Overview of the ILRS Contribution to the Development of ITRF2013

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Overview of the ILRS contribution to the development of ITRF2013

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Abstract

Satellite Laser Ranging (SLR) data have been fundamental over the past three decades for the realization of the International Terrestrial Reference Frame (ITRF), which is based on an inter-technique combination of the geodetic solutions obtained from an intra-technique combination strategy performed at each IAG Technique Centre. This approach provides an opportunity to verify the internal consistency for each technique and a comparison of Analysis Center (AC) adherence to internal procedures and adopted models.

The International Laser Ranging Service (ILRS) contribution is based on the current IERS Conventions 2010 as well as on internal ILRS ones, with a few documented deviations.

The main concern in the case of SLR is monitoring systematic errors at individual stations, accounting for undocumented discontinuities, and improving the satellite target signature models. The SLR data re-analysis for ITRF2013 extends from 1983 to the end of 2013 and was carried out by 8 ACs according to the guidelines defined by the ILRS Analysis Working Group (AWG). These individual solutions have been then combined in the official solution by the ILRS Combination Center.

This work allows point-wise monitoring of the quality of the SLR contribution and a thorough investigation on the time behaviour of its characteristic products, i.e. origin and scale of ITRF. The stability and consistency of these products are discussed for the individual and combined SLR time series. The critical issues from this analysis will be presented to highlight the key points that SLR should take into account to contribute in the best possible way to the present and future ITRF realizations.

Keywords: International Laser Ranging Service, Satellite Laser Ranging, International Terrestrial Reference Frame, Geocenter, Scale

Introduction

The next realization of the ITRF will follow the same approach already adopted for ITRF2008 (Altamimi et al. 2011). It will be constructed using time series of station positions and Earth Orientation Parameters (EOPs) from the four space geodetic techniques (SLR, VLBI, GNSS, DORIS).

The IERS Technique Centers are requested to provide time series that are as long as possible and preferably covering the full history of observations of their technique.
Thus, the Technique Combination Centers' role implies the responsibility of generating an official mono-technique solution merging, in an optimal way, all the available AC solutions.
The role of SLR for the ITRF realization is fundamental both for its temporal data coverage, starting at the beginning of the eighties, and its specific sensitivity to the terrestrial origin and scale. As in the case of ITRF2008, it is expected that SLR will realize the ITRF origin and, in conjunction with VLBI, its scale.
The official ILRS (Pearlman et al. 2002) contribution to the new ITRF2013(1) is generated by the Primary ILRS Combination Center (CC) at the Space Geodesy Center of the Italian Space Agency (ASI/CGS) and is named ILRSA. A backup solution time series (named ILRSB) is computed at the Goddard Earth Sciences and Technology Center (GEST/UMBC), the backup CC.
The ILRS contribution to ITRF2013 is a time series of weekly station coordinates and daily EOPs (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) from January 1983 to December 2013. Each weekly solution is obtained through the combination of weekly solutions submitted by the official ILRS Analysis Centers. Both the individual and combined solutions have followed strict standards agreed upon within the ILRS AWG to provide products of the highest possible quality.

(1) Note
At the time of the REFAG 2014 meeting, the Call for Participation for ITRF2013 was still valid. The decision to extend the series to 2014, and go for the realization of ITRF2014, came later. The description of the ILRS contribution is applicable to ITRF2014 with the extension of the series to 2014.

Individual solutions

The individual solutions are computed by the official ILRS ACs (see **Error! Reference source not found.**) using the SLR data acquired from the worldwide network observing the satellites LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2. The dataset is made only by LAGEOS data from 1983 to 1992, called from now on the "historical period", and completed with the LAGEOS-2 and ETALON satellites starting from 1993 (see **Error! Reference source not found.**). The main difference in the data amount is due to the LAGEOS-2 data, the amount of ETALON data is one tenth of the two LAGEOS data and have a practically negligible impact in the data analysis results even with an increase of data during specific campaign of intensive tracking organized by the ILRS.
The SLR observations are retrieved from the CDDIS and/or EDC archive facilities and analysed to generate the individual EOP and positions 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 include X_p,Y_p and LOD, all computed as a daily average (3 day average when only Lageos-1 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 product quality is affected by different factors such as: conventions adopted, application/estimation of system biases, satellite center of mass correction, data coverage, hidden constraints. These factors were addressed in the past years within the ILRS AWG in order to give the ACs some guidelines. 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 computation models follow the prevalent IERS Conventions as closely as possible.
- 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 loading effects are not corrected.
- The stations are included in the weekly analysis if the number of observed LAGEOS 1 plus LAGEOS 2 ranges is greater than 10. Data weighting is applied according to the analyst's preference. However, the AWG 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 takes account of the various laser station technologies and tracks the changes 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 database (Data Handling file) on the ILRS website.
- 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.

