  501 L 08:288:00000 08:290:54321 R     0.0173   0.002    m
 7810 51  501 L 08:290:54321 08:295:00000 R     0.0183   0.002    m
 7810 60  501 L 08:288:00000 08:295:00000 R     0.0163   0.002    m
-MODEL/RANGE_BIAS
```

```
*         1         2         3         4         5         6         7         8
*23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
*---------------------------------------------------------------------------------------
+MODEL/TIME_BIAS
*SITE PT UNIT T START_DATE__ END_DATE____ M __E-VALUE___ STD_DEV _E-RATE__ CMNTS
 1824 -- us   A 02:084:68460 12:085:00000 T      -24.400   5.000    0.0000 -----
 1873 -- us   A 07:059:00000 09:110:00000 T      -21.750  50.000   -0.2600 drift
-MODEL/TIME_BIAS
```

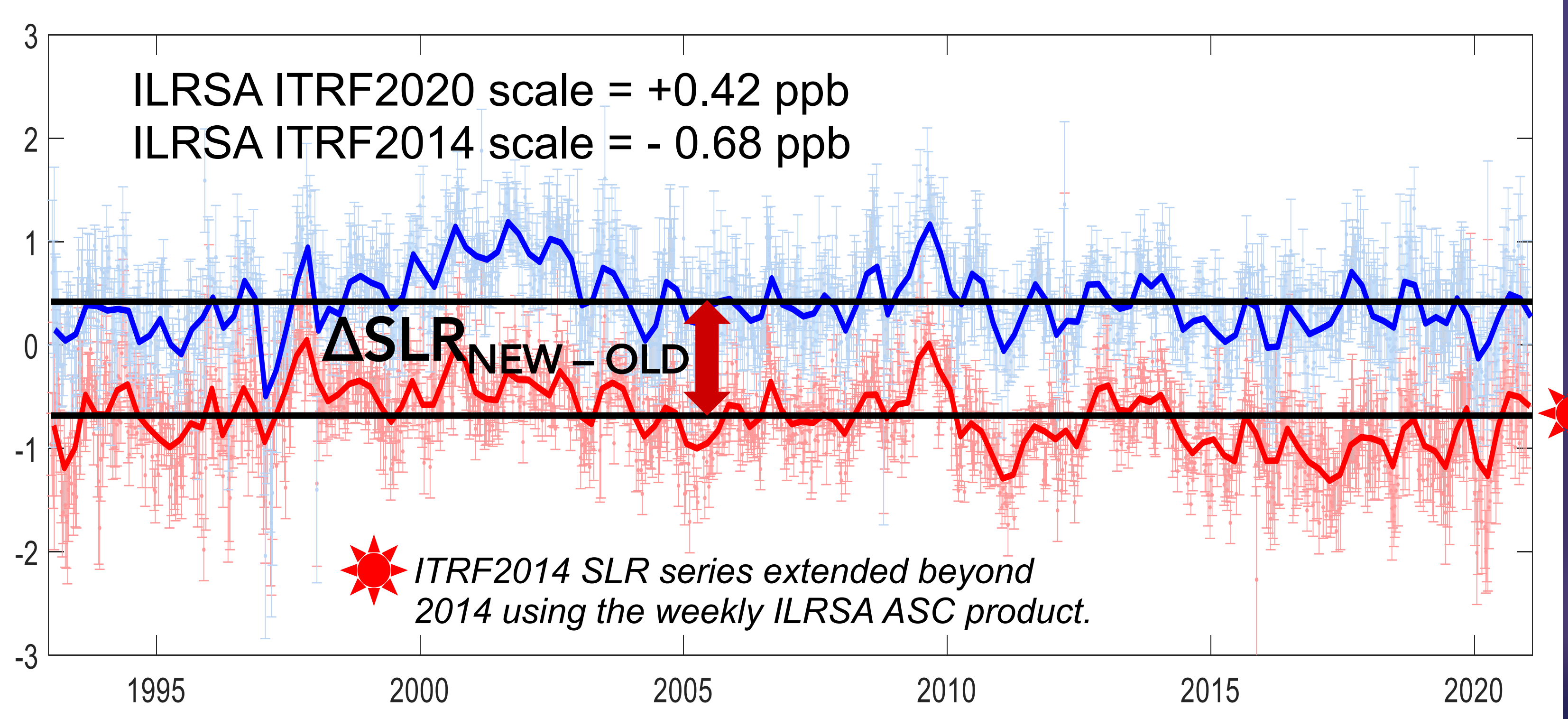
```
*         1         2         3         4         5         6         7         8
*23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
*---------------------------------------------------------------------------------------
+MODEL/TARGET_SIGNATURE_GEOMETRY
*SITE PT SOLN T START_DATE__ END_DATE____ M   COM_CORR STD_DEV UNIT
 1873 51  501 L 08:288:00000 08:295:00000 C     0.1234   0.002    m
 1879 52  501 L 08:288:00000 08:295:00000 C     0.1234   0.002    m
 7810 53  501 L 08:288:00000 08:295:00000 C     0.9373   0.005    m
 7810 60  501 L 08:288:00000 08:295:00000 C     0.0163   0.002    m
-MODEL/TARGET_SIGNATURE_GEOMETRY
```





SLR Scale From the ITRF2020 Reanalysis:

- Upper curve:
  - SLR scale from SSEM
  - Mean: +0.42 ppb
- Lower curve:
  - SLR scale in ITRF2014
  - Mean: - 0.68 ppb
- Mean difference:



0.42 ppb – (- 0.68 ppb) = 1.10 ppb

- VLBI - SLR ≈ 0.28 ± 0.10 ppb *

- $\Delta SLR_{NEW-OLD} \approx 1.10$ ppb

* WRT VLBI @ ITRF2014 !!!

