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Systematic errors in SLR data and their impact on the ILRS products

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Abstract

The satellite laser ranging (SLR) technique has the potential to make extremely precise measurements to retroreflector arrays on orbiting satellites, with normal point range precision at a level of 1 mm for the core tracking stations of the International Laser Ranging Service (ILRS). The main limitation to achieving a similar level of range accuracy is the presence of uncorrected systematic errors, which can be attributed to various sources at the stations (e.g., calibration and/or synchronization procedures, hardware malfunctioning, nonlinearities in the time-of-flight measurement devices), as well as to modeling deficiencies, especially in the ability to refer the range measurements to the center of mass of the spacecraft. The ILRS has always been active in adopting rigorous procedures to detect and remove systematic errors from the data: a group of ILRS analysis centers routinely performs data quality control a few hours after data acquisition; the ILRS Analysis Standing Committee (ASC) is in charge of long-term monitoring and characterization of systematic errors in the observations used for the ILRS products; a Quality Control Board was established in 2015 to address SLR systems' biases and other data issues. In particular, the ASC is devoting efforts on an investigation of an alternative approach whereby a simultaneous estimation of site coordinates and range biases provides station positions that are in principle free of systematic errors. Results using this approach have shown a significant impact on the realization of the TRF, in particular by reducing the existing scale offset between the VLBI and SLR solutions and reaching a closer agreement with the ITRF2014 scale. This paper outlines the work that continues to be done to improve these products and in particular focuses on new research to evaluate rigorously any impact on the strength of coordinate solutions and geophysical inferences when systematic range errors are determined simultaneously with reference frame parameters. Future procedures for handling systematic errors will be informed by the outcome of the current investigations.

Keywords SLR · ILRS · Systematic errors · ITRF

1 Introduction

The precision of individual SLR observations and normal point data exceeds that of currently available modeling standards, as a cursory look at the full-rate data and post-fit range residuals of any core tracking station of the ILRS network shows. Individual retroreflector tracks are clearly

visible in the full-rate data of high-repetition rate laser stations (≥ 0.1 kHz firing rate), indicating that these systems are operating at a similar precision to that achieved for ground calibration targets (typically 1–3.5 mm, Kucharski and Kirchner 2006). It must be noted that this has nothing to do with the high number of detections per unit of time these systems achieve, as there is no averaging involved in full-rate data; this level of precision is intrinsic to modern ranging systems, which merely becomes more evident when a high density of observations is achieved. In the case of normal point data, residuals over single satellite passes show a precision reaching 1 mm, whereas typical RMS values for single station observations over 7-day arcs approach 1 cm. The more pressing question is whether these intrinsically precise systems are affected in a systematic way over time scales comparable to the time periods of interest, i.e., from individual arcs to months and years, and whether the potential

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presence of those systematic errors can be detected and their effect on geodetic products mitigated.

Ideally, SLR stations should at most exhibit small and constant systematic errors to high precision. The presence of time-varying or range-dependent errors, for example, is particularly problematic and their removal is often non-trivial. Highly correlated with station height estimates over short periods, depending upon quantity of measurements, varying range errors may introduce spurious jumps in the site coordinate time series. The SLR network has traditionally relied on analysis results with a quick turnaround schedule for quality control (QC) monitoring, based on fixed station positions. These efforts are very successful in detecting major problems and system malfunctions, but they are insufficient to detect varying errors below a threshold of a few centimeters. Considering that an unidentified range error of 6 mm can be misinterpreted as a scale change of ~ 1 ppb, it is paramount to develop procedures able to deal with the potential presence of such systematic errors not revealed by the regular QC schemes.

2 Systematic error sources in SLR data

The 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. In the analysis, the range bias is the most critical, being highly correlated with station height over short periods. Their presence can corrupt the estimation of site coordinates, which ultimately define the scale of the global network and the geocenter. Intermittent biases can introduce jumps in coordinate time series and have an impact on the computed site velocities. A non-homogeneous treatment of biases among the analysis centers can also affect the combined product.

The nature of the errors affecting the SLR technique can be divided into three categories, as already defined by Pearlman (1984): ranging machine errors (calibration and/or synchronization issues, hardware malfunctioning, intrinsic device limitations), timing errors (station clock issues) and modeling errors (e.g., satellite center of mass offsets, force model deficiencies). Following good practices and procedures at the ground stations should help to identify and minimize errors of the first two categories. On the other hand, accurate modeling of the measurement process and orbit dynamics is fundamental to achieve an accurate estimation of the parameters of interest, in turn aiding in the identification of systematic errors elsewhere.

Although mathematically very simple, the notion of range biases itself is rather elusive, with ambiguous physical meaning. Biases are often interpreted as something tracking

stations have, own and ultimately should take responsibility. This is, however, a limited view of what may constitute a range bias. Depending on the specific technique employed to evaluate range errors and the time scale of the analysis, the lines between genuine physical problems in the measuring systems, modeling deficiencies, measurement precision, accuracy and statistical correlation may be blurred to some degree. An operational definition of range biases would simply identify them with whatever values are obtained when an explicit allowance for the presence of range errors is made in the observation equations of a least squares system of SLR data. In terms of information content, range biases are scalars with no preferred orientation pointing to their origin. Identifying the actual causes of estimated biases is a difficult, separate problem that may require in-depth knowledge of hardware systems, operation procedures, measurement process, signal behavior and modeling issues, as well as having available all the relevant meta-data and ancillary information.