The individual AC solutions are stored at CCDIS and EDC, available for the ILRS CC only.

ILRSA intra-technique combination

The 8 ACs have submitted several versions of their SLR SSC/EOP solutions in order to give their best time series, in strict cooperation with the CCs. One of the key strength of the contributing solutions is the use of different SW for the single AC data reduction. This "SW biodiversity" gives the opportunity to check and tune the implemented models and avoids the situation of a combination with high precision and low accuracy. Beyond the quality of the single ACs solutions, the final combined product quality is also affected by the balance in the contribution of all the ACs solutions and the application of outlier editing, which affects the iterative computation of the solution scaling factors in the combination process. The first step in the combination process is the rigorous check of each single AC time series in terms of looseness, application or estimation of biases for the set of sites over specific periods, data deletion whenever not recoverable, as indicated by the AWG guidelines. This phase is, in general, time consuming, with a strong interaction between the ACs and the CCs and can take several months, above all in case of time series reprocessing.

Once the input AC solutions are fully checked, the CCs are ready to start. 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 GEST/UMBC, the backup CC.
The ILRSA solution has been obtained by a direct combination of the loosely constrained solutions, provided by the official ILRS ACs, taking advantage by the fact that loose solutions give ill-defined coordinates but preserve the geometry of the figure.
The combination is based on the method described in "*Methodology for global geodetic time series estimation: A new tool for geodynamics*", (Davies and Blewitt 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.
Each contributing solution (and related variance-covariance matrix) is used like an 'observation' whose misclosure with respect to the combined solution must be minimized in an iterative Weighted Least Square approach. Each solution is stacked using its full covariance matrix rescaled by an estimated 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) and Σ_i the solution covariance matrix, the imposed conditions are:

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

The first guess for the combination is obtained with $\sigma_i=1$ for each solution.
The scale factors for each contributing agency are reported in **Error! Reference source not found.** as mean value and standard deviation over the period 1993-2013 when the solutions are more stable with the complete 4 satellites configuration. Five ACs have similar scale factors (between 4 and 5) while 3 ACs need higher scale factors to reach its balanced contribution in the combination, which means that they have higher residuals with respect to the combined solution.
A rigorous editing (Brockmann 1996) has been introduced to eliminate outliers with respect to the combined solution following a 5σ criterion for: sites with less than 10 observations, erroneously present in the contributing solutions, sites with too large uncertainties (> 1m) and sites with coordinate residuals with respect to the *a priori* SLRF2008(2) (>0.5m).

(2) Note
SLRF2008 is an extension of ITRF2008 including the new SLR stations active in the network after the ITRF2008 release.

ILRSA assessment

The combined time series is subject to several checks before its release.
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 arc using all the coordinate residuals, in the 3 components, of all the sites contributing to the arc solution. The time series of the 3D wrms for each agency are represented in **Error! Reference source not found.** as yearly running average, from 1993 to 2013, in order to make more visible the mean values and their rates. The internal "agreement" is roughly 4 mm in the last years, with a higher value for 3 input solutions, as mentioned above.
The external precision is checked comparing the ILRSA solutions with SLRF2008 and the EOPs with the USNO final daily values.
The two tables below show a comparison in terms of:

- mean of the 3D wrms of the site coordinates residuals w.r.t. SLRF2008 (see **Error! Reference source not found.**);
- translation and scale parameters of ILRSA w.r.t. SLRF2008.