Time Series of Origin Variations in ITRF2020 Reanalysis

T_X

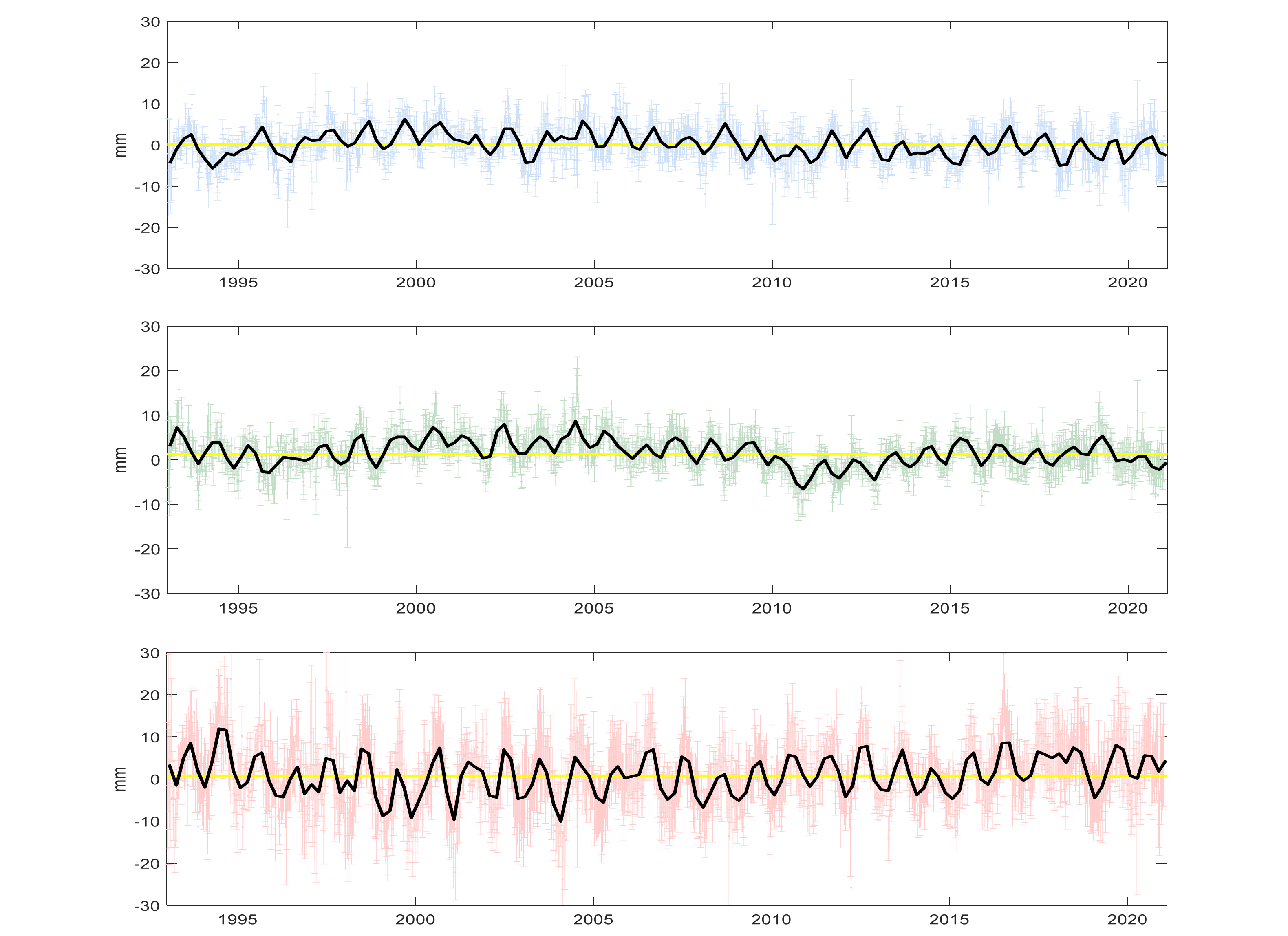
$$W_{mean} = 0.15\ mm$$
$$W_{RMS} = 3.68\ mm$$
$$Lin.rate = -0.081 \pm 0.012\ mm/y$$

T_Y

$$W_{mean} = 1.25\ mm$$
$$W_{RMS} = 3.45\ mm$$
$$Lin.rate = -0.113 \pm 0.012\ mm/y$$

T_Z

$$W_{mean} = 0.75\ mm$$
$$W_{RMS} = 6.32\ mm$$
$$Lin.rate = 0.045 \pm 0.021\ mm/y$$



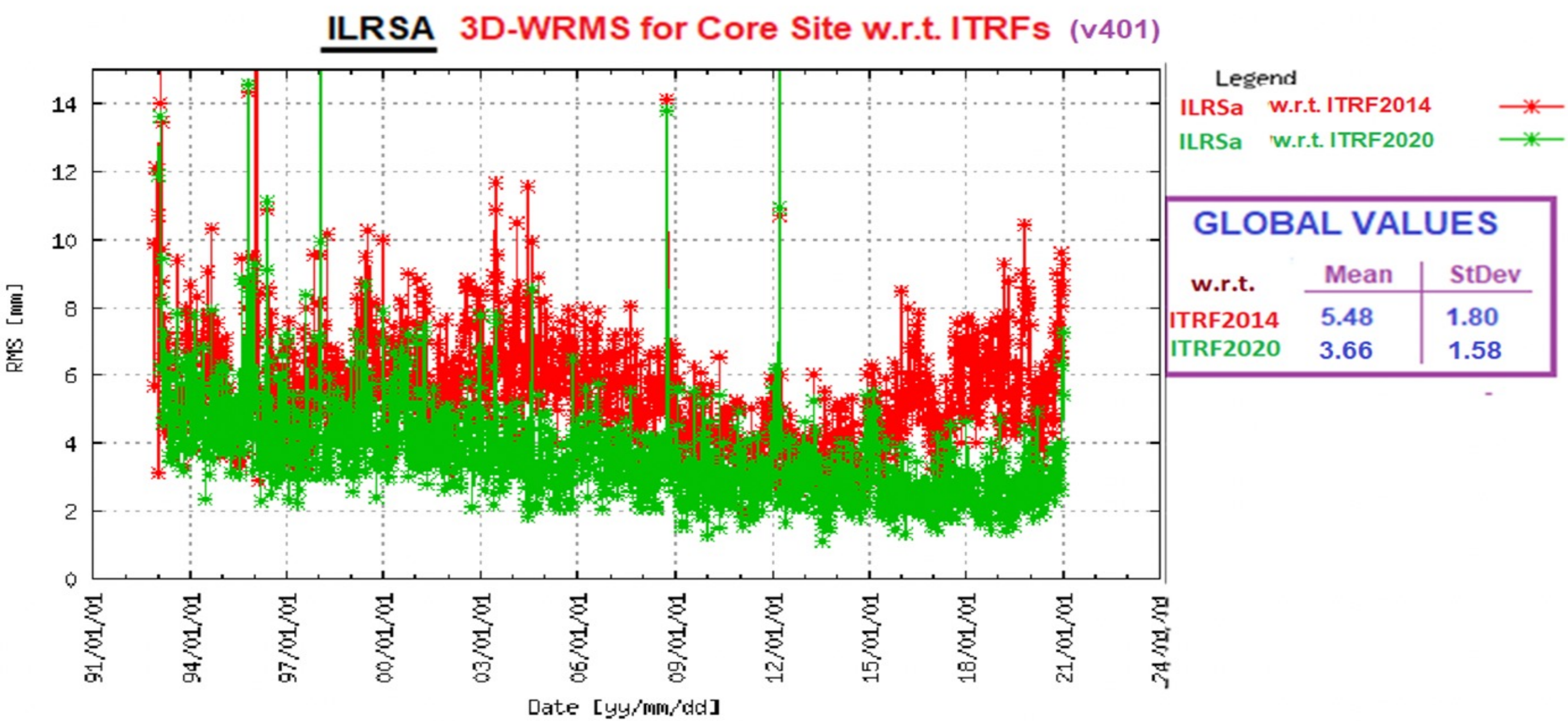
ASI AC/CC Tests *Luceri et al. (2022)*

- The ITRF2020P evaluation was performed by ASI/CGS considering the solutions spanning 1993.0 – 2021.0, with LAGEOS-1, LAGEOS-2, Etalon 1 and Etalon 2 SINEX files from REPRO2020.
- The evaluation was made at different levels:
  - - use ITRF2020P as *a priori* reference frame, for both, the generation of the ASI solution and for the combined ILRSA time series. The new ILRSA combination, made for this evaluation, was obtained using the individual ACs time series originally submitted to make the official ILRSA for ITRF2020 (v401).
  - - evaluate the PSD model comparing the ITRF2020P *a priori* coordinates and the ASI-estimated coordinates.
  - - verify the discontinuities.

ASI AC/CC Tests cont.

