The ILRS contribution to ITRF2020

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The ILRS contribution to ITRF2020 consists of a pair of time series of weekly and bi-weekly station position estimates along with daily and 3-day averaged Earth Orientation Parameters (X-pole, Y-pole and excess Length-Of-Day (LOD)) estimated over 7-day arcs (1993.0 – 2021.0) and 15-day arcs for the period 1983.0-1993.0) aligned to the calendar weeks (Sunday to Saturday), starting from January 1983. Each solution is obtained through the combination of loosely constrained weekly/biweekly solutions submitted by each of the seven official ILRS Analysis Centers. Both, the individual and combined solutions have followed strict standards agreed upon within the ILRS Analysis Standing Committee (ASC) to provide ITRS products of the highest possible quality.

Individual solutions

The individual solutions are computed by the official ILRS ACs (ASI, BKG, DGFI, ESA, GFZ, JCET and NSGF) using the SLR data acquired from the global tracking network that observed the satellites LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2. From 1983 to 1992 the dataset is made up of LAGEOS data only (historical data). This dataset is complemented with the LAGEOS-2 and ETALON satellites starting from 1993. The main difference in the data amount is due to the LAGEOS-2 data; the amount of the Etalon data is roughly one tenth the data of the two LAGEOS, and have practically a negligible impact on the results.

AC code	**Analysis Center**	**SW**	**Time span**
ASI	Agenzia Spaziale Italiana	Geodyn/SOLVE	1983.0-2021.0
BKG	Bundesamt für Kartographie und Geodäsie	Bernese	**1993.0**-2021.0
DGFI	Deutsches Geodätisches Forschungs Institut	DOGS	1983.0-2021.0
ESA	European Space Operation Center	Napeos	1983.0-2021.0
GFZ	GeoForschungsZentrum Potsdam	EPOSOC	1983.0-2021.0
JCET	Joint Center for Earth Systems Technology – NASA Goddard & UMBC	Geodyn/SOLVE	1983.0-2021.0
NSGF	NERC Space Geodesy Facility	SATAN	1983.0-2021.0

The SLR observations are retrieved from ILRS' CDDIS and/or EDC data center archives and analyzed to generate the individual EOP and station position solutions. The measurements are processed in intervals of 7 days (15 days in 1983-1992) to generate a loosely-constrained solution for station coordinates and EOP. The EOPs (χ_p,y_p and LOD) are all computed as daily averages since 1993 and as 3-day averages when only LAGEOS data are available. Daily UT parameters are also solved for, but they are of course considered as weakly-determined parameters by any satellite technique and are not included in the analysis product that is submitted to the combination centers. The station positions, with the midpoint of each 7-day (15-day for the period 1983-1992) interval as reference epoch, refer to the official station markers.

The ITRF2020 ILRS contribution was developed following an innovative approach to handling systematic errors in the network, that was never before utilized. Based on a several years pilot project of the ILRS ASC, documented in Luceri et al., (2019, https://doi.org/10.1007/s00190-019-01319-w): the ***Station Systematic Error Monitoring*** PP (**SSEM**) delivered a series of estimates of long-term mean biases for each station, along with the time intervals of applicability and their statistics. These were derived from freely adjusted station position and EOP solutions for the period

1993.0 to 2020.5. The use of the latest satellite CoG model and the simultaneous estimation of the station heights and measurement biases resulted in a self-consistent set of weekly bias estimates for each site. These were subsequently analyzed for breaks and "jumps" which when identified, triggered the calculation of the mean of these estimates in each period, along with its standard deviation. Once the mean bias was pre-applied in the re-analysis, the remaining jitter due to the variability of the bias was mostly white noise and had no visible effect on the results. This approach strengthened the estimation process while it did not compromise the accuracy of the final results. All results of the SSEM PP were entered in a special edition of the Data Handling File (release 2021/01/27) which was distributed privately and only to the AC teams supporting the development of the ITRF2020. This was done to avoid confusing general users of the DH file with a very tailored version that necessitates the *a priori* application of the SSEM model and the use of a specific CoG model.

An additional benefit of the new approach is the fact that these estimated long-term mean biases can be examined by the system engineers and in some cases, they may identify the root cause and perhaps a correction process. In that case, in a future re-analysis these can be removed from the model as long as the "corrected SLR data" are used. On the other hand, upon adopting this approach with the SSEM model products we now face the problem of maintaining and keeping current this model. This will require the development of a new product that will extend the estimation of the mean biases beyond the end of the SSEM period of applicability and up until this approach is revised or changed. The ILRS ASC is thus implementing such a process to seamlessly extend the SSEM up to present and then maintain the estimation process into the future. The new "product" will be the SSEM-X model that will be used for present day analyses and also as a means to examining the quality of the delivered data from all stations.

