Appendix 5 ILRS contribution

The ILRS contribution to ITRF2014

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The ILRS contribution to ITRF2014 is a time series of weekly station coordinates and daily Earth Orientation Parameters (X-pole, Y-pole and excess Length-Of-Day (LOD)) estimated over 7-day arcs (15-day arcs for the period 1983-1992) aligned with calendar weeks (Sunday to Saturday), starting from January 1983. Each weekly solution is obtained through the combination of loosely constrained weekly solutions submitted by each of the official ILRS Analysis Centers. Both the individual and combined solutions have followed strict standards agreed upon within the ILRS Analysis Standing Committee 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, GRGS, 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. 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 a practically negligible impact on the results.

AC code	**Analysis Center**	**SW**	**Time span**
ASI	Agenzia Spaziale Italiana	Geodyn/Solve	1983-2014
BKG	Bundesamt für Kartographie und Geodäsie	Bernese	1993-2014
DGFI	Deutsches Geodätisches Forschungs Institut	DOGS	1983-2014
ESA	European Space Operation Center	Napeos	1983-2014
GFZ	GeoForschungsZentrum Potsdam	EPOSOC	1983-2014
GRGS	Groupe de Recherche de Géodésie Spatiale – Observatoire de la Cote d'Azur	GINS	1983-2014
JCET	Joint Center for Earth Systems Technology – NASA Goddard & UMBC	Geodyn/Solve	1983-2014
NSGF	NERC Space Geodesy Facility	SATAN	1983-2014

The SLR observations are retrieved from ILRS' CDDIS and/or EDC data archive facilities 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 (X_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.
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:

- The computational models follow the prevalent IERS Conventions as closely as possible (with documentation of any exceptions).
- Daily series of the Mean Pole (MP) coordinates and their rates based on the interpolated/extrapolated IERS MP series are adopted, instead of the fixed polynomial version in the IERS 2010 Conventions.

- As requested by the ITRF2013 Call for Participation, the non-tidal atmospheric loading effects are 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 center-of-mass correction for each satellite is applied following the site- and time-specific tables provided by Graham Appleby (Appleby et al. 2013) that take into account the various laser station technologies and mode of operation recorded in their site-logs over the years.
- Range corrections were modeled or estimated for a number of sites based either on engineering reports from these sites or long-term analysis of their systematic behavior. All of the applied corrections are documented in the ILRS Data Handling file available at http://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx.
- 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.

Additional details on the individual AC analysis strategy can be found on the ILRS web page http://ilrs.gsfc.nasa.gov/science_analysis/analysis_centers.html and the comments included with each individual AC contribution.

ILRSA Combined time series

The official ILRS combined solution is produced by the Primary Combination Center, ASI/CGS, and named 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.

The scale factors for each contributing AC are reported in the Table below as mean value and standard deviation over the period 1993-2013 when the solutions are more stable with the complete 4 satellites configuration.

	ASI	BKG	DGFI	ESA	GFZ	GRGS	JCET	NSGF
Mean	4.3	4.9	11.6	3.9	7.6	4.7	5.4	10.6
Standard deviation	2.7	4.1	5.5	1.7	5.4	2.9	3.5	6.0

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* SLRF2008 (>0.5m).