- In subsequent tests, the official ILRSA time series was used to compare some parameters, after its roto-translation to ITRF2020P and ITRF2014:
  - - comparison of the 3D-WRMS with those constrained to the ITRF2014 frame, showing a global mean improvement of about 1.7 mm.
  - - inspection of UEN coordinate residuals for both, core and non-core stations: the improvements using ITRF2020P were particularly visible in the UP offset.
  - - Helmert parameters: the ILRSA translations w.r.t. ITRF2020P show the expected behavior, with a mean value of the Y-component smaller than the one computed w.r.t. ITRF2014.
  - - major improvement in the scale, with the offset decreasing to -0.12 ppb at 2015.

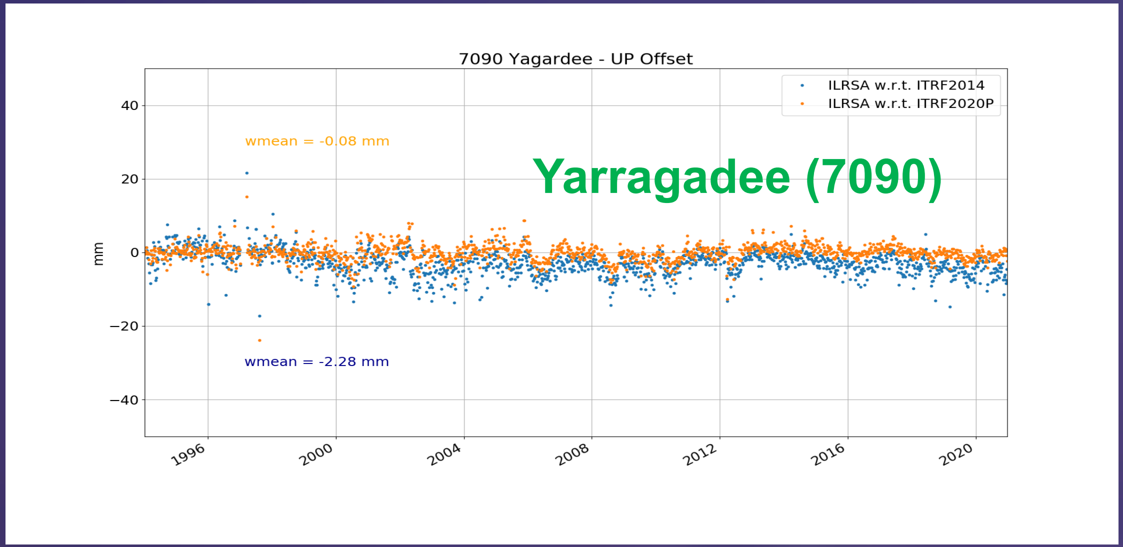
ASI AC/CC Tests cont.

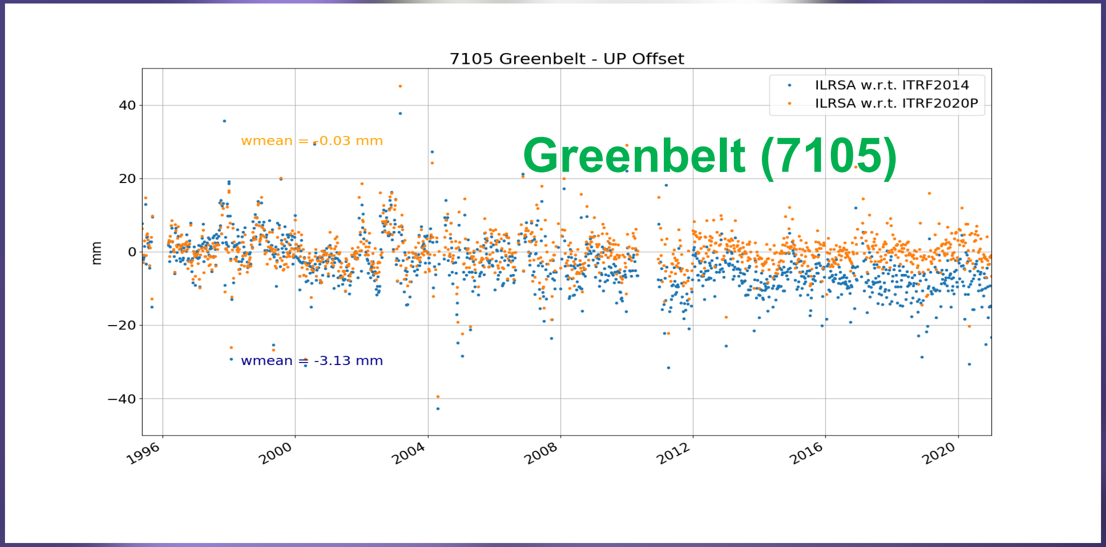


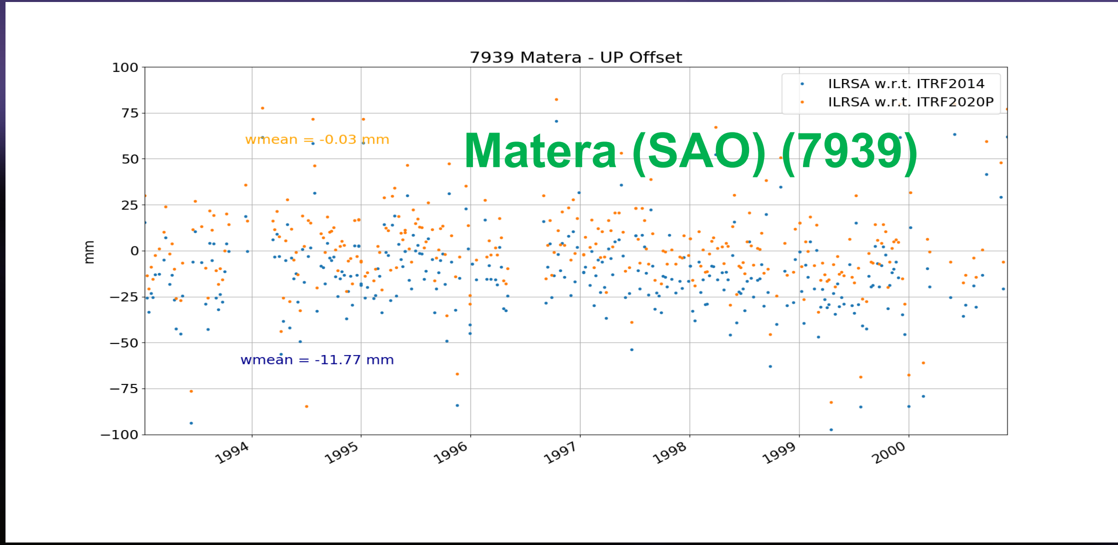
GLOBAL VALUES

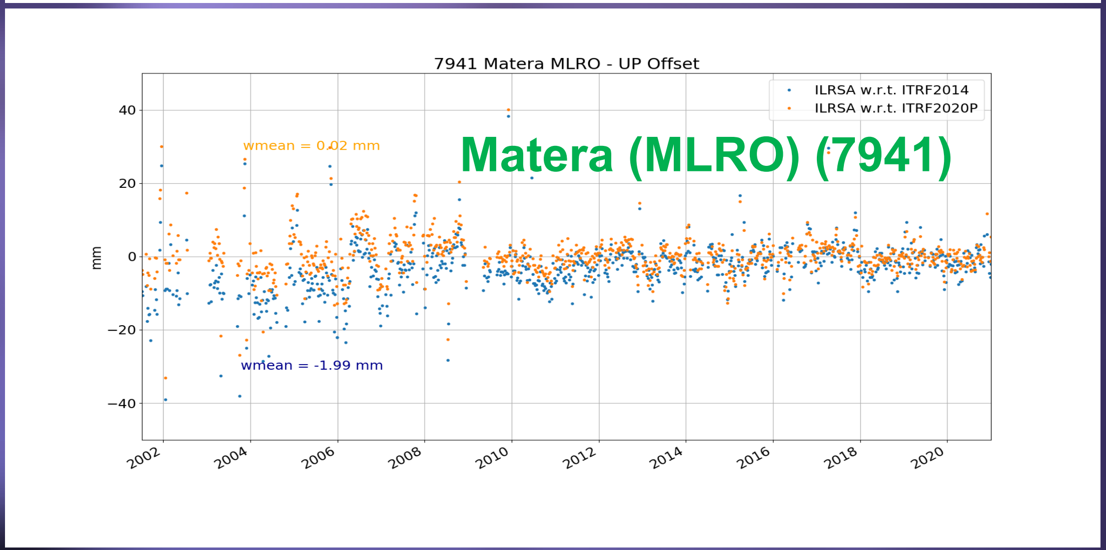
w.r.t.	Mean	StDev
ITRF2014	5.48	1.80
ITRF2020	3.66	1.58

ASI AC/CC - Station Height Comparisons: ITRF2020 vs ITRF2014

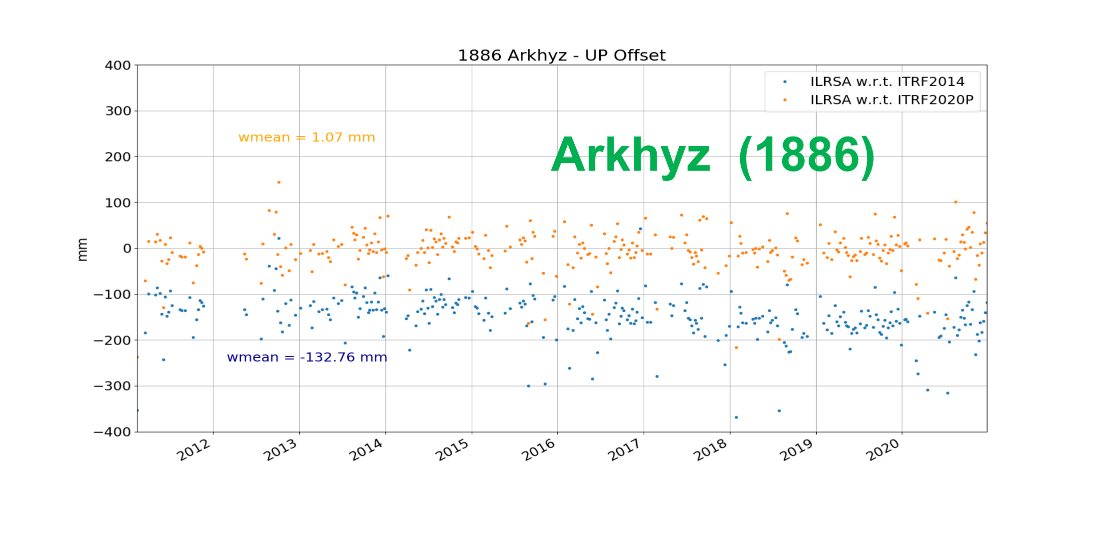


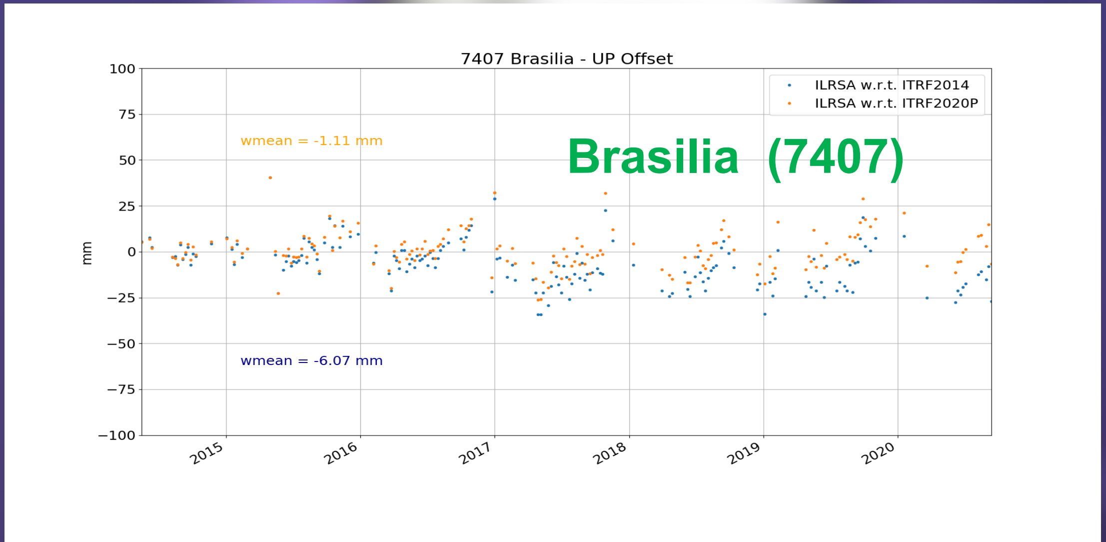


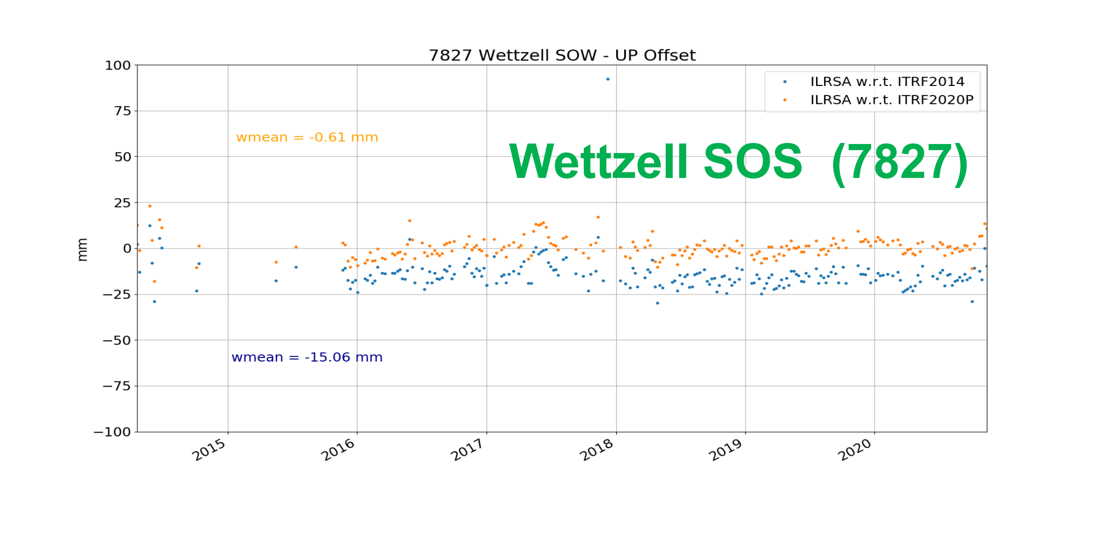


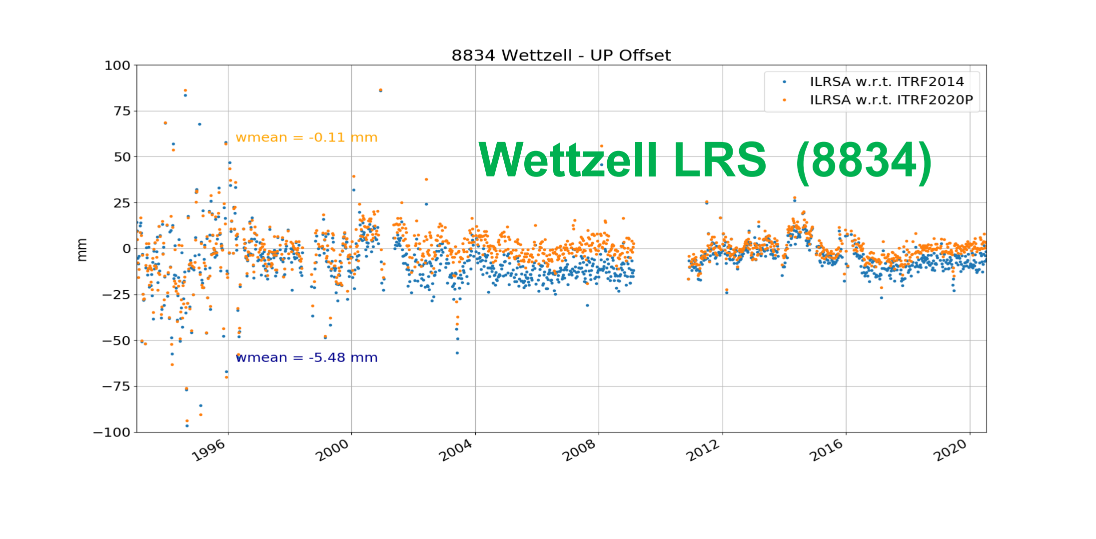


ASI AC/CC - Station Height Comparisons: ITRF2020 vs ITRF2014









ASI AC/CC – Conclusions:

- No issues in using ITRF2020P as *a priori* in the ASI v401 SINEX time series for 1993-2020