Time errors in the epochs of SLR data have not been a major issue of concern affecting the quality of the observations. The accuracy demands of the time-tagging of the observations are in the order of 1 microsecond (whereas time-of-flight measurements require a few picoseconds accuracy). However, recent work by Exertier et al. (2017), exploiting the T2L2 time-transfer experiment onboard Jason-2 and the observational support provided by the ILRS network, shows that while for most ground stations time biases are relatively low and stable, there are instances where this is not the case and detected as well 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, which can reach a few mm level in the east–west component (Exertier et al. 2017).

A particularly important modeling issue in SLR is the determination of the reflection point of the laser pulses on the retroreflector array, relative to satellite center of mass. Inaccuracies in the values of the center of mass offsets directly translate to ranging errors. Considered to be a minor issue, or outright ignored, in the first decades of laser ranging operations, satellite and station-specific center of mass corrections are nowadays a major component of the technique error budget. Center of mass offsets depend on the geometry and physical characteristics of the retroreflector arrays as well as on a number of features of the tracking stations and mode of operation at the particular instant, such as laser pulse length, energy and wavelength; detector type, jitter and rise time; precision of timing device; mode of operation; and data reduction procedures. Center of mass corrections currently employed and recommended by the ILRS for the geodetic spherical satellites have been computed on the basis of information available on the construction of the satellites and characteristics of individual ground

Table 1 ILRS QC analysis center

AC code	QC analysis center	S/W
HITO	Hitotsubashi University, Japan	Concerto
JCET	Joint Center for Earth Systems Technology—NASA Goddard & UMBC, USA	Geodyn/solve
MCC	Mission Control Center, Russia	???
SHAO	Chinese Academy of Sciences, Shanghai, PRC	???

stations (Otsubo and Appleby 2003; Otsubo et al. 2015). The assumed accuracy of these corrections depends on the type of system under consideration. For stations operating in the so-called single-photon mode, i.e., carefully controlling the energy of the returned pulses so that on average no more than a single photoelectron is detected, the expected CoM accuracy approaches the mm level for the LAGEOS satellites. For stations employing microchannel plate (MCP) or PMT detectors operating at higher levels of returned energy, the ambiguity and greater complexity of the detection process means that the uncertainty is about 1 cm for LAGEOS and up to 5 cm for Ajisai and Etalon. Recent work aimed at enhancing the determination of CoM offsets has shown substantial improvements (up to 1 cm) for the Etalon satellites and significant changes in the CoM corrections for LAGEOS (Rodríguez et al. 2018). These modeling upgrades will result in the publication and release of revised CoM values for the main spherical geodetic satellites currently tracked by the ILRS network (Rodríguez et al. 2019).

3 ILRS quality control service

The ILRS has always strived to characterize the quality of the data produced by its network before releasing it to the user community. To achieve this, a number of different “check points” have been in use since the very early days, some even predating ILRS itself. The first level of quality control (QC) is always performed at the station collecting the data. A very simple comparison to predicted data on the basis of the predicted orbits “flattens” the residual series and helps identify gross outliers. Stations that belong to a group supported by an operation center (OC) have a second level of QC performed at the OC, using somewhat higher quality of orbits. The next available check is done by a few ACs that are dedicated to perform this QC service on a daily or even more frequent schedule, based on accurate orbits fitted to the data and station positions from the best available ITRF model at the time.

The ILRS ACs that routinely perform QC analysis of SLR data on various satellites are listed in Table 1. At a minimum, the “ITRF-contributing” targets are included, for more

details see: <https://ilrs.cddis.eosdis.nasa.gov/science/dataAnalysisResources/>.

At this level, and mainly due to the fact that the station positions are kept fixed, the QC process can identify changes in the performance of the station at the few centimeter level, and over time estimate averaged biases at the few millimeter level, however, in all cases conditional on the adopted positions. Although this practice can help stations by quickly identifying abrupt changes in their systematics if they persist over time, it cannot objectively estimate the absolute magnitude of the errors. At best one only finds out about a change from prior level of performance. This activity is even less capable of detecting small time biases, most of which persist only over very short intervals. 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 a few centimeters. A very detailed description of this QC service provided by the ILRS today is given in (Otsubo et al. 2018).

A Quality Control Board was organized at the 19th International Workshop on Laser Ranging to address SLR systems biases and other data issues that have degraded the ILRS data and data products. The board meets monthly by telecon or in person to discuss the relevant topics and take actions to help and give guidance to the stations and analysts. Notes from the meetings to date are publicly available at <https://ilrs.cddis.eosdis.nasa.gov/science/qcb/index.html>.

4 Systematic error handling in the ILRS products

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. The ILRS main product is the weekly averaged estimate of site coordinates and daily resolution Earth Orientation parameters, using LAGEOS and Etalon normal point data, obtained from the combination of individual analysis center (AC) solutions. The time series of weekly solutions is the fundamental contribution to the International Terrestrial Reference Frame (ITRF) and the latest ILRS official product for ITRF2014 has adopted a common bias strategy for the single AC solutions as described hereafter.