Analysis contributors are generally free to follow their own computation model and/or analysis strategy, but a number of constraints must be followed for consistency and adherence to IERS Standards and Conventions:

- The computational models follow the prevalent IERS Conventions 2010 as closely as possible (with documentation of any exceptions).
- Mean Pole: Based on the UAW2017 IERS decision, the new Secular Pole was used via a fixed polynomial and associated adopted rates.
- The Desai-Sibois (2019) High Frequency EOP model was used, following its adoption by the IERS DB into the interim IERS Conventions.
- As requested by the ITRS, the non-tidal atmospheric loading effects on station positions were not modeled.
- The stations are included in the weekly analysis if the total number of observed LAGEOS plus LAGEOS 2 ranges is greater than 10. Data weighting is applied according to the analyst's preference. However, the ASC has agreed to down-weight "non-core" sites significantly.
- The target signature model (CoG, formerly known as the "center-of-mass correction") for each satellite is applied following the site- and time-specific tables provided by José Rodriguez/NERC (Rodríguez, J. et al., (2019), https://doi.org/10.1007/s00190-019-01315-0) that take into account the various laser station technologies and the mode of operation recorded in their site-logs over the years (release 2021-05-11).
- Range corrections were modeled or estimated for a number of sites based either on engineering reports from these sites or the SSEM results. All of the applied corrections are documented in a special release of the ILRS Data Handling file that will be made available at CDDIS and EDC, along with the official set of SINEX files delivered to ITRS.

- The weekly solutions are loosely constrained with an *a priori* standard deviation on station coordinates of ~1 meter and the equivalent of at least 1 m for EOPs.
- Following the UAW2017 discussions on information to be included in the ILRS SINEX files for ITRF2020, three **new** SINEX Blocks were designed and implemented by each AC and CC:
    1. The "MODEL/RANGE_BIAS" Block:

```
+MODEL/RANGE_BIAS
*CODE PT SOLN T START_DATE__ END_DATE____ M __E-VALUE___ STD_DEV _E-RATE__ UNIT   CMNTS
 1874 51  501 A 14:019:00000 20:138:00000 R        -17.8     0.8               mm
 1879 51  501 A 13:188:00000 18:322:00000 R         17.9     1.3               mm
 1887 51  501 A 11:303:00000 15:256:00000 R         21.5     1.8               mm
 1887 51  501 A 16:101:00000 18:343:00000 R        -21.6     1.5               mm
 1890 51  501 A 12:001:00000 21:001:00000 R         12.9     1.1               mm
 1893 51  501 A 05:212:00000 21:001:00000 R        -33.4     1.6               mm
 7080 51  501 A 96:133:00000 01:140:00000 R         -8.4     0.5               mm
-MODEL/RANGE_BIAS
```

    2. The "MODEL/TIME_BIAS" Block:

```
+MODEL/TIME_BIAS
*CODE PT SOLN T START_DATE__ END_DATE____ M __E-VALUE___ STD_DEV _E-RATE__ UNIT   CMNTS
 7090 -- ---- A 09:344:31560 09:345:70200 T      0.90920                       ms
 7105 -- ---- A 12:296:55000 12:297:02400 T       7.0470                       ms
 7110 -- ---- A 10:173:00000 10:208:27000 T      0.00640                       ms
 7110 -- ---- A 11:115:00000 11:316:00000 T      0.00780                       ms
 7110 -- ---- A 13:164:00000 13:173:00000 T      0.89990                       ms
 7124 -- ---- A 19:295:00000 19:324:00000 T        -1.00                       ms
 7237 -- ---- A 17:038:04000 17:038:60600 U      +1.0000                       ms   ETO
 7237 -- ---- A 17:037:43200 17:037:86400 U      +1.0000                       ms   ETO
 7501 -- ---- A 00:183:00000 04:279:86399 T     -0.00605                       ms
-MODEL/TIME_BIAS
```

```
+MODEL/TIME_BIAS
*CODE PT SOLN T START_DATE__ END_DATE____ M __E-VALUE___ STD_DEV _E-RATE__ UNIT
 1824 --  501 A 10:126:00000 10:127:00000 T      -17.750   1.000    0.0000   us
 1824 --  501 A 10:132:00000 10:133:00000 T       -5.750   1.000    0.0000   us
 1824 --  501 A 12:084:68460 12:085:00000 T      -24.400   5.000    0.0000   us
 1873 --  501 A 09:059:00000 09:110:00000 T      -21.750  50.000   -0.2600   us
 1873 --  501 A 09:111:00000 09:160:00000 T       -3.300  50.000   -0.1000   us
 1873 --  501 A 09:324:00000 10:095:00000 T        2.000  50.000    0.0750   us
-MODEL/TIME_BIAS
```