- No issues in using ITRF2020P as *a priori* for the ILRSA combination time series 1993-2020
- The PSD model fits well the effects of earthquakes on the coordinates
- Improvements in the 3D-WRMS for the core sites
- Improvements in coordinate offsets, for both, core and non-core stations
- Improvements in the Helmert parameters' mean and scatter:

Scale	Wmean (mm)	σ- WMean (mm)	Slope (mm/yr)	σ- Slope (mm/yr)
vs ITRF2014	2,654	0,069	-0,028	0,009
vs ITRF2020P	-0,743	0,063	0,084	0,008

DGFI-TUM AC *Bloßfeld et al.* (2022)

Areas of ITRF application that were tested:

- SLR datum parameter analysis
  - transformation parameter time series
  - spectra of transformation parameter time series
- SLR EOP analysis
  - absolute EOP time series and differences
- POD of spherical satellites (LAGEOS-1/-2, Etalon-1/-2) based on ITRF2020P
  - SLR orbit RMS, solar radiation and Earth albedo, empirical accelerations
- POD of non-spherical LEO satellites (T/P, Jason-1/-2/-3) based on ITRF2020P
  - SLR orbit RMS, station-specific RMS
- Range bias estimates for spherical satellites (LAGEOS-1/-2, Etalon-1/-2)
  - mean range bias differences per station (for post 1993 era)

DGFI-TUM AC Tests cont.

Helmert Transformation Parameters weighted mean values

830102 – 921225	Tx [mm]	Ty [mm]	Tz [mm]	Sc [mm]
v40x	13.7	1.6	12.6	-3.3
v410	10.4	0.1	11.1	-12.0

930109 – 210102	Tx [mm]	Ty [mm]	Tz [mm]	Sc [mm]
