Systematic Error Mitigation in SLR Products for ITRF2020

V. Luceri (1), E. C. Pavlis (2), M. Pirri (1), M. Kuzmicz-Cieslak (2), K. Evans (2) and G. Bianco (3)

(1) e-GEOS SpA, ASI/CGS-Matera, Italy
(2) Joint Center for Earth Systems Technology, University of Maryland, Baltimore, USA (3) Agenzia Spaziale Italiana (ASI), CGS-Matera, Italy

Errors affecting the SLR technique

- SLR data provide a direct measure of the station-satellite distance at specified measurement times. Systematic errors in range are commonly called range biases, and systematics affecting the epoch of the observations are known as time biases.
- The nature of the errors affecting the SLR technique can be divided into 3 categories:
  1. ranging machine errors
     - calibration and/or synchronization issues
     - hardware malfunctioning
     - intrinsic device limitations
  2. timing errors (station clock issues)
  3. modeling errors (e.g. satellite center of mass offsets, force model deficiencies, etc.).
- Following good practices and procedures at the ground stations should help to identify and minimize errors of the first two categories.
- Time biases for most ground stations are relatively small and stable. There are sporadic episodes of very large clock errors. The impact of time biases in the geodetic products is mainly restricted to the horizontal components of station coordinates (east-west component), which can reach a few mm.

ILRS Activities to Control Systematic Errors

- ILRS characterizes the quality of the data produced by its network before releasing them to the user community. To achieve this, a number of "check points" are in use:
  - The first level of quality control (QC) is always performed at the station collecting the data
  - Daily analysis for quality control (QC) of range and time biases
  - Quality Control Board (QCB) addressing laser ranging data quality issues via bi-monthly telecons
- These efforts are very successful in detecting major problems and system malfunctions, but they lack the ability to detect varying errors below a threshold of 1-2 centimeters.
- The ILRS ASC paid attention to the systematic error handling from the very beginning of its activities in order to provide ILRS products as free from systematic errors as possible and to monitor the long-term performance of stations at the mm level maintaining a record of known problems in the "Data Handling" file…

