Assessment of DTRF2014 and ITRF2014 by Satellite Laser Ranging

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Abstract. Satellite laser ranging orbital solutions, using observations of satellites LAGEOS and LAGEOS-2 collected from 2000 to 2017, were used to test the performance of two reference frame realisations, ITRF2014 and DTRF2014. We compare the post-fit residuals from solutions where only initial conditions and orbit parameters were solved for, leaving apriori coordinates unchanged. We examine some differences that arise, and explore the behaviour of SLR sites affected by earthquake events. The combined ILRS-A solution, input for both reference frames, is compared to each TRF as well, and disparities discussed. The main finding of this exercise is that the scales of the SLR subnetworks of both TRF products differ by approximately 0.6 ppb, resulting from an unchanged scale of DTRF2014 relative to the input ILRS site coordinates, as opposed to the average frame scale between the VLBI and SLR networks employed in ITRF2014. Analysis of the residuals obtained here, as well as the site coordinates estimated from solutions computed outside the scope of this work, indicate that ITRF2014 is less subject on average to the effects of systematic errors present in the input solutions, although by no means exempt.

Introduction

The particular choice of terrestrial reference frame employed for the computation of routine ILRS products (daily solutions of combined LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2), has a very limited impact on their quality. Since site coordinates are estimated in this type of solutions, as long as the apriori frame is a reasonable representation (centimetres) of the secular motions of the stations, essentially the same results should be obtained following iteration. On the other hand, any differences in the apriori frame will become apparent if coordinates are left fixed. In particular, since satellites LAGEOS and LAGEOS-2 are the workhorse of the ILRS solutions ($\sim 90\%$ observations) that were used as an input for the production of both ITRF2014 and DTRF2014, a useful comparison of the performance of the two frames, in terms of post-fit residuals, can be obtained from re-computing the orbits of these two satellites. Any differences in the coordinates of SLR sites (in particular the UP component) between these two TRFs should be readily detectable in the observation residuals of the new solutions. Furthermore, as we are comparing these products on the basis of the very input data they relied on in the first place, we will be able to draw some additional conclusions as to the nature of the differences obtained.

Analysis

Solution description

For both DTRF2014 and ITRF2014 we computed orbital solutions using normal point observations of satellites LAGEOS and LAGEOS-2, using our orbit dynamics analysis software SATAN. Except for some updates (e.g. ocean loading, FES2004 to FES2014), the background modelling and orbit parameterisation was identical to what the ILRS NSGF AC employed for the solutions submitted to the official ILRS combination centres in preparation for ITRF2014. Seven-day orbital arcs were computed for years 2000 through 2017, a period that extends beyond the input data employed for both DTRF2014 and ITRF2014 (up to 2015). Station coordinates were fixed to the apriori values, obtained by propagating their initial positions with the corresponding velocities. For ten SLR sites affected by earthquakes, the linearly propagated coordinates were corrected with the post-seismic functions supplied with ITRF2014 (for this frame only). Additional solutions were computed where we solved for weekly bias parameters, combined for LAGEOS and LAGEOS-2, to best follow the differences between both TRFs. Full reference frame solutions (coordinates, EOPs, biases, and orbits estimated), computed for the development of new ILRS products with systematic error estimation, were also employed to compare site heights over certain periods.

Solution statistics

At the most elementary level, no major differences between the two reference frame realisations considered are apparent, when employed to model the positions of SLR stations used to derive orbits of the LAGEOS satellites. Table 1 details the total number of stations, normal points (after initial screening and iterative rejection), average values and RMS of post-fit residuals (after outlier rejection), for the two satellites included in the analysis (2000–2017). It appears that ITRF2014 included a few more stations than DTRF2014, but these only account for a minimal proportion of the normal point data and should not have any noticeable impact on any key TRF parameters. Considering the totality of stations simultaneously, no TRF represents an advantage over the other, judging from the nearly identical post-fit residuals RMS. These values are reduced when biases are estimated, as expected, and although the RMS of residuals obtained with ITRF2014 are marginally smaller, the results in this case appear essentially identical to each other as indicated by the identical averages of the residuals obtained. We note that this is not exactly the case for the solutions where only orbits were estimated (no range bias parameters); the average value of all post-fit observation residuals obtained with ITRF2014 as a fixed frame are 2 mm higher than those obtained with DTRF2014. Since the altitude of the orbits is constrained by the timing of the observations over the course of one arc, and there are no other differences between the two solutions, this implies that the heights of the laser ranging stations as