v40x	0.9	4.2	0.4	4.1
v410	-0.3	0.7	0.5	-0.4

830102 – 210102	Tx [mm]	Ty [mm]	Tz [mm]	Sc [mm]
v40x	1.1	4.1	0.7	4.0
v410	-0.2	0.7	0.7	-0.6

- early years show significant offset for all datum parameters
- weighted mean offset in Ty changed by more than 3 mm due to post-ITRF2014 years
- weighted mean scale changed by more than 4 mm!

DGFI-TUM AC - Summary of test results:

- SLR datum parameter analysis
  - significant offset of datum parameters for early years prior to 1993
  - SLR long-term mean scale changed by more than 4 mm
- SLR EOP analysis
  - EOP differences are very small (negligible)
- POD of spherical satellites (LAGEOS-1/-2, Etalon-1/-2) based on ITRF2020P
  - insignificant changes in the SLR orbit parameters
- POD of non-spherical LEO satellites based on ITRF2020P
  - Albedo scaling factor significantly different
  - potential error in Z-component of Riga (1884) velocity
- Range bias estimates for spherical satellites (LAGEOS-1/-2, Etalon-1/-2)
  - some stations show reduced estimated long-term mean range biases for post 1993 era

GFZ AC - *M. Vei (2022)*

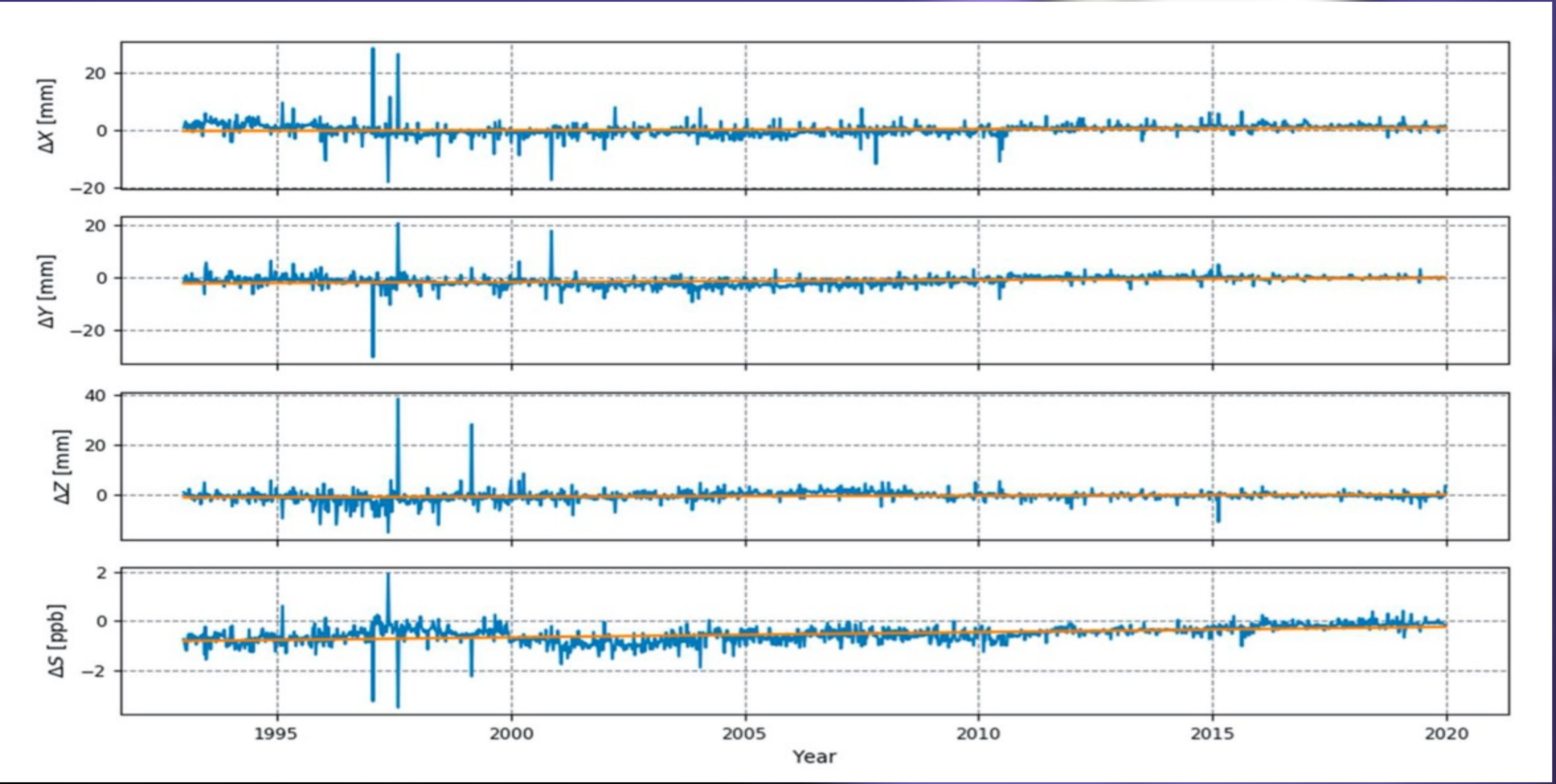
- The ITRF2020P reference frame evaluation performed at GFZ consists of reprocessing of 572 weekly arcs starting with 2010.01.03 and up to 2020.12.13. The reanalysis was done using the same models as for REPRO2020 and following strictly the DHF for handling the biases.