The initial decade of the solution (1983-1992) consists of less precise estimates. However, the old portion of the series is a valuable and unique contribution of the SLR to the long-term Terrestrial Reference Frame definition, contributing a number of sites from the early stages of space geodetic networks. The 3D wrms is computed for the full network and for a subset of "core sites", namely those sites selected by the ILRS AWG for their stability, data history and well modeled in SLRF2008 (see **Error! Reference source not found.**).
Error! Reference source not found. shows the 3D wrms values for both the input solutions and the combination, the black line is a polynomial fit highlighting the trend in the ILRSA solution.
The datum stability of the ILRSA solution is assessed through the computation and analysis of the translations and scale with respect to SLRF2008. In the last ITRF realization (ITRF2008), the ITRF origin was defined by the ILRS SLR time series and the ITRF scale was by the average of VLBI and SLR scales/rates. The next ITRF datum will be presumably made in the same way and the quality of the frame defining parameters will largely depend on SLR; the weak and noisy solutions of the "historical period" will have a small or null impact on the frame definition. The translations showed in **Error! Reference source not found.** are relative to the 1993-2013 time span. No significant offset or drift are visible while seasonal variations are present, as expected. A small deviation from the trend is visible in Ty after 2010; this deviation is present in all the input time series and the reason is not clear. Tz is noisier, as expected. The linear fit on the scale (**Error! Reference source not found.**) time series presents a clear negative slope (-0.37 mm/yr) and an anomalous signature around 2010, unexplained at the moment. It seems an isolated event with the following part of the time series that reconnects to the main linear trend. As in the case of the translations, all the input AC solutions show the same behavior and a deeper investigation will be undertaken. A summary of the Helmert parameters drift is in **Error! Reference source not found.**.
As stated above, another external comparison is made for the EOPs 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 expected from the technique: 167 μas for the X component, 190 μas for the Y component and 32 μs for LOD.
A further step in the assessment of the ILRSA solution will be the detection of discontinuities in the site coordinates time series. These discontinuities will be

discussed with the IERS ITRS centre in charge of the official release of the next ITRF in order to reach an agreement on the set to be delivered with the ITRF.

Conclusion

The ILRS contribution to the next ITRF has been delivered following the guidelines of the Call for Participation. The 8 ILRS Analysis Centers produced the time series of station coordinates and EOPs (X_p,Y_p and LOD) over the period 1983-2013 under the constraints agreed within the ILRS Analysis Working Group. The ILRS Combination Centers delivered the official ILRSA combined time series and the backup ILRSB. As for the ITRF2008 contribution, the ILRSA solution is computed by a direct combination of the loosely constrained solutions, whose contribution to the final product is balanced using a solution scale factor. The internal and external precision of the combined time series has been evaluated through the comparison between the input solution and the combined, between the combined and SLRF2008 and, for the EOPs, with the USNO values.
These comparisons show good performance of the quality parameters (site coordinates WRMS, Helmert parameters time series) for the final combined solution and a remarkable coherence for the single AC solutions: the 3D WRMS of the Core Site residuals w.r.t. SLRF2008 reaches 5mm in the last years, the Helmert parameter time series (origin and scale) are neat, allowing to detect small secular and periodic components while Tz is noisier, as expected. A signature starting around 2010 is visible in the Ty and scale and will be investigated.
As requested by the IERS ITRS centre, the ILRS time series will be extended to include 2014; the network will benefit by a considerable number of new stations, mainly Russians, but the quality of the ILRS contribution will not be substantially affected.

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Fig. 1 Input dataset of the ILRS solutions

Fig. 2 3D WRMS of the coordinate residuals w.r.t. ILRSA (yearly running average)

Fig. 3 3D WRMS of the core site coordinate residuals w.r.t. SLRF2008

Fig. 4 ILRSA translation with respect to SLRF2008

Fig. 5 ILRSA scale with respect to SLRF2008

Table 1 Current ILRS Analysis Centers

ASI	Agenzia Spaziale Italiana	Italy
BKG	Bundesamt für Kartographie und Geodäsie	Germany
DGFI	Deutsches Geodätisches Forschungs Institut	Germany
ESA	European Space Operation Center	Germany
GFZ	GeoForschungsZentrum Potsdam	Germany
GRGS	Groupe de Recherche de Géodésie Spatiale – Observatoire de la Cote d'Azur	France
JCET	Joint Center for Earth Systems Technology – NASA&UMBC	USA
NSGF	NERC Space Geodesy Facility	Great Britain