Station Systematic Error Monitoring Report

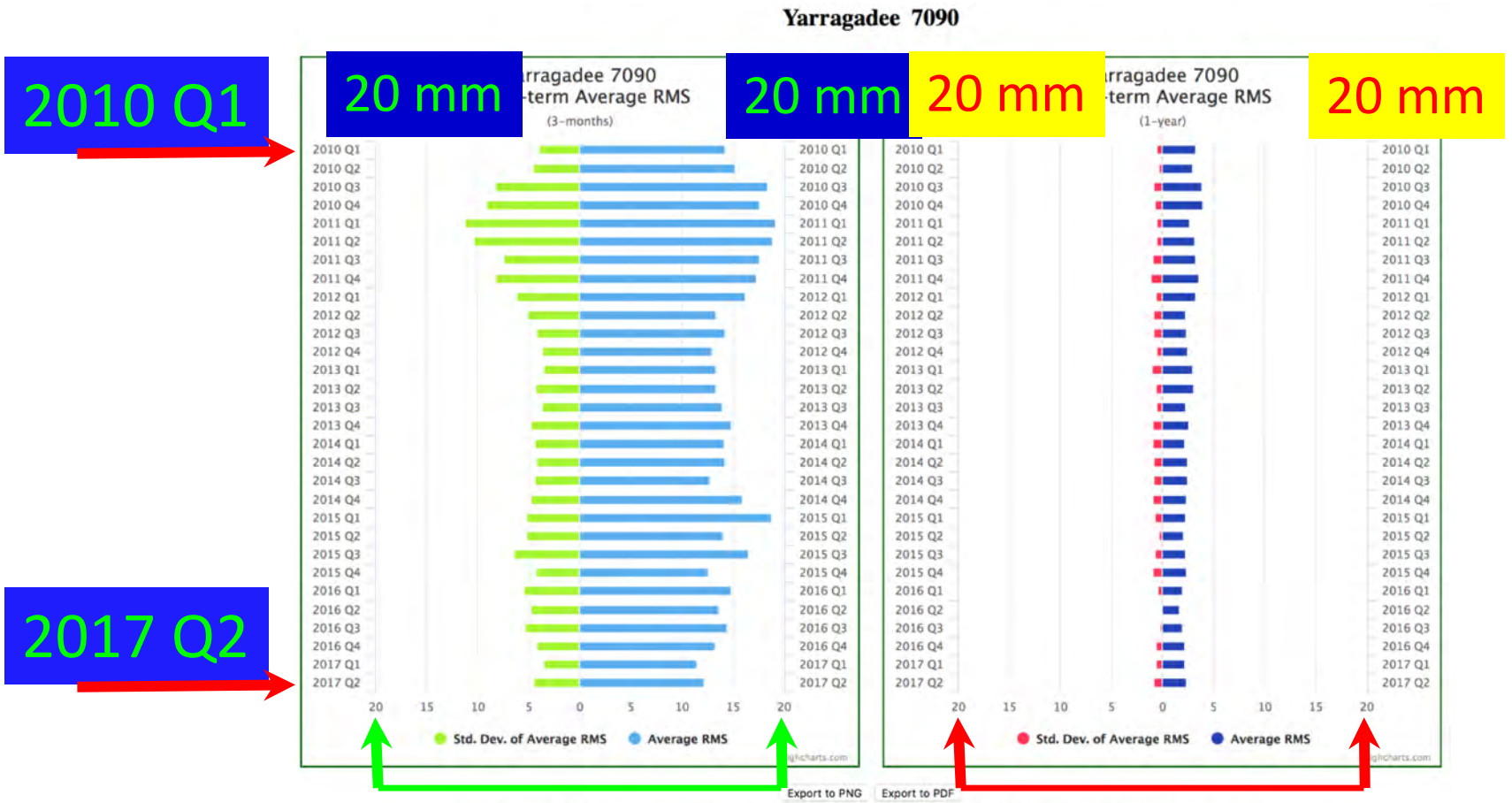
Since 1998 ILRS has used the Global Report Card to evaluate and monitor the station performance https://ilrs.cddis.eosdis.nasa.gov/network/system_performance/

Site Information		DGFI Orbital Analysis				Hitotsubashi Univ. Orbital Analysis				JCET Orbital Analysis				MCC Orbital Analysis				SHAO Orbital Analysis			
Station Location	Station Number	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP
Baseline		10.0	20.0	10.0	95	10.0	20.0	10.0	95	10.0	20.0	10.0	95	10.0	20.0	10.0	95	10.0	20.0	10.0	95
Yarragadee	7090	3.7	15.6	1.8	100.0	2.0	7.5	1.9	100.0	3.2	14.8	2.8	99.8	2.4	16.6	2.9	98.3	1.7	15.2	2.0	91.9
Changchun	7237	4.2	26.7	4.7	99.1	3.1	25.2	2.8	99.7	3.1	28.6	3.5	96.8	4.1	30.9	10.5	96.4	3.1	32.3	10.0	90.3
Mount_Stromlo_2	7825	4.2	14.1	4.1	100.0	3.1	8.1	2.0	100.0	3.5	15.2	3.7	99.9	4.1	12.9	3.3	95.4	2.7	12.9	3.1	95.1
Zimmerwald_532	7810	3.1	11.6	7.8	99.9	1.4	5.4	3.1	99.8	2.1	13.0	7.8	99.9	2.6	13.6	3.2	98.3	1.5	11.2	3.7	95.0
Wettzell	8834	3.7	13.1	3.8	100.0	2.5	8.6	2.2	100.0	3.1	12.4	3.9	99.4	2.6	11.5	4.2	96.2	1.5	12.3	5.2	94.2
Graz	7839	2.5	11.2	3.8	100.0	0.8	4.4	1.8	100.0	1.9	11.7	4.9	98.5	1.9	12.0	4.5	98.0	0.7	9.3	2.5	95.5
Matera_MLRO	7941	2.6	12.0	4.7	99.9	1.2	6.0	2.6	100.0	2.1	12.4	4.4	100.0	1.8	14.3	3.7	99.5	2.1	32.0	3.6	97.6
Greenbelt	7105	4.5	12.9	4.2	99.9	2.2	6.6	1.7	99.8	3.3	11.5	2.8	99.2	2.5	16.6	5.5	97.0	2.3	13.5	3.3	91.0
Herstmonceux	7840	2.7	9.8	3.5	100.0	1.4	5.4	1.5	100.0	1.7	11.6	2.9	100.0	2.6	8.9	2.7	96.9	1.7	11.4	2.5	97.2
Monument_Peak	7110	5.8	17.2	5.3	99.7	3.8	12.3	2.0	99.7	5.7	20.5	4.9	98.0	3.9	20.5	3.9	94.4	3.5	14.6	6.2	91.0
Hartebeesthoek	7501	4.8	18.6	5.0	99.9	2.8	8.4	3.2	99.9	3.8	18.7	5.4	98.8	3.3	23.5	4.6	96.3	2.5	19.0	6.2	92.0

- The short term stability is the standard deviation of the pass-by-pass range biases during the last 3 months
- The long term stability is the standard deviation of the pass-by-pass range bias estimates during the past year.

Station Systematic Error Monitoring History

Now available online (http://geodesy.jcet.umbc.edu/ILRS_REPORT_CARD) separately for each site, averaged over the five AC series along with a std. dev.



Average RMS: It is computed from the input QC RMS's from the individual ACs that contribute to these series
Std. Dev. of Average RMS: The statistical standard deviation of the "above" average RMS.