- The new SINEX files are also in REPRO2020 style, with the 3 new BLOCKS included. Unfortunately, although Helmert transformations for every arc were done as a quality check, the results were not submitted yet.
- The ITRF2020P EOP series and Station files were utilized in the reanalysis. X_{pol}, Y_{pol} and UT1 were replaced with the ITRF2020P series, however, UT1 was not interpolated, simply replaced, and for the days when there was information missing (i.e. value was zero) the values of the original analysis (i.e. IERS 14 C04) were used.
- All of the new SINEX files have been submitted to the ILRS ASC, to be used in test combinations along with the other series from contributing ACs.

NSGF AC - *A. Susnik & G. Appleby (2022)*

- This ITRF2020P reference frame evaluation, performed by NSGF Analysis center is based on solutions, processed using LAGEOS-1, LAGEOS-2, Etalon 1 and Etalon 2 normal point dataset, spanning from 1993.0 – 2021.0. Range biases were estimated for selected stations only – i.e. as it was done for the purposes of REPRO2020. Apart from adopting the software for the usage of ITRF2020P input data (a priori station coordinates, post-seismic deformations…), no other change has been made.

- Evaluation was performed by comparing, firstly from very general point of view in terms of residual statistical information, followed by looking into the RMS of 7-day orbital fits of generated orbits, comparing estimated Earth Orientation Parameters, range-biases (for selected stations only), station coordinates and Helmert Transformation Parameters with our solutions generated using ITRF2014 as a-priori.

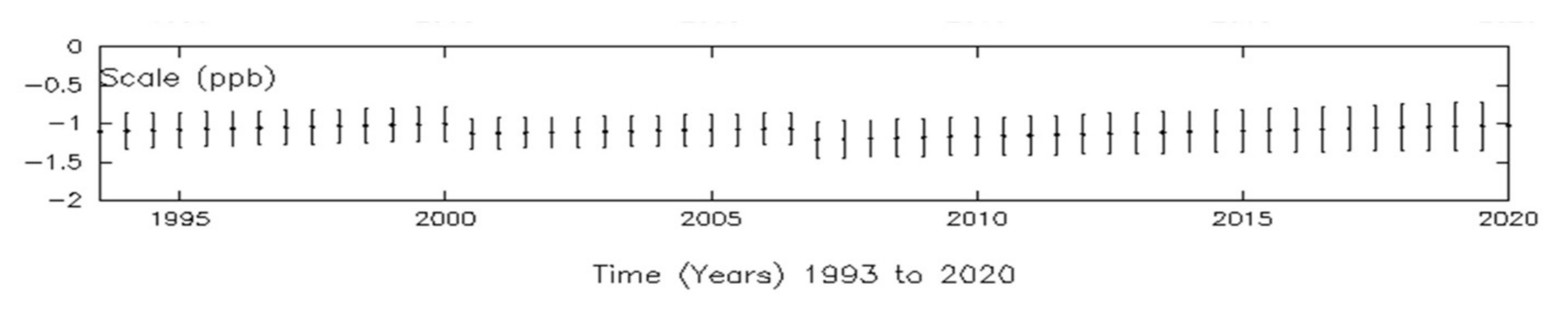
NSGF AC cont.



ΔX [mm]
ΔY [mm]
ΔZ [mm]
ΔS [ppb]
20
0
−20
40
2
−2
1995
2000
2005
2010
2015
2020
Year

NSGF AC cont.

- The most significant change observed in the Helmert Transformation Parameters is in the scale, as it can be expected after adopting the new approach in accounting for system biases in the reanalysis. As a last evaluation step, NSGF took the positions and velocities of 21 stations that are common to both ITRF2014 and ITRF2020P and, taking into account the different base epochs for the two realizations (ITRF2014 at 2010; ITRF2020P at 2015), evaluated the coordinates at 0.5-year intervals from 1993 to 2020. For each of those epochs, they have iteratively solved for a 7-parameter Helmert transformation of the coordinates from ITRF2014 onto ITRF2020P.