4.1 Background

The work done by the ILRS ASC to make an in-depth characterization of station systematic errors started in the 2000s at the time of the definition of the ILRS official products. The initial approach was focused on the recovery of information from historical and engineering reports, site logs, communication with the stations and, if required, a direct

estimation of the suspected errors. The recovered information was validated with the use of the so-called multi-year solution using the LAGEOS data: The full SLR data set was used to estimate fortnightly range biases together with the site coordinates, velocities, Earth Orientation Parameters (EOP) and other parameters typical of a classical geodetic solution. Since the interest is the detection of long-term effects, only the persistent presence of range biases over a long time span (months) was considered, and a mean value was computed to be adopted as a correction to be applied to the data. Whenever the estimated mean biases were different from the expected values reported in the archives or were not reported at all, the stations were involved in the analysis and in the final decision so that the adopted values were as close as possible to the perceived real systematic errors. One of the non-trivial problems was the systematic nonlinearity effects of the Stanford counters used in SLR (roughly 1 cm with a few exceptions), affecting ~ 15 stations over several years. Much practical work on this problem was carried out by the Herstmonceux group using several such counters (Gibbs et al. 2007) which concluded that post-correction of observations using Stanford counter-calibrations is fraught with problems and uncertainties.

As regards the time biases and meteorological corrections (e.g., errors in the measured atmospheric pressure at the station), no further analysis was made on the information recovered from the archives. The aforementioned work by Exertier et al. (2017) using the T2L2 time-transfer system on the oceanographic mission Jason-2 shows that for the large majority of SLR stations only negligible time biases are present, although in some instances considerable biases may be present over long time periods.

This process led to the establishment of a periodically updated “data handling” file containing all types of data corrections, made available online through the ILRS portal (https://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx). The file is used by all the ILRS AC in the generation of all the official geodetic products.

However, a major flaw in this scheme is that any long-term systematic error, if not explicitly solved-for simultaneously with the reference frame, will be absorbed primarily in station height and thus not detected unless the systematic error itself changes at some point in time; it should be considered that all stations can potentially produce biased data at some level until data analysis suggests otherwise. This was precisely the case with the UK station at Herstmonceux. In 2007, a highly accurate event timer was installed to replace the Stanford counters that had been in use since the mid-1990s. As an unexpected result, a jump in station height of 14 mm was detected by the ILRS QC procedures. However, a thorough investigation by station personnel (Appleby et al. 2016) revealed that the post-2007 data are of excellent quality whereas the pre-2007 observations were biased by

up to 14 mm. This bias, never explicitly solved-for, had been absorbed into station height and remained undetected. Similar findings have been obtained during recent upgrades of the timing devices of NASA stations (Varghese et al. 2019), with the Greenbelt, MD system MOBLAS-7 (7105) showing a -4 mm systematic difference between TIU and ET referenced ranges (Fig. 1).

In the past 2 years, technologically outdated time-interval counter units (TIU) have been replaced by modern event timers (ET) at most MOBLAS stations of the NASA network. Analysis of the data collected simultaneously with the TIU and ET systems during the validation stage showed excellent agreement between the old devices and their replacements in all but one station (at MOBLAS 7 at GGAO, #7105), where a consistent 4 mm bias was detected in the observations to all satellites (Varghese et al. 2019).

4.2 The impact on the reference frame

The ILRS SLR time series plays a fundamental role in the definition of the ITRF origin (ITRF2014 has null translation parameters at epoch 2005.0 and null translation rates with respect to the ILRSA SLR time series) and a major role in the definition of the ITRF scale (null scale and scale rate between ITRF2014 and the average of VLBI and SLR scales and their rates). The ILRS contribution to the realization of the last ITRF2014 has strictly followed the application of the error corrections as defined in the data handling file, as already implemented in ITRF2008 and updated since that time. An immediate evidence of the benefit coming from the proper data error correction is the elimination of artifacts in the coordinate time series.

The improvement in the estimate of the individual site coordinates has a direct impact in the reference frame datum.

The realization of ITRF2005 showed a disagreement between the SLR and VLBI scales (Altamimi et al. 2011) of 1.4 ± 0.11 ppb at epoch 2005.0 and 0.08 ± 0.01 ppb/year for the scale and scale rate, respectively. The effort spent in the improvement in the technique solutions for ITRF2008 resulted in a reduction in the scale differences to 1.05 ± 0.13 ppb at epoch 2005.0 for the scale and 0.049 ± 0.010 ppb/year for the scale rate.

The ITRF2014 results show a scale factor between VLBI and SLR solutions of 1.37 ± 0.10 ppb at epoch 2010.0 and a scale rate of 0.02 ± 0.02 ppb/year, confirming the ITRF2008 finding (Altamimi et al. 2017). The cause of the scale discrepancy is still an open question under investigation, although systematic errors are suspected to play a significant role here.