The "Data Handling" file:

```
=SNX 2.00 DGF 18:066:00000 ALL 76:121:00000 00:000:00000 L 00000 2
*-------------------------------------------------------------------------------
+FILE/REFERENCE
 RELEASE DATE       2018/03/07
 DESCRIPTION        range, time and pressure biases to be applied to SLR tracking
                    data and periods not to be used in analysis.

 INPUT              Corrections to SLR tracking data collected from
                    various tables at CDDIS and resolutions from the ILRS/ASC
                    and the T2L2 @ Jason-2 project over July 2008 to December 2016.

 OUTPUT             ILRS SINEX file with data handling recommendations

 ACCESS             https://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx

 CONTACT            Horst Mueller <horst.mueller@tum.de>
 CONTACT            Margarita Vei <vei@gfz-potsdam.de>
-FILE/REFERENCE
*-------------------------------------------------------------------------------
+FILE/COMMENT

Last Updated: Mar. 07 2018  New release with the T2L2 (edited) set of TB included
              Jun. 06 2017  Yarragadee  (7090) release 0 incorrect Met data day 17:152
              May  11 2017  Station Kunming2 (7819) new station replaces 7820 (Kunming)
              Apr. 20 2017  Station Changchun (7237) time bias of 1 ms on Feb. 16 and 17 2017
              Jul. 19 2016  Station 7394 (Sejong) new station, replaces 7359 (Daedok)
              May  12 2016  Station 7080 (MLRS) solve for range bias due to new configuration
              Nov. 18 2015  Station 7105 (MOBLAS7) data edited from Nov. 9 2015 00:00 h UTC until Nov. 17 18:00 h UTC
              Sep. 30 2015  Adding stations Irkutsk (1891) Brazilia (7407), Wettzell SOSW (7827) as new stations
              Jul. 09 2015  Zimmerwald (7810) data not valid July 3 2015 to July 6 2015 8h
              Jul. 06 2015  San Fernando (7824) data not valid from June 17 2015 21h to June 18 2015 4h
              Sep. 09 2014  changed end date of Graz (7839) range bias to 1996/09/28
              Jul. 16 2014  remove of quarantine entries in the file (data are in quarantine in the data centers)
              May. 06 2014  Mt. Stromlo quarantine
              Apr. 29 2014  deletion of double lines
              Apr. 04 2014  Updated biases 7080 in 1990
              Mar. 26 2014  Updated biases for ITRF2013 processing
              Mar. 18 2014  Update from CDDIS free format data corrections, new flag
              Feb. 19 2014  Change of Flag for stations with preliminary coordinates to V (P = pressure bias)
              Feb. 05 2014  incorrect weather data at Haleakala (7119) data to be deleted
              Feb. 04 2014  solve for range biases for Kunming
              Jan. 30 2014  Kunming released  from quarantine
              Jan. 27 2014  Wettzell back from quarantine but solving for a range bias is necessary
              Oct. 29 2013  McDonald back to normal operation, without time bias
              Oct. 22 2013  new station Deadok, in quarantine
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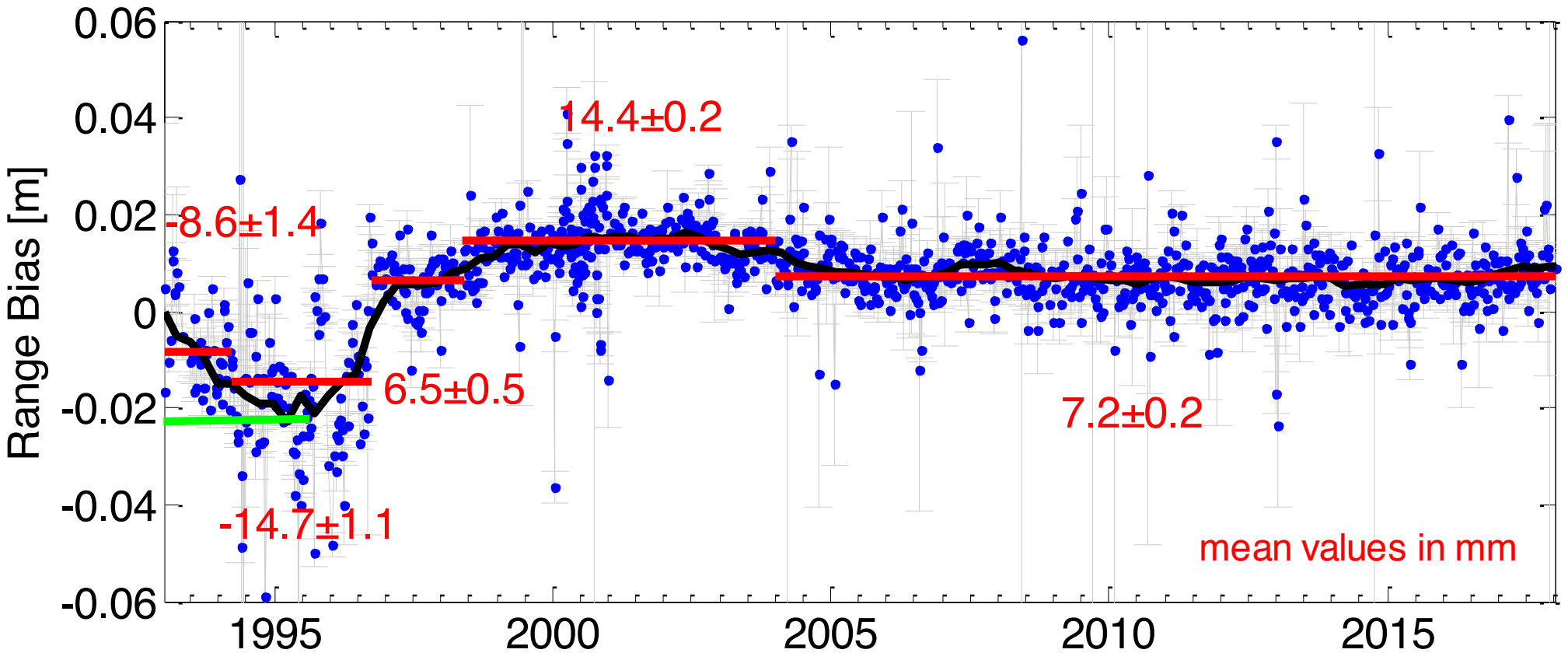
```