Table 2 Scaling factors applied to the individual AC solutions

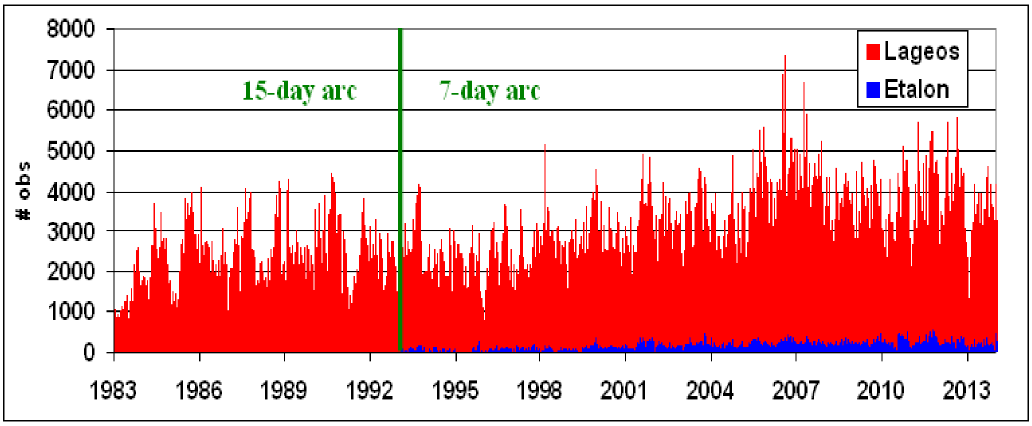
	ASI	BKG	DGFI	ESA	GFZ	GRGS	JCET	NSGF
Mean	4.3	4.9	11.6	3.9	7.6	4.7	5.4	10.6
Standard deviation	2.7	4.1	5.5	1.7	5.4	2.9	3.5	6.0

Table 3 3D WRMS of the ILRSA coordinate residuals w.r.t. SLRF2008

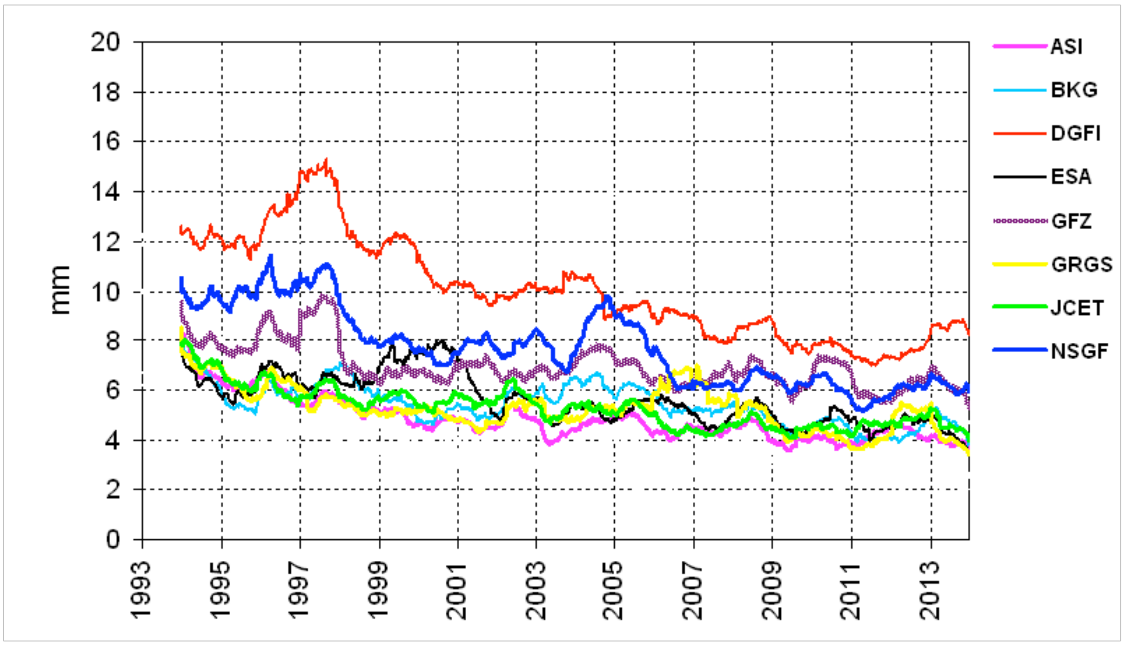
Units in millimeters (mm)	1983-1992	1993-2013
All sites (mean)	15.4	7.7
Core sites (mean)	11.2	5.0