Discussions within the ASC and at several Unified Analysis Workshops prompted an independent piece of research by analysts from the ILRS AC based at Herstmonceux (NSGF) who used more than 20 years of LAGEOS

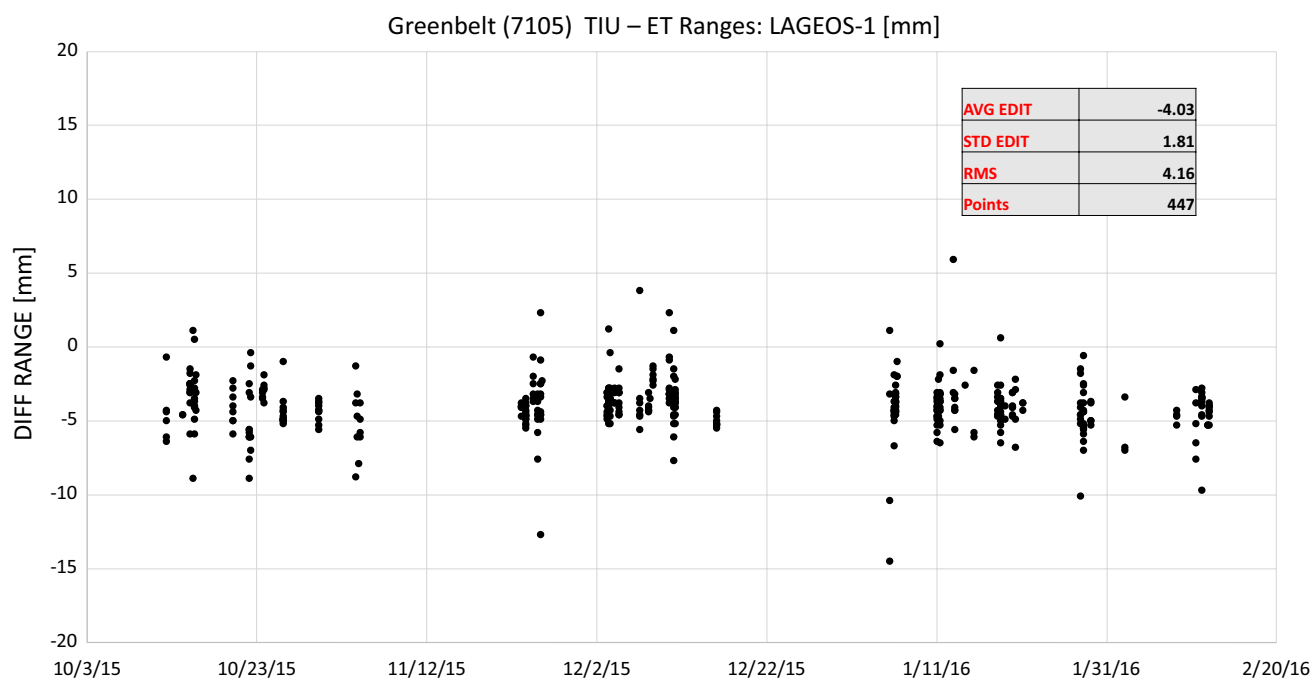


Fig. 1 Greenbelt, MD (7105) range differences between TIU-based and ET-based measurements to LAGEOS-1 (same bias was observed LAGEOS-2 and LARES)

and LAGEOS-2 observations from the ILRS network and carried out 7-day solutions by adjusting satellite state vectors, empirical accelerations, daily Earth orientation parameters (x-pole, y-pole, LOD), geocentric station coordinates and a single systematic correction (Range Bias, RB) to all the range measurements made by every station that contributed observations. Also computed were the same 7-day solutions where RB was solved simultaneously for only those stations that had previously been designated to require the solution of a bias by earlier work within the ASC; this latter philosophy has been used for all ILRS solutions toward ITRF2005, 2008 and 2014. The investigation found that these two different treatments led to two systematically different estimates of reference frame scale; the solutions with estimated systematic errors at every station implied a TRF scale 0.7 ppb larger than those using the standard bias approach (Appleby et al. 2016). This result halves the existing difference in scale between the ILRS and VLBI solutions (Altamimi et al. 2017), a significant result. The work also led to a time series of yearly averaged RB values for each station and is prompting further work to unravel the causes and to develop a scheme going forward that minimizes the impact on the ITRF of systematic error in the measurements or in their treatment. A first step was an NSGF AC recommendation to the ASC that a pilot study be carried out to allow all the ACs to update their software and to compare results on systematics, as discussed in the next section.

5 State-of-the-art: the new approach of continuous monitoring station systematics

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.

While the work done up to now has improved the quality of the latest ILRS combined series for the ITRF, close monitoring of systematic errors into the future is essential to keep the ILRS products at the highest quality level. To achieve this level, a routine process needs to be established, ensuring the accuracy of the ILRS products at all times.

At the Matera 2015 ILRS Technical Workshop, several action items were discussed regarding the identification, mitigation and communication of systematic error issues in the network and a different approach was proposed to determine whether or not any or all of the ILRS stations have released biased data at some level during the last two decades. Regardless of the existence of reported problems or configuration changes at the stations, the approach allows the observations from each station to determine in a simultaneous dynamical solution both its coordinates and an estimate of any range bias (Appleby et al. 2016). A potential bias, which may otherwise have been absorbed in station coordinates that are now included in the ITRF, is now freely determined independently from the data.