-SITE/ID
*-------------------------------------------------------------------------------
+SOLUTION/DATA_HANDLING
*CODE PT_ UNIT T _DATA_START_ __DATA_END__ M __E-VALUE___ STD_DEV ___COMMENTS_____
*-------------------------------------------------------------------------------
*  list of sites with mandatory arc dependent biases to be estimated
*-------------------------------------------------------------------------------
 1864 --- mm   A 00:000:00000 00:000:00000 E
 1868 --- mm   A 00:000:00000 00:000:00000 E
 1953 --- mm   A 00:000:00000 00:000:00000 E
 7080 --- mm   A 16:106:00000 00:000:00000 E                    small remaining range bias
 7548 --- mm   A 00:000:00000 00:000:00000 E
 7308 --- mm   A 00:000:00000 00:000:00000 E
 7810 --- mm   B 00:000:00000 00:000:00000 E                    Infrared only
 7845 --- mm   A 00:000:00000 08:001:00000 E
 7403 --- mm   A 10:265:00000 00:000:00000 E                    small remaining range bias
 8834 --- mm   A 10:319:00000 00:000:00000 E                    small remaining range bias
 7820 --- mm   A 12:001:00000 00:000:00000 E                    unknown range bias
 7821 --- mm   A 09:148:00000 10:069:00000 E                    unknown range bias
 7249 --- mm   A 12:067:00000 00:000:00000 E                    small remaining range bias
*-------------------------------------------------------------------------------
*  list of new sites  with preliminary coordinates (not included in ITRF2014)
*-------------------------------------------------------------------------------
 1874 --- mm   A 00:000:00000 00:000:00000 V                    new station
 1891 --- mm   A 00:000:00000 00:000:00000 V                    new station
 7394 --- mm   A 15:218:00000 00:000:00000 V                    new station
 7407 --- mm   A 00:000:00000 00:000:00000 V                    new station
 7827 --- mm   A 00:000:00000 00:000:00000 V                    new station
*-------------------------------------------------------------------------------
*  list of mandatory range biases to be applied on observation (ILRS/ASC Oct 2007)
*  with updates from ILRS/ASC reprocessing results
*-------------------------------------------------------------------------------
 1873 --- mm   A 95:001:00000 00:001:00000 R      -270.00
 7080 --- mm   A 88:001:00000 89:349:00000 R       -40.00
 7080 --- mm   A 90:094:00000 93:168:00000 R        25.00        IRLS/ASC 14/04/04
 7080 --- mB   A 95:065:00000 96:026:00000 P        -2.10        source CDDIS
 7080 --- mB   A 96:026:00000 96:116:00000 P       -10.30        source CDDIS
 7080 --- mB   A 96:116:00000 96:130:00000 P        -9.70        source CDDIS
 7109 --- mm   A 00:000:00000 88:347:00000 R        10.00        ILRS/ASC 09/05/06
 7109 --- mm   A 97:009:00000 97:018:00000 R       164.90        source CDDIS
 7110 --- mm   A 84:001:00000 84:136:00000 R        30.00
 7110 --- mm   A 87:300:00000 88:025:00000 R        30.00
 7110 --- mm   A 96:240:00000 96:277:00000 R       163.60        source CDDIS
 7122 --- mm   A 84:122:00000 87:074:00000 R        30.00
```

ILRS Activities to Control Systematic Errors (cont.)