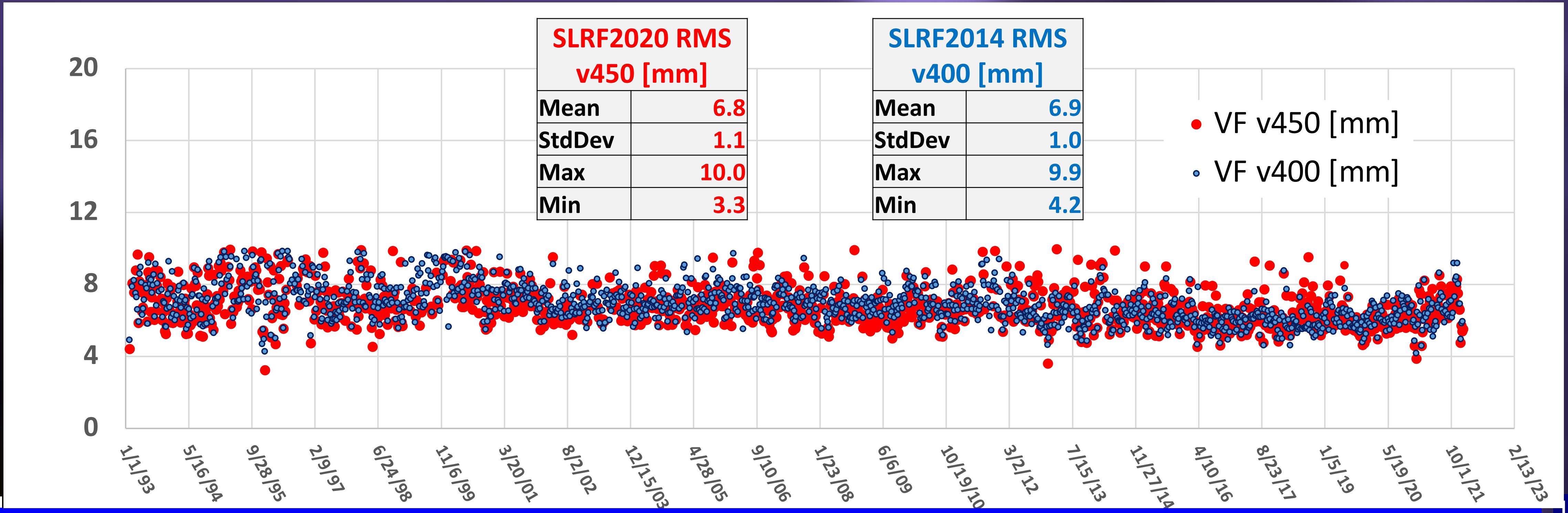


NSGF AC - Conclusions

- Of particular interest is the average scale difference, given our previous findings that systematic range errors at many of the tracking stations impact directly the reference frame scale.
- Averaged over the 54 0.5-year solutions, the scale difference is -1.09 ppb, with an estimated standard error of 0.05ppb. This elegant test removes the effect of the varying network geometry, since only the same stations common to both TRFs are used and demonstrates the significant scale change observed already in the preliminary versions of the SLR contribution to ITRF2020.

JCET AC/CC - *Pavlis et al., (2022)*

- Preliminary reanalysis of all four satellites for 1993-2022
- Modeling kept as in REPRO2020 series for ITRF2020
- New SINEX series constructed, RMS compared



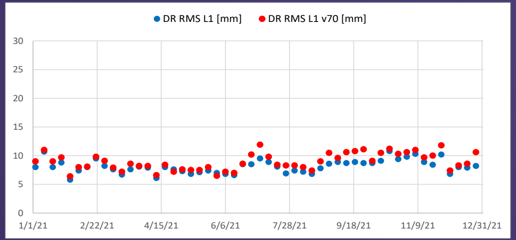
SLRF2020 RMS v450 [mm]	
Mean	6.8
StdDev	1.1
Max	10.0
Min	3.3

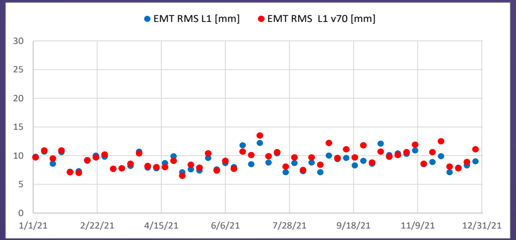
SLRF2014 RMS v400 [mm]	
Mean	6.9
StdDev	1.0
Max	9.9
Min	4.2

JCET AC/CC - 2021 Orbital Fits : ITRF2020 vs ITRF2014

Orbital fits with ITRF2020 and ITRF2014 over the year 2021 which has NOT contributed SLR data in either TRF, shows clear improvement for ITRF2020.

LAGEOS1





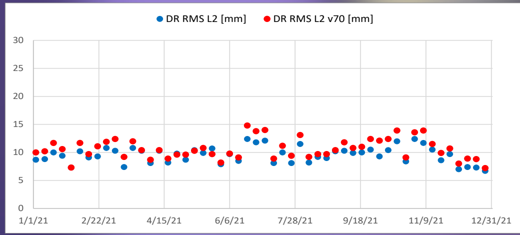
DR RMS L1 [mm]	
Mean	8.1
StdDev	1.1
Max	10.8
Min	5.8
Count	52

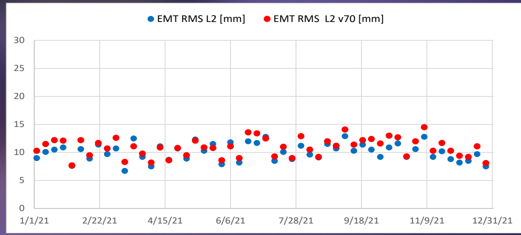
DR RMS L1 v70 [mm]	
Mean	8.9
StdDev	1.5
Max	11.9
Min	6.4
Count	52

EMT RMS L1 [mm]	
Mean	9.0
StdDev	1.4
Max	12.2
Min	7.1
Count	52

EMT RMS L1 v70 [mm]	
Mean	9.5
StdDev	1.5
Max	13.5
Min	6.5
Count	52

LAGEOS2





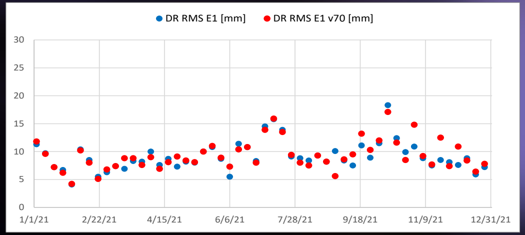
DR RMS L2 [mm]	
Mean	9.6
StdDev	1.4
Max	12.4
Min	6.7
Count	52

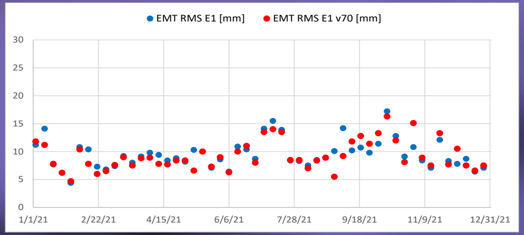
DR RMS L2 v70 [mm]	
Mean	10.6
StdDev	1.8
Max	14.8
Min	7.2
Count	52

EMT RMS L2 [mm]	
Mean	10.1
StdDev	1.5
Max	12.9
Min	6.7
Count	52

EMT RMS L2 v70 [mm]	
Mean	10.9
StdDev	1.6
Max	14.5
Min	7.7
Count	52

ETALON1





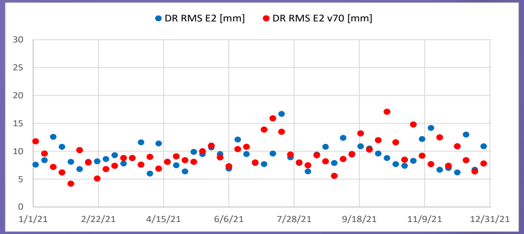
DR RMS E1 [mm]	
Mean	9.1
StdDevp	2.5
Max	18.3
Min	4.1
Count	52

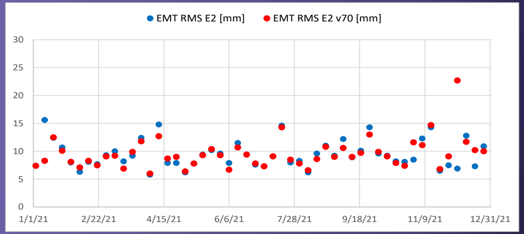
DR RMS E1 v70 [mm]	
Mean	9.3
StdDev	2.6
Max	17.1
Min	4.2
Count	52

EMT RMS E1 [mm]	
Mean	9.6
StdDev	2.5
Max	17.2
Min	4.4
Count	52

EMT RMS E1 v70 [mm]	
Mean	9.3
StdDev	2.6
Max	16.3
Min	4.7
Count	52