Table 2 ILRS analysis centers

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

A pilot project was proposed and agreed to, with the following goals:

- to demonstrate the ability to recover real errors as measured and reported in the historical archives;
- to verify the agreement among the values estimated by each of the ILRS analysis centers; and
- to check the impact on the reference frame and particularly on the scale.

The organized pilot project to explore the alternative approach involved all the ILRS analysis centers (list in Table 2).

They were tasked to use their software to determine daily EOPs, weekly station coordinates and weekly range bias for each of the tracking stations using the LAGEOS satellites for the test period of 2005–2008 inclusive (later expanded to 1993–2018) with no a priori biases applied from, for example, the data handling file. The single AC solutions were loosely constrained, similarly to the official ILRS products but with the additional bias parameters. As with the official ILRS products, they were combined by the ILRS Combination Centers rigorously, including all the estimated parameters, i.e., site coordinates, EOP and the biases.

This analysis strategy can recover real biases, and the agreement among the ACs is generally within the uncertainty of the estimates, except in a few cases usually involving stations with poor or sparse data records. As an example, we show in Fig. 2 the case of a known, existing range bias in the data from station MLRO (Matera Laser ranging Observatory, Italy) between February and October 2007, close to a value of 25 mm as determined by the station engineers, with a 2–3 mm uncertainty. The estimated biases are represented in the plot both as 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 are satisfactory.

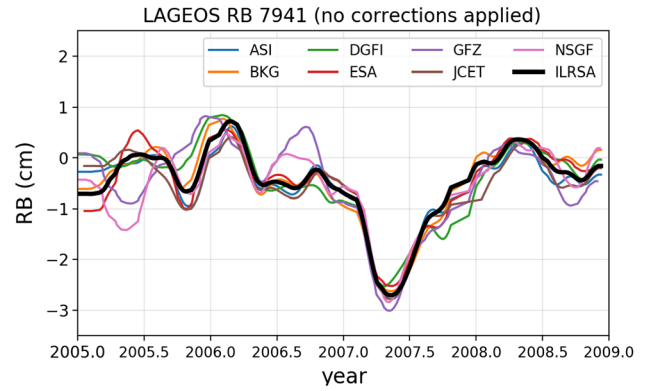


Fig. 2 MLRO estimated range biases. LAGEOS and LAGEOS-2 estimated range biases by the official ILRS ACs and their combination (ILRSA), station 7941 (known corrections to engineering biases not applied). The time series have been smoothed with a moving average for display purposes

The general agreement among the solutions provided by the ILRS ACs is more clearly shown in Fig. 3 with the histogram of the mean biases over the years 2005–2008, for the top 20 most prolific stations in the SLR worldwide network during these years. The figure refers to the initial tests, but this behavior is typically observed over any period. It is worthwhile to underline that this estimation process cannot yield millimeter accuracy in each single estimate, 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. Some evidence pointing to differences in the range biases between these two satellites, of the order of about 1 mm in the long term, is currently under investigation. Possible differences at this level will not, however, alter in any significant way the conclusions regarding the presence of biases in the network and their overall magnitude. Another feature visible in Fig. 3 is that a majority of the estimated range biases are positive (observed ranges longer than computed). Although it cannot be ruled out in principle that this is the result of mere coincidence, the suggestion that it may be caused by an underlying modeling problem is strong. In particular, biases in the center of mass offsets for specific combinations of station technology and ranging policy may be the cause, as it has been verified in the case of the Etalon satellites (Rodríguez et al. 2016, 2018).

The agreement among the AC results and the robustness of the approach strongly suggested that the analysis should be extended beyond the 4-year timespan of the pilot study. The ongoing work within the ASC planned a complete reanalysis, starting from 1993, with the estimation of the range biases for all the stations separately for the two LAGEOS and in combination for the two Etalon satellites