- The ILRS ASC is going to adopt a new model for the range biases strongly motivated by the need to remove the VLBI-SLR scale difference. The model will be obtained estimating RB simultaneously with all other parameters.
- A Pilot Project is currently ongoing with the data reanalysis performed by the ILRS ACs (ASI, BKG, DGFI, ESA, GFZ, JCET, NSGF):
  - Weekly estimation of coordinates, EOP and range biases RB
  - Time frame: 1993-2018
  - Data: LAGEOS , LAGEOS 2, Etalon 1&2
  - Time series with separate range biases for LAGEOS, combined for Etalon
  - Combination of the time series estimated by the ILRS ACs
  - Computation of mean range biases over medium/long time scale

An example of the estimated RB is given in the next figure on the right where the blue dots are the weekly combined RB estimates for GRAZ.

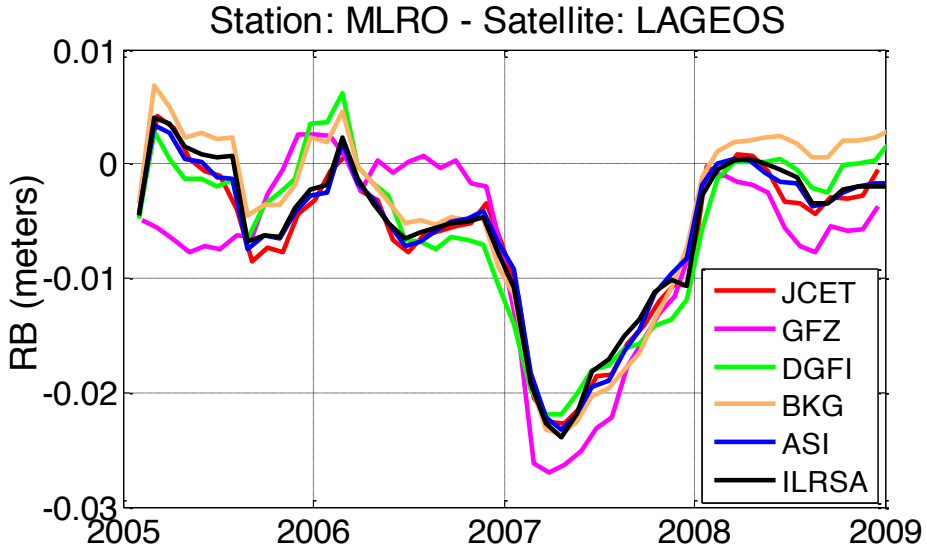
GRAZ: ILRSA time series for LAGEOS-2



Green line represents the actual bias value used in the analysis, as reported in the adopted data handling file

Results of the SSEM PP – an Example (Matera)

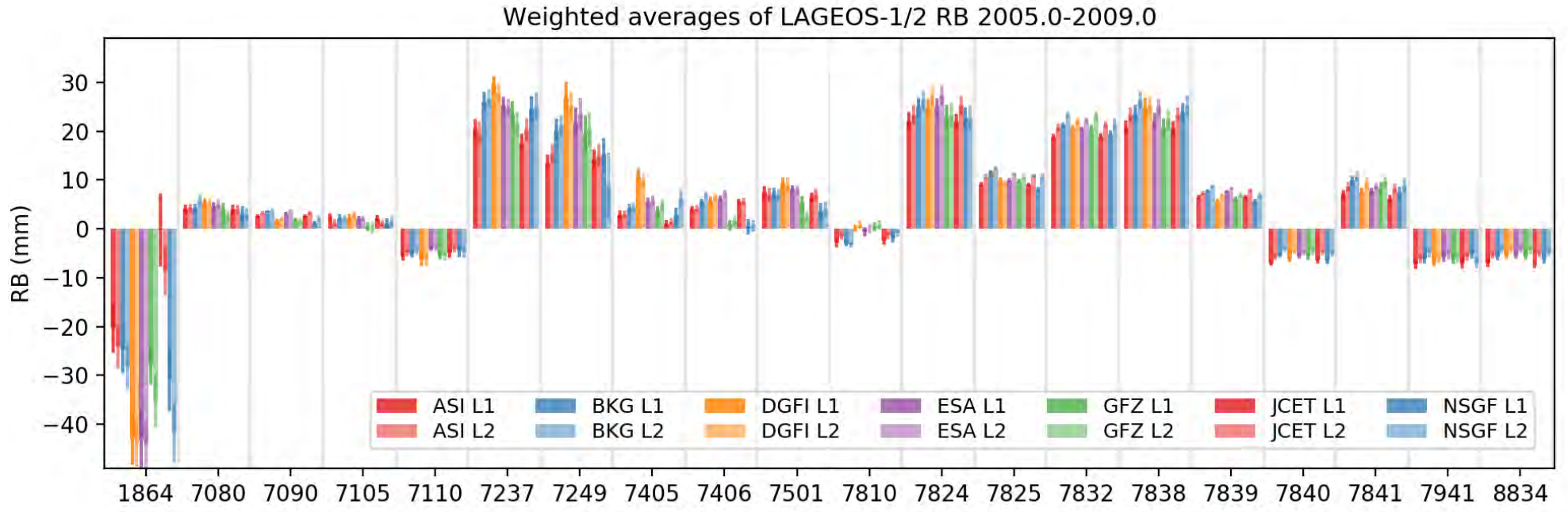
- The results show that real biases can be recovered and that the agreement among the ACs is generally within the uncertainty of the estimates, except in a few cases involving stations with poor or sparse data records.