    3. The "MODEL/TARGET_SIGNATURE_GEOMETRY" Block:

```
+MODEL/TARGET_SIGNATURE_GEOMETRY
*CODE PT SOLN T START_DATE__ END_DATE____ M __E-VALUE___ STD_DEV _________ UNIT   CMNTS
 1873 51  501 L 08:288:00000 08:295:00000 C       0.1234   0.002             m    2020-06-08
 1879 52  501 L 08:288:00000 08:295:00000 C       0.1234   0.002             m    2020-06-08
 7810 53  501 L 08:288:00000 08:295:00000 C       0.9373   0.005             m    2020-06-08
 7810 60  501 L 08:288:00000 08:295:00000 C       0.0163   0.002             m    2020-06-08
-MODEL/TARGET_SIGNATURE_GEOMETRY
```

Additional details on the individual AC analysis strategy can be found on the ILRS web page https://ilrs.gsfc.nasa.gov/science/analysisCenters/index.html.

ILRSA Combined time series

The official ILRS combined solution is produced by the Primary Combination Center, ASI/CGS, and labeled ILRSA; a backup combined solution (ILRSB) is computed at JCET/UMBC, the backup CC.

The ILRSA solution has been obtained by a direct combination of the loosely constrained solutions, taking advantage of the fact that loosely constrained solutions, although they possess an ill-defined datum, they still preserve the relative geometry of the station polyhedron figure.

The combination is based on the method described in "*Methodology for global geodetic time series estimation: A new tool for geodynamics*", [P. Davies and G. Blewitt, JGR, vol. 105, no. B5, 2000] and allows handling input solutions easily, with no inversion problems for the solution variance-covariance matrix, no need to know a priori values for the estimates and no need to estimate or remove relative rotations between the reference frames before combining the solutions.
Each contributing solution (and related variance-covariance matrix) is treated as an 'observation' whose misclosure with respect to the combined solution must be minimized in an iterative Weighted Least Squares approach. Each solution is stacked using its full covariance matrix rescaled by an estimated scale factor. A scaling of the covariance matrix of the *i*-th solution is required because the relative weights of the contributing solutions are arbitrary. Imposing $\chi^2=1$ for the combination residuals and requiring that each contribution to the total χ^2 is appropriately balanced, the relative scaling factors (σ_i) are estimated iteratively together with the combined solution. If R_i represents the solution residuals (with respect to the combined product), Σ_i the solution covariance matrix and N the number of solutions, the imposed conditions are:

$$R_1^T(\sigma_1\Sigma_1)^{-1}R_1 = \cdots = R_i^T(\sigma_i\Sigma_i)^{-1}R_i \cdots = R_N^T(\sigma_N\Sigma_N)^{-1}R_N \quad \text{and}$$
$$\chi^2 = R_1^T\Sigma_1^{-1}R_1 + \cdots + R_N^T\Sigma_N^{-1}R_N = 1$$

The first guess for the combination is obtained with $\sigma_i=1$ for each solution.