Table 4 - Translation and scale w.r.t. SLRF2008

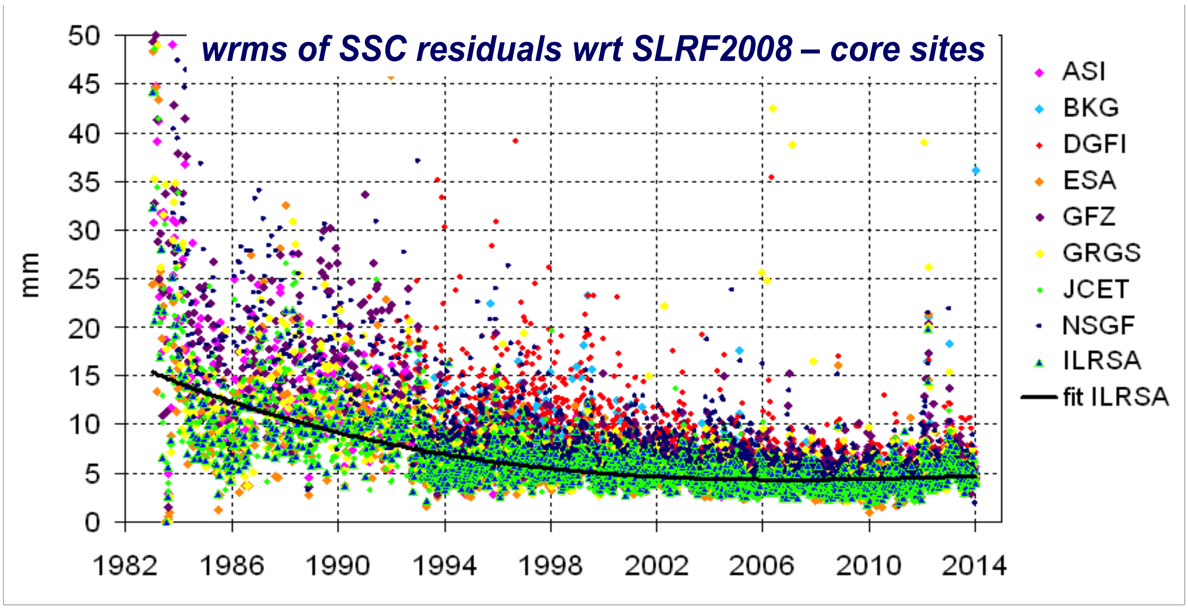
	T_X	T_Y	T_Z	SCALE
Slope (mm/y)	-0.01±0.01	-0.12±0.01	0.28±0.03	-0.371±0.001