- The figure on the right shows the case of a known, existing range bias in the data from station MLRO (Matera Laser Ranging Observatory, Italy) in 2007, close to a value of 25 mm as determined by the station engineers, with a 2-3 mm uncertainty.



- The estimated biases (running averages of each AC's time series) and of the combined time series, named ILRSA. A few sporadic discrepancies at the sub-centimeter level notwithstanding, the identification and quantification of a systematic range error is satisfactory.

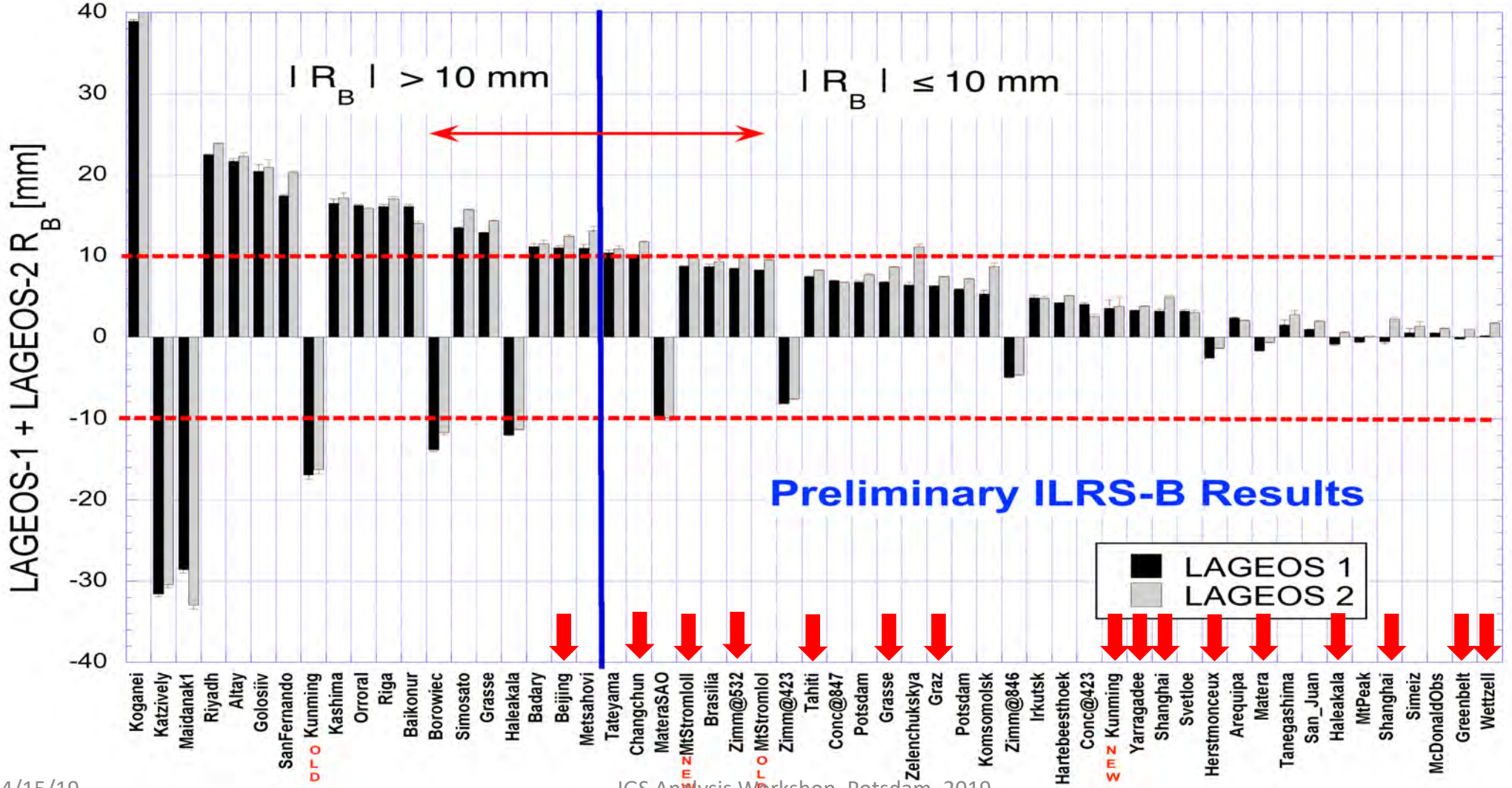
Results of the SSEM PP – Main Sites

- The general agreement among the solutions provided by the ILRS ACs is more clearly shown in the figure below on the right with the histogram of the mean biases over the entire 2005-2008 period, for the top 20 most prolific stations in the SLR worldwide network during these years. It is worthwhile to underline that this estimation process cannot yield millimeter accuracy in each single estimation but it can nevertheless reach such an accuracy in the mean value. The mean biases estimated for LAGEOS and LAGEOS-2 have very similar values, as expected from their nearly identical construction and similar orbits.