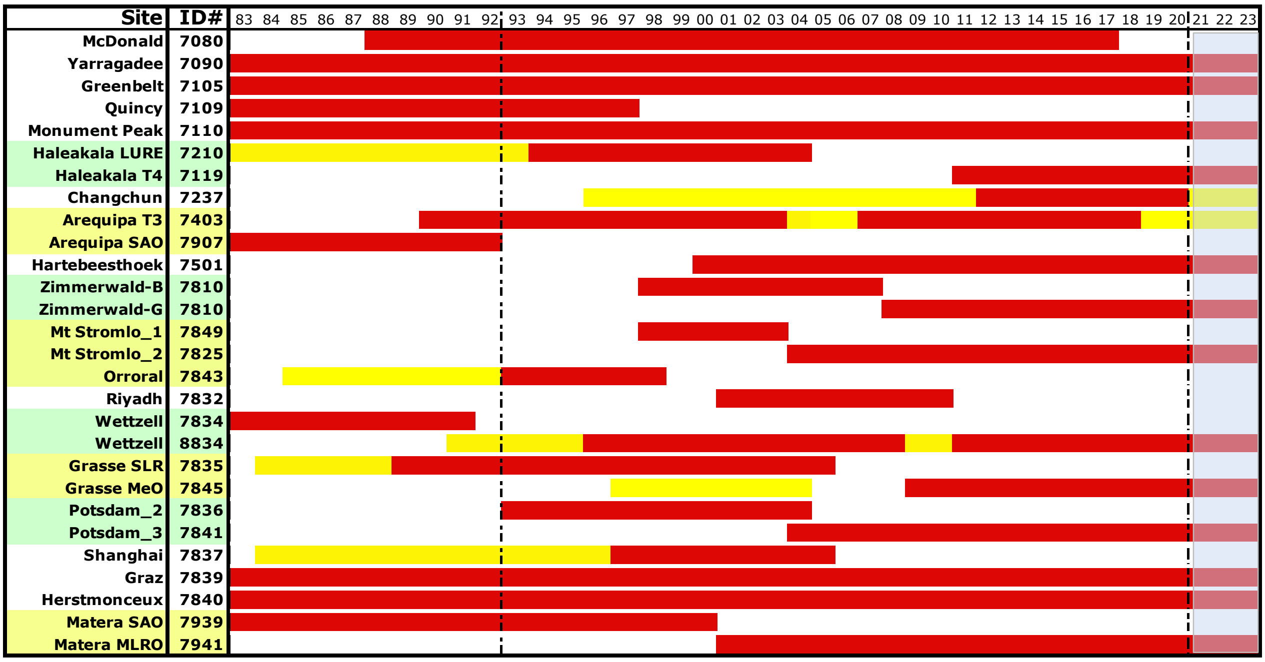


Figure 1: The adopted ILRS "core" sites that are used in aligning the individual AC solutions to the combined ILRS solutions over the time span of data used in developing ITRF2020 (and the proposed extension beyond 2020).

A rigorous editing (Brockmann, 1996) has been introduced to eliminate outliers with respect to the combined solution following a 5σ criterion for:

1. sites with less than 10 observations, erroneously present in the contributing solutions,
2. sites with too large uncertainties (> 1m) and
3. sites with large coordinate residuals with respect to the *a priori* SLRF2014 (>0.5m).

The internal precision of the ILRSA solution is checked through the computation of the weighted root mean square (WRMS) over the time series of the coordinate residuals of each input solution with respect to the combination. The coordinate residuals are computed after a rototranslation of each loose AC solution with respect to the combined solution using a set of core sites. The list of core sites has been officially defined, within the Analysis Standing Committee, considering the quality and stability of the entire set of network sites over several decades (Fig. 1).

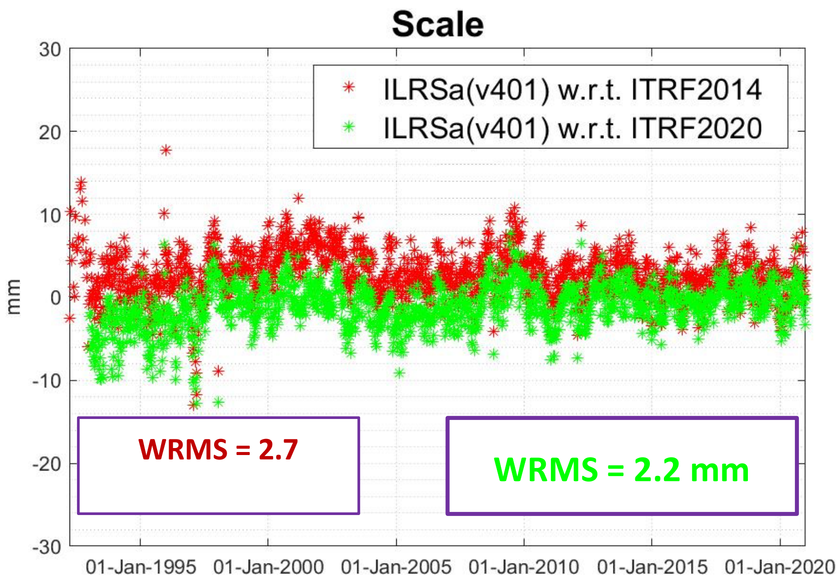
The ILRSA solution has been compared to ITRF2014 in terms of the 3D WRMS of the site coordinates residuals. The 3D WRMS computed using the full network is not so representative since it involves a lot of new sites and sites with lower than average performance. The subset of "core sites" which are well-defined is by far a more representative figure of merit.

3D WRMS of the ILRSA coordinate residuals with respect to ITRF2014 & ITRF2020

Units in millimeters (mm)	**1993-2020**
ITRF2014 Core sites (average)	5.48 ± 1.80
ITRF2020 Core sites (average)	3.66 ± 1.58

In addition to the official ILRSA combination series from the re-analysis products, the back-up Combination Center at JCET/UMBC delivered a back-up series designated ILRSB. The ILRSB series are developed in a slightly different formalism, using the de-constrained normal equations derived from the individual AC solutions and relative weighting of the input AC series determined through Variance Component Estimation.

As a result of the improved reanalysis and the new approach in handling systematic errors, the SLR scale with respect to the new ITRF2020 is by more than a full 1 ppb closer to the ITRF2020 overall scale than in previous TRFs.



Scale	Wmean (mm)	σ- WMean (mm)	Slope (mm/yr)	σ- Slope (mm/yr)
vs ITRF2014	2,654	0,069	-0,028	0,009
vs ITRF2020	-0,743	0,063	0,084	0,008