Table 1: *Number of NPs, mean post-fit residual values and RMS (mm) for the solution types computed for this comparison. Solutions where range errors were estimated are noted as* RB*.*

solution	stations	satellite	NPs	mean res.	RMS
ITRF2014	65	LAGEOS	1,234,336	0.7	12.2
		LAGEOS-2	1,114,336	1.4	12.3
DTRF2014	57	LAGEOS	1,230,690	−1.2	12.2
		LAGEOS-2	1,109,704	−0.7	12.3
ITRF2014 (*RB*)	65	LAGEOS	1,213,992	−0.5	10.8
		LAGEOS-2	1,094,006	0.3	10.5
DTRF2014 (*RB*)	57	LAGEOS	1,207,192	−0.5	11.0
		LAGEOS-2	1,087,365	0.2	10.7

modelled in ITRF2014 are higher than in DTRF2014, on average. This is the case for most stations of the network, as it can be seen from the difference between the average values of post-fit residuals per station shown in Fig. 1. The significance of this will be further discussed in the following sections of this report.

Regarding possible differences, per station, on the RMS values of the range residuals obtained with each frame, no evident trends at any significant level can be appreciated. From inspection of Fig. 1, it can be said that the performance of both TRFs is nearly identical for the 25 most productive stations of the network over the period of analysis. RMS differences for all of these stations (except two), are within 0.1–0.2 mm. Stations on the right hand side of the plot, beyond position 25 approximately, have submitted an order of magnitude less data volumes than the most prolific tracking sites; their overall weight on both the ILRS combined solutions and, ultimately, on the terrestrial reference frame, is quite limited. The quality of the solutions derived for these stations—when not of the observations themselves—is reduced compared to the more prolific sites; the greater variability seen in the RMS values is to be expected and bears little useful information for the purposes of TRF comparison.

Earthquake sites In ITRF2014, the positions of 123 stations affected by earthquake events were modelled using non-linear functions in addition to the standard secular velocities. Of these, ten sites are SLR stations, indicated in the previous plots of statistics of residuals. Focusing on these stations, only the average value of the post-fit residuals for station 7821 SHA2 (Shanghai, China) is notably different between the two solutions, with $+6$ mm higher mean residuals in ITRF2014 relative to DTRF2014. Notably, this site also presents the greatest RMS difference of all stations, with ap-