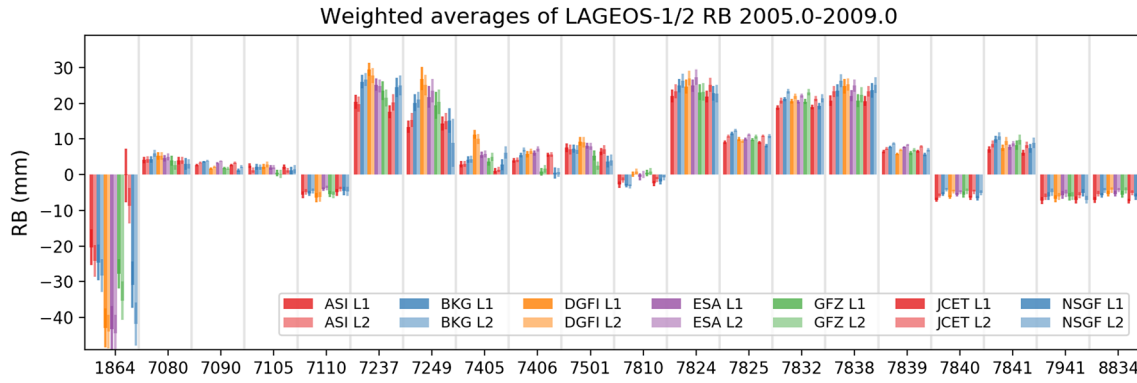
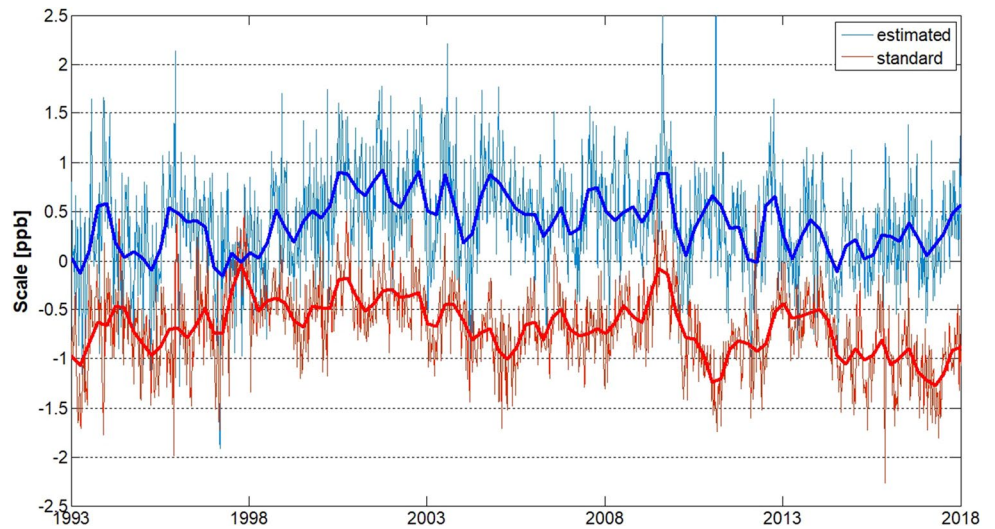


Fig. 3 Weighted averages of LAGEOS-1/2 RB 2005.0–2009.0. Weighted mean of the estimated LAGEOS-1/2 biases over 2005–2008 (inclusive) for the 20 most prolific stations during this period. Corrections from the ILRS data handling file not applied for testing

Fig. 4 Scale with respect to ITRF2014. Weekly scale offsets obtained with a similarity transformation with respect to ITRF2014. The red time series is the standard ASC solution, and the blue one is the time series with the RB estimated, with a moving average for display purposes



(mainly due to their limited data set). The combined time series was again obtained through a rigorous combination of each weekly solution (i.e., coordinates, EOP and biases).

The impact of the 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.¹ While the origin translations are not significantly different, except for a slight smoothing of the annual component, the offset in the scale is significantly reduced, as shown in Fig. 4. Furthermore, the mean change that is of the order of ~ 1 ppb is toward a closer agreement with the ITRF2014 scale, indicating a reduction in the scale difference between the SLR and VLBI

realizations of the TRF, in line with the results from Appleby et al. (2016). Even though the results indicate that we are steadily moving in the right direction, we cannot ascribe all of the recovered biases to identified systematic errors at the ground stations. As noted earlier, the majority of these biases are positive, indicating with a significant probability that the currently used CoM model is in error for some station–satellite pairs. With the release of a new CoM model (Rodríguez et al. 2019) for testing, the ASC is now in the process of a final reanalysis of the 1993–2018 data set, using the newly adopted model.

5.1 Solution assessment

The potential for correlation between the height component of station coordinates and range biases has already been noted. Seasonal variations at annual and semiannual periods caused by geophysical fluid loadings are expected and indeed have been observed, in the coordinate time series

¹ https://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx.

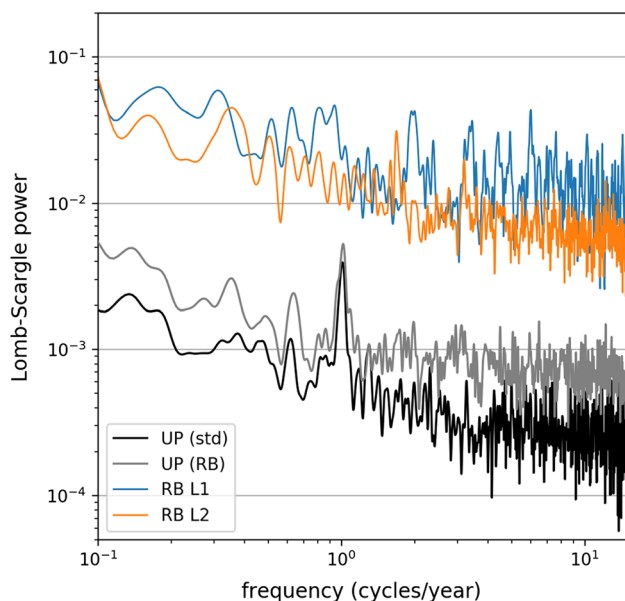


Fig. 5 Spectra of SLR height (UP) and range bias (RB) time series. Stacked spectra of the SLR heights and RB time series (1993.0–2018.0) computed by ASI AC. Stations with at least 4.5 years of weekly positions in total were included (34 stations). Black; UP (std): periodogram of heights from standard (std) solution (no RB estimated). Gray; UP (RB): periodogram of heights from solution with RB estimation. Blue and orange: periodograms of time series of estimated range biases for LAGEOS and LAGEOS-2, respectively

of the various space geodetic techniques (Ray et al. 2008). In order to assess whether the estimated biases may have absorbed geophysical signals of interest, we have performed a frequency analysis of the coordinates and range bias results. The interest here is not whether the estimated biases for an individual station may for whatever reason show seasonal periodic signals. The concern is whether, due to the correlation between estimates of height and range bias, mediated by the globally determined satellite orbits, geophysical effects that should be reflected in the station coordinates may instead be absorbed by the computed biases.