Results of the SSEM PP – Active Sites

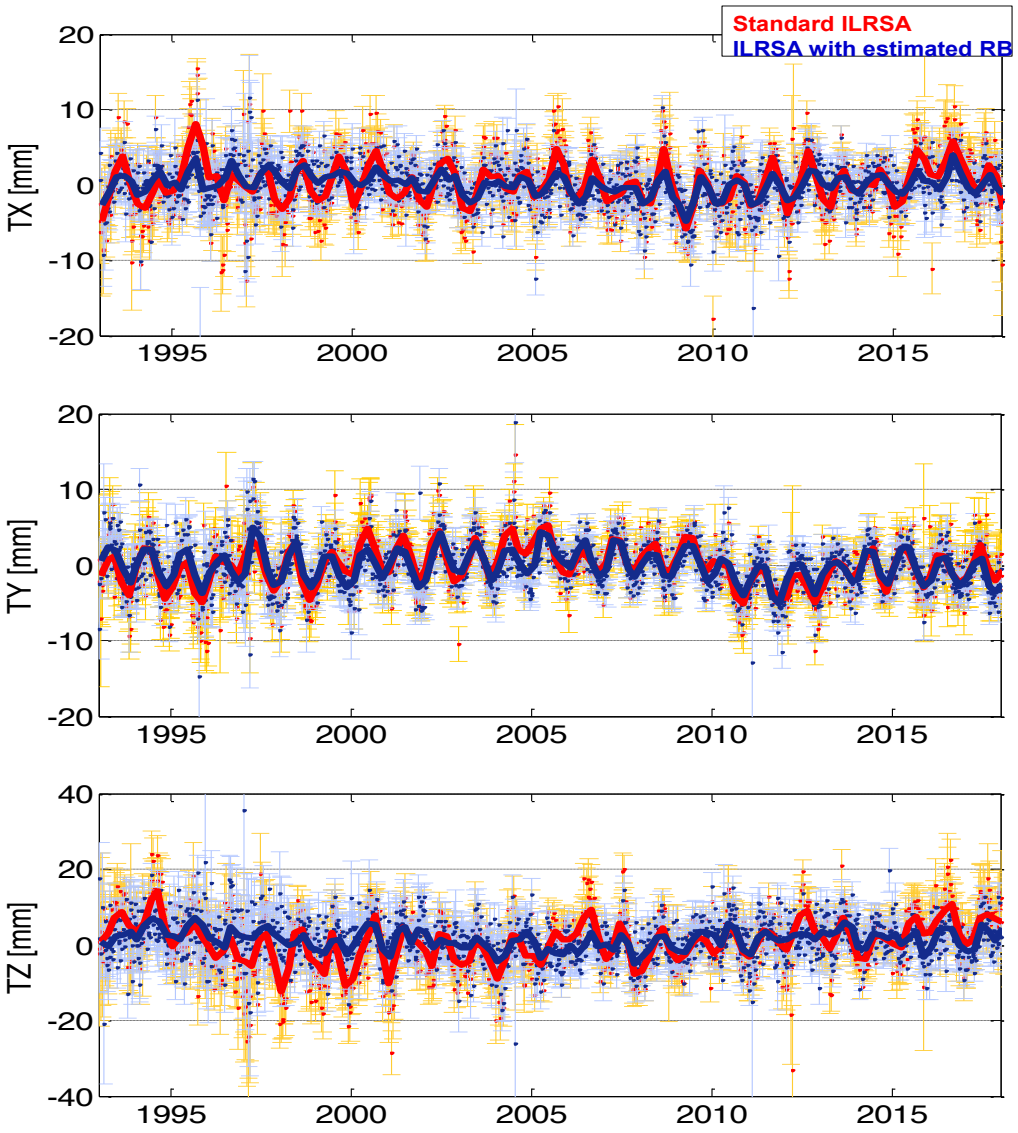
- The graph shows the mean estimates for LAGEOS and LAGEOS-2 bias for all active stations in the SLR worldwide network during the years 1993-2018. **Red arrows indicate Core Sites.**



Impact on the Reference Frame - Origin

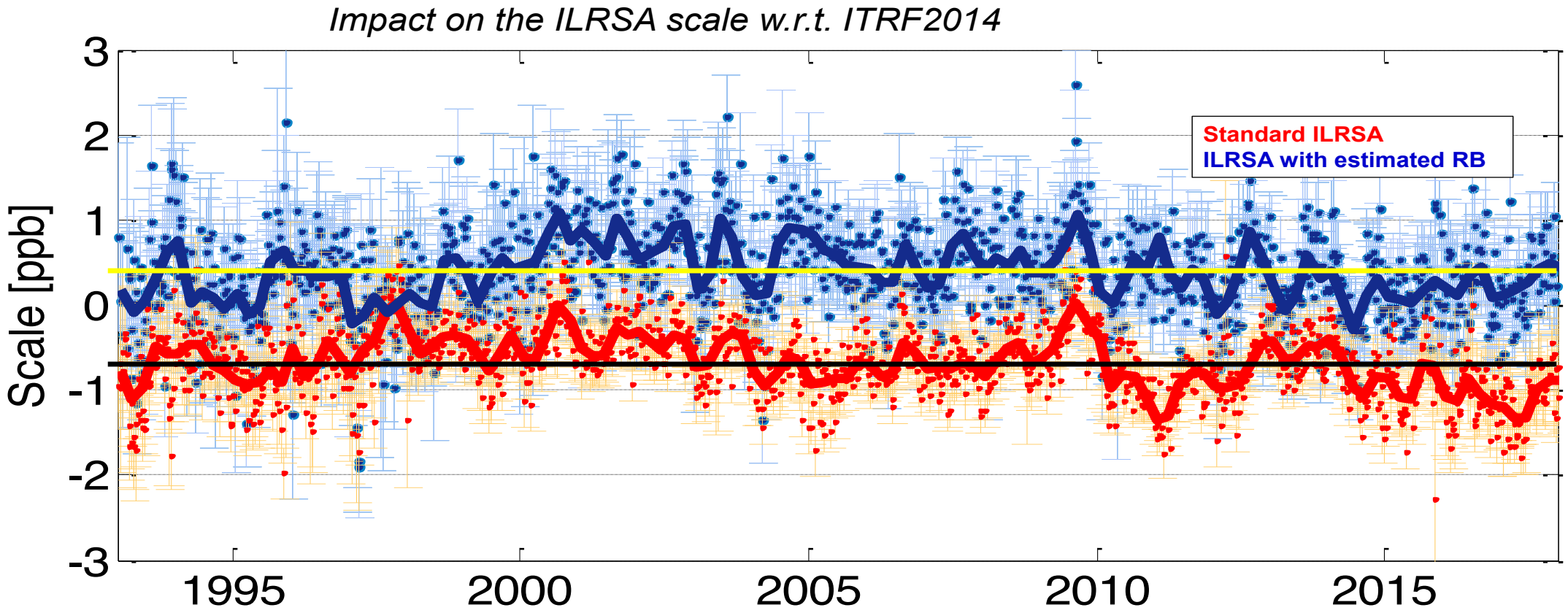
- The impact of the new approach on the reference frame was investigated by looking at the translations and scale of the loosely constrained combined time series with respect to ITRF2014 in comparison with the values obtained with the standard approach, i.e., with the application of the corrections listed in the Data Handling file.
- The origin translations are not significantly different, except for a slight smoothing of the annual component and general reduction of some extreme values.

Impact on the ILRSA TX/TY/TZ w.r.t. ITRF2014



Impact on the Reference Frame - Scale

- While the origin translations are not significantly different, the offset in the scale is significantly reduced, as shown in the figure. Furthermore, the mean change that is of the order of ~1 ppb is towards a closer agreement with the ITRF2014 scale, indicating a reduction in the scale difference between the SLR and VLBI future realizations of the TRF.



Operational phase

- The monitoring of systematic errors is an ongoing task to keep the ILRS operational product at a high quality standard, maintaining close contact with the onsite engineers.
- Items to be considered towards an operational phase:
  - New satellite Center of Mass (CoM) model - just delivered (mid-November ‘18)
  - Full reanalysis to take into account the new satellite CoM corrections
  - Mean station systematic errors inserted into the ILRS Data Handling file
  - Start of the operational service to maintain the table routinely updated
  - Use of the updated Data Handling file for all the official ILRS products, ITRF2020 included.
- Expected operational by this summer…

Changes in SLR Data Analysis

- Once ILRS adopts the new Data Handling file with the results from the current reanalysis, the users of SLR data will have to:
  - Adopt the new systematics and apply them *a priori* for each tracking site
  - Use the new satellite Center of Mass (CoM) model for supported targets
  - Use the same station coordinates as those used by ILRS in the reanalysis (SSEM PP)
  - Interrogate the Data Handling file (often, daily) to ensure there are no changes in the adopted mean biases or new additions (DH file carries a time stamp which changes with each release).

Thank you!