ETALON2





DR RMS E2 [mm]	
MeaN	9.2
StdDev	2.2
Max	16.7
Min	6
Count	52

DR RMS E2 v70 [mm]	
Mean	9.3
StdDev	2.6
Max	17.1
Min	4.2
Count	52

EMT RMS E2 [mm]	
Mean	9.5
StdDev	2.4
Max	15.6
Min	5.8
Count	52

EMT RMS E2 v70 [mm]	
Mean	9.6
StdDev	2.7
Max	22.7
Min	6
Count	52

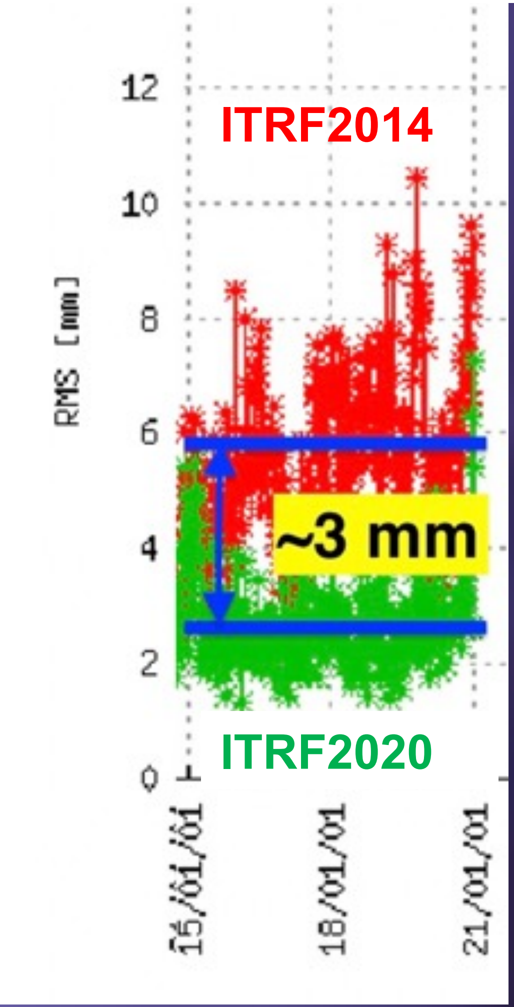
JCET AC/CC - Summary

- The new model ITRF2020 shows major improvement in the scale with respect to VLBI.
- Data reduction for the four contributing satellites LAGEOS 1 & 2 and Etalon 1 & 2, results in combined weekly SINEX solutions with improved data fits, although more fine-tuning of the systematics in the recent years (NOT included in ITRF2020) is still required (and planned).
- The SLR-dedicated version of ITRF2020 – SLRF2020 has been released for testing with success.
- To complete the release to the public we still need to include instructions on how systematics MUST be handled by means of a revised Data Handling File (in preparation).

ILRS ASC - Conclusions

- The general conclusion reached by all AC/CCs based on the performed tests, is that ITRF2020 is a significant improvement over ITRF2014.
- Over the 2015.0 – 2021.0 period which ITRF2014 contains no data from, the new model does 100% better in station position RMS, based on actual observations.
- There were some minor issues to be addressed, e.g. some discontinuity adjustments, these however were handled via direct communication between the ITRS and the ILRS ASC.

Core Sites' 3D-WRMS
2015.0 - 2021.0



Based on the ITRF2020 results, the new ILRS contribution limits the systematic scale difference VLBI - SLR to 0.15 ppb *(~1 mm)*

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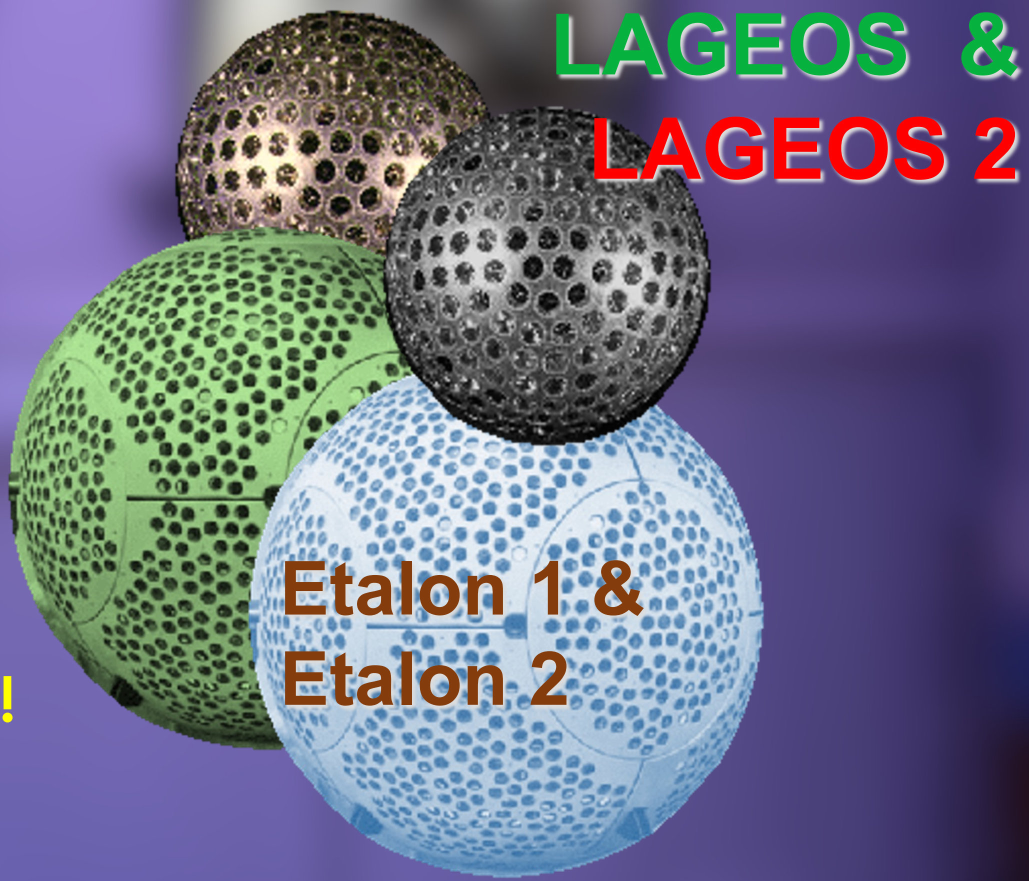
- The ILRS ASC stablished a new analysis approach for its contribution to ITRF2020;
- It will be implemented in the operational series after adoption of ITRF2020;
- The complete SLR series for the 38-year period 1983 – 2021 will be reanalyzed in early summer 2022 using the new TRF and bias model;
- ITRS has corroborated the ILRS results on the expected scale difference between SLR & VLBI.
- **From nearly 1 cm ΔScale(SLR-VLBI) to 1 mm !!!**



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Thank you!

Background picture:
ESA’s new SLR at Izaña, Tenerife

Credits:
Andrea Di Mira, ESA