From a set of solutions covering the period 1993–2018, we selected the stations with at least the equivalent of 4.5 years of weekly positions (34 stations), computed the periodograms (Lomb–Scargle algorithm) of the height residuals relative to ITRF2014 and of the weekly estimated range biases and finally stacked the results for both coordinates and biases (separately). As displayed in Fig. 5, the most significant feature of the SLR station height periodograms is an annual signal well above the noise level, which is most likely to have a geophysical origin. For comparison, the period analysis includes the station heights derived from ‘standard’ solutions where range biases were not estimated [“UP (std)” in the figure]. It appears that no loss of annual signal in heights takes place when range bias parameters are included in the solutions [“UP (RB)” in the figure]. A clear signal

at ~ 0.63 cpy, close to the draconitic period of LAGEOS (560 days, 0.65 cpy), is the other distinctive feature in the series of heights. This signal is present in the LAGEOS RB periodogram, but absent in that of LAGEOS-2. We note that the stacked periodogram of LAGEOS biases shows some broadband features of no evident origin at different frequencies, as well as a semiannual signal that is absent from the rest of the traces. A signal corresponding to the draconitic period of LAGEOS-2 (222 days, 1.65 cpy) can be identified in the RB periodogram for this satellite, indicating that bias estimation is absorbing to some extent orbit mismodeling effects. Most importantly, in contrast with what is seen in the case of station heights, no significant signals are seen at annual periods in the stacked range bias periodograms. Thus, we conclude that combined SLR observations to LAGEOS and LAGEOS-2 satellites are sufficiently robust to overcome geometric correlations, allowing range bias parameter estimation without absorbing signals of geophysical origin.

The performance in terms of orbit quality of the solutions that include range bias estimation can be evaluated by assessing the degradation of the orbits when artificially introducing biases in the observations of some prolific stations of the network. This exercise has previously demonstrated the robustness and bias recovery capabilities achievable with SLR data, as well as showing an improved resilience of orbit quality to the presence of substantial errors in the observations (Appleby et al. 2016). Here we present orbit comparison results in graphical form, as shown in Fig. 6. The observations of five stations of the network that contributed about a fifth of all the normal point data during the period of this test (2010–2012) were deliberately biased with up to 7 cm of artificial errors. Weekly orbit comparisons (radial, along- and cross-track components) relative to the unbiased, standard solution are shown for the solutions with added station bias (with and without RB estimation). The RMS differences between the standard solution and the solution with RB estimation where no artificial biases have been added are the benchmark for this comparison (“standard solution vs unbiased RB solution” in the figure). The orbital differences in this case are very small as expected, indicating that the level of errors in the actual observations does not lead to major problems in the orbit determination. When significant errors are artificially added, orbit quality is degraded, as revealed by the visible increase in the orbit differences. Evidently, in the period when the added biases are minimal (central part of the time series in the figure), orbit differences are comparable in all cases. As the added biases become more significant, the RMS in all components increases noticeably. However, the orbits of the biased solution with RB estimation (“standard solution vs biased RB sol.”), although degraded at times when the added biases are at a maximum, appear much less so than their biased standard counterparts ($\sim 50\%$ RMS) and are not significantly