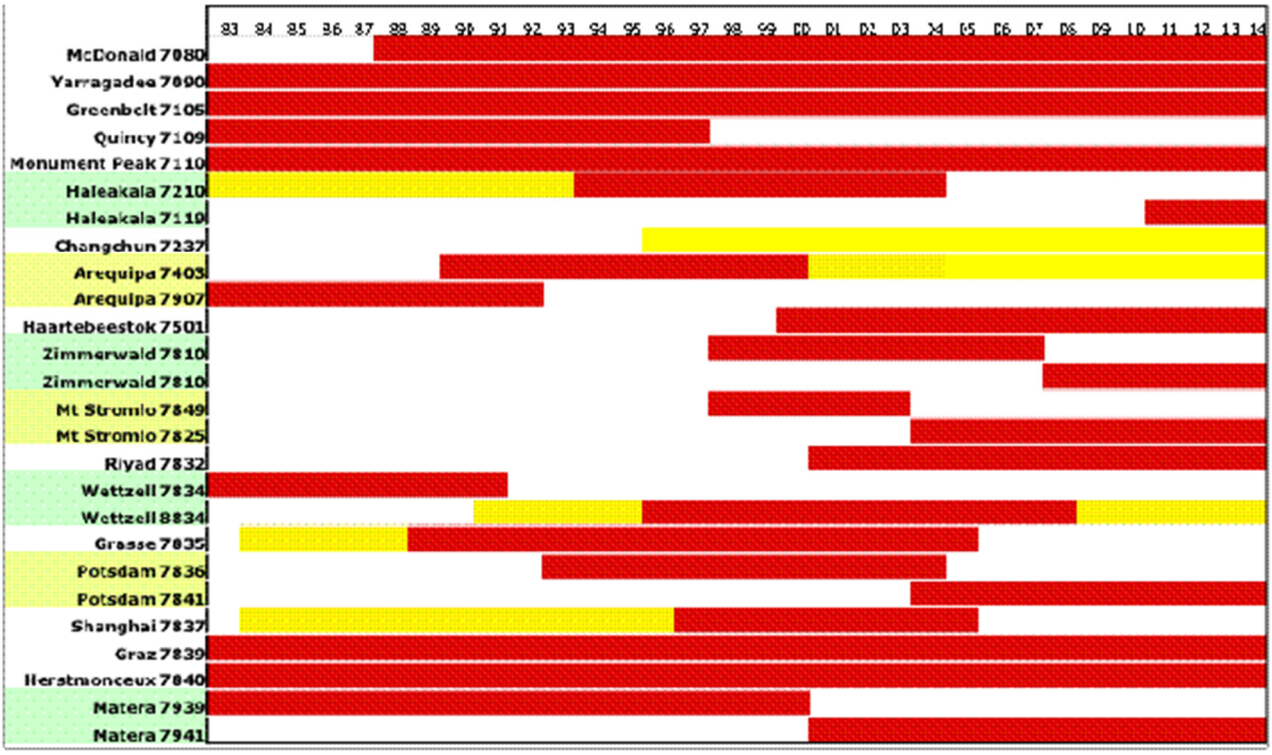

Figure 1: The adopted ILRS "core" sites that are used in aligning the individual AC solutions to the combined ILRS solutions over the time span of data used in developing ITRF2014.

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. Thus, a cumulative 3-dimensional value of the WRMS (3D WRMS) is computed for each solution using the coordinate residuals in all three components, of all the sites contributing to each solution (see table below). 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).

3D WRMS of coordinate residuals wrt ILRSA

	1983-1992		1993-2014	
	mean	std	mean	std
ASI	14.0	9.1	4.7	2.4
BKG	---------	---------	5.2	2.9
DGFI	12.0	5.4	7.8	3.0
ESA	11.9	9.7	5.2	3.1
GFZ	19.3	9.9	7.1	2.9
GRGS	15.5	11.4	4.9	2.7
JCET	16.9	10.0	5.0	2.6
NSGF	14.6	5.4	7.7	3.5

The ILRSA solution has been compared to SLRF2008 in terms of 3D WRMS of the site coordinates residuals. The 3D WRMS is computed using both, the full network and using a subset of "core sites".

3D WRMS of the ILRSA coordinate residuals with respect to SLRF2008

Units in millimeters (mm)	1983-1992	1993-2013
All sites (mean)	15.4	7.7
Core sites (mean)	11.2	5.0

The ILRSA EOPs have been compared with the USNO final daily values. The comparison is performed in terms of WRMS of the residuals and the results agree in general with what is expected from the SLR technique and the current network capability: 167 μas for the X-component, 190 μas for the Y-component and 32 μts for LOD are the mean values in the 1993-2014 time span.

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. The two series however show excellent agreement in all reported parameters, with differences between the two being much smaller than their formal statistics. This is an additional internal check of the quality of the ILRS-delivered products.