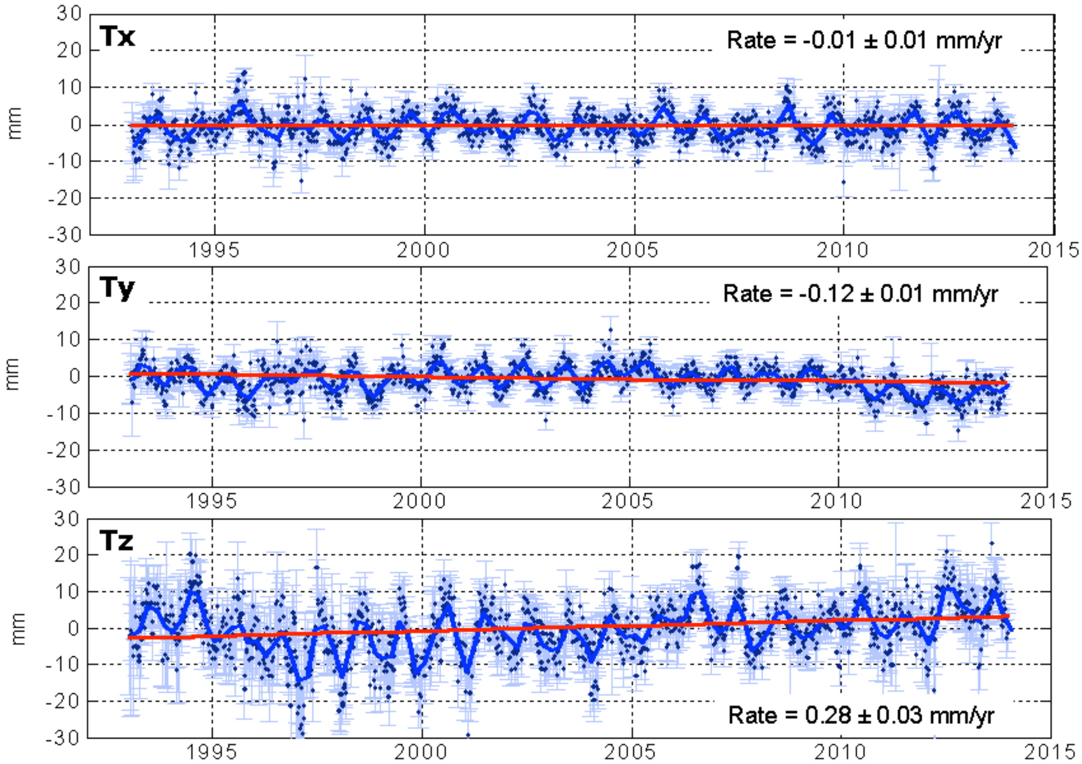
8000
7000
6000
5000
4000
3000
2000
1000
0
obs
15-day arc
7-day arc
Lageos
Etalon
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013

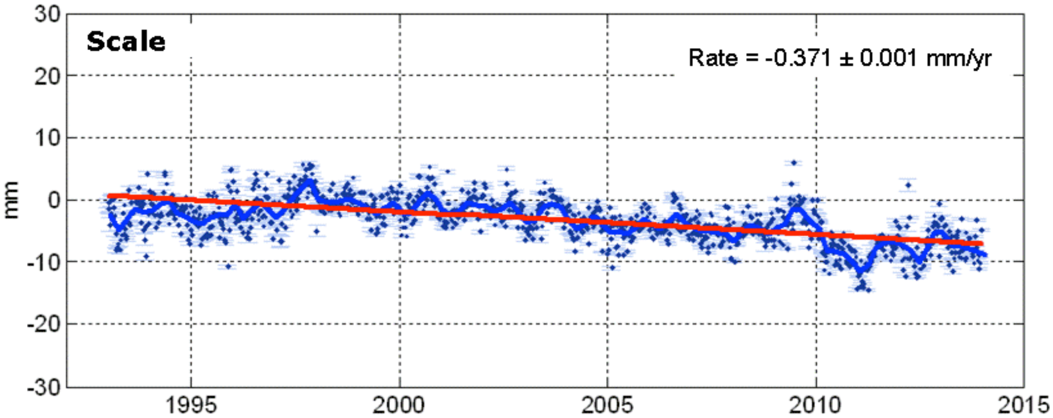


20
18
16
14
12
10
8
6
4
2
0
mm
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
ASI
BKG
DGFI
ESA
GFZ
GRGS
JCET
NSGF



wrms of SSC residuals wrt SLRF2008 – core sites
50
45
40
35
30
25
20
15
10
5
0
mm
1982
1986
1990
1994
1998
2002
2006
2010
2014
ASI
BKG
DGFI
ESA
GFZ
GRGS
JCET
NSGF
ILRSA
fit ILRSA


Tx
Rate = -0.01 ± 0.01 mm/yr
Ty
Rate = -0.12 ± 0.01 mm/yr
Tz
Rate = 0.28 ± 0.03 mm/yr
mm
30
20
10
0
-10
-20
-30
1995
2000
2005
2010
2015


Scale
Rate = -0.371 ± 0.001 mm/yr
mm
30
20
10
0
-10
-20
-30
1995
2000
2005
2010
2015