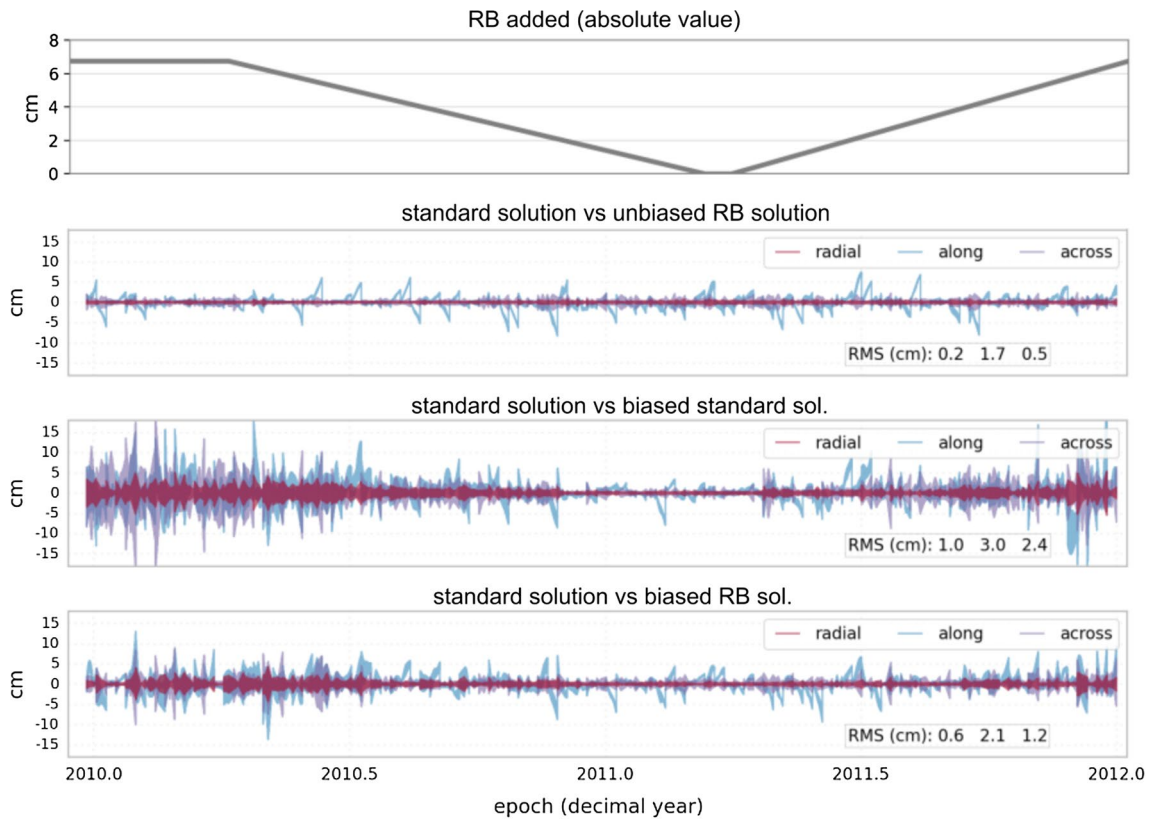


Fig. 6 Orbit comparison. Weekly RMS in radial, along- and cross-track components of orbits obtained from artificially biased data (~20% of NPs biased), relative to orbits computed from regular observations, over a 2-year period. Top: magnitude of added biases. Bottom three: RMS of standard solution relative to: (1) unbiased

orbits with RB estimation; (2) biased orbits with no RB estimation; (3) biased orbits with RB estimation. Errors in the observations degrade the quality of the orbits, albeit the impact is reduced when range biases are estimated

affected in this test by the addition of biases of up to approximately 4 cm.

6 Future perspectives

Due to the correlation between range biases and site heights, the weekly solutions of coordinates and EOPs show higher residual WRMS when the range biases and the coordinates are simultaneously estimated and the site coordinate time series, primarily the heights, are more scattered, even though they are in fact less prone to systematic error and thus are more accurate. In order to avoid weaker ILRS products and a lower-weight contribution to the realization of the ITRF, the solutions with simultaneous estimation will only be used to estimate the mean range correction over significant time periods (months, years) depending on the discontinuities that we can identify in the time series themselves. Reapplying the resulting range bias averages as a priori values in a subsequent computation where these parameters are no longer estimated ensures that the solutions are not affected

by systematic errors, while avoiding additional height jitter in the time series (Appleby et al. 2016).

Following the reanalysis and the establishment of the first release of the model, weekly routine bias estimation performed by the ILRS ACs and CCs will keep the model up to date, while providing high-quality estimates that other users can adopt for their analyses.

The data handling file will also be updated with a wider list of time biases measured using the Time Transfer by Laser Link (T2L2) instrument and provided to ILRS by CNES/GRGS (Exertier et al. 2018). The instrument gives the possibility to synchronize the clocks of the observing SLR stations that provided laser ranging data on the satellite Jason-2. The use of a primary calibrated master station assures the synchronization of those clocks to the same international time scale (GPS time → GPS UTC) and at an accuracy of approximately 5 ns. The primary result from the T2L2 tracking is the discovery of the presence of systematic errors in the times of laser ranging measurements between 100 ns and a few microseconds. The larger of these time biases will be included in the data handling files. As mentioned previously, the main impact of observation time

errors in the determination of the station positions is in the horizontal plane components (primarily east–west) because the time bias affects the estimation of the along-track component of the satellite orbit. Large values of time biases can cause errors that reach the millimeter level in station coordinates (e.g., 1 microsecond has an effect of 2–6 mm) (Exertier et al. 2017).

7 Conclusion

Handling systematic errors in SLR data is a long-standing activity and is still engaging the ILRS with rapid quality checks, in modeling and in site characterization. The ILRS ASC is working for an improved a priori model for the systematic errors to be used in the official ILRS routine products and in the ILRS contribution to the next realization of the ITRF. As regards the range biases, the model will be built using the results of the simultaneous estimation of site coordinates and range biases. The time biases are less critical; nevertheless, the corrections obtained from the T2L2 experiment will be included in the a priori model. The adoption of the new model is expected to improve the agreement between the SLR and VLBI frame scales in the realization of the next ITRF, although it is unlikely to remove entirely the offset between the two. This scale difference, obtained by at least two of the three groups that periodically perform a multi-technique combination of space geodesy solutions to realize a global reference frame (IGN and JPL), demands the attention of analysts and engineers from both the SLR and VLBI techniques to identify and minimize any potential error sources that could affect the absolute accuracy of the observations and of the models employed. With the recent and current work within the ILRS, and the planned strategy in preparation for the next reanalysis, as described here, official SLR solutions and their combined products are anticipated to be considerably less affected by systematic errors.

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