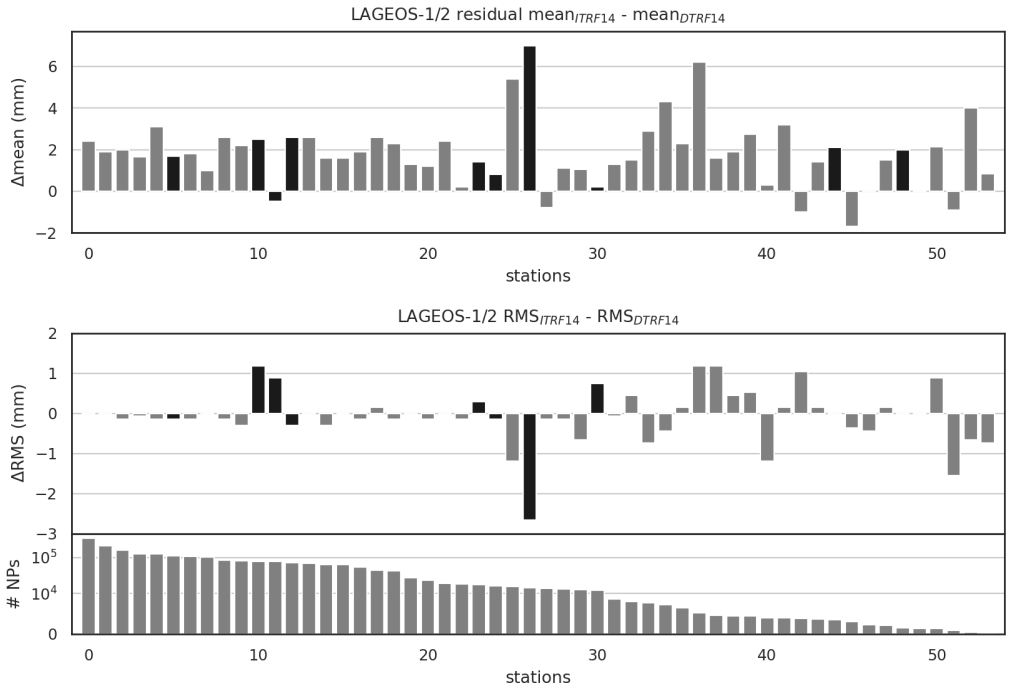

Fig. 1: *Difference (ITRF2014 – DTRF2014) of mean (top) and RMS (bottom) values of post-fit range residuals obtained with these two TRF (fixed). Stations are ordered by number of observations provided (2000–2017). Darker bars indicate sites affected by earthquake events.*

proximately $+2.5$ mm higher RMS for the range residuals obtained with DTRF2014. Inspection of the modelled station positions and velocities, as well as of the range biases obtained in the solutions where these parameters were estimated, reveals that the differences in the post-fit residuals are mainly caused by disparities in the propagated positions of this station after 2014 (see Fig. 2). After an apparent low-productivity period between 2012 and 2014, the amount of data available to obtain an accurate estimate of the position and velocities for this station towards the end of the time period included in ITRF2014 and DTRF2014 was perhaps somewhat limited.

It must be noted that the range bias estimates displayed in Fig. 2 only represent the apparent range errors caused solely by the use of different TRFs. These estimates are not genuine systematic errors at the observation or analysis level, which at this stage, if present, are already absorbed in the coordinates of the stations as modelled by each frame. The range bias time series obtained with both frames for all SLR stations affected by earthquakes can be found in Figs. 6,7,and 8, at the end of this document. The differences arising from the use in ITRF2014 of non-linear functions to model the postseismic deformation motions, as opposed to employing only the classical linear velocities in DTRF2014, are relatively minor for the few laser ranging sites affected by earthquakes. The main exception may be 7403 AREL (Arequipa,

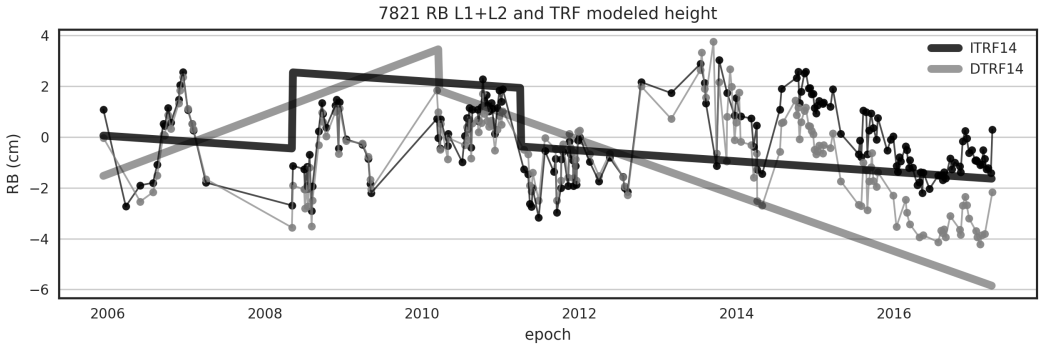

Fig. 2: *Time series of estimated biases for SLR site 7821 SHA2 (Shanghai), computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted.*

Peru), where centimetre-level differences in the modelled heights are seen throughout the analysis period. Disparities between the two TRFs in the break points chosen to delimit discontinuities appear in some cases to cause noticeable differences in the height/RB time series (e.g. 2008–2011 for 7237 CHAL (Changchun, China); 2001–2002 for 7403 AREL). This latter difference in the coordinates discontinuity is severe enough that observations from Arequipa station were discarded during iteration in our computations employing DTRF2014 (no weekly solutions obtained during this period).

Aside from the kind of site-specific differences pointed out above, a remarkable feature present in most of the plots shown for sites affected by earthquakes are the predominant greater station heights as modelled by ITRF2014. With very few exceptions, and normally for no more than some fraction of the entire time series, coordinates propagated with ITRF2014 result in greater SLR site heights than those from DTRF2014. This again points to a systematic difference between the scales of the whole SLR network in the two frames, which we examine next.

Comparison to ILRS-A

In order to assess the extent to which the input ILRS solution, result of the combination of eight independent solutions provided by the official ILRS Analysis Centres[1], differs from the end product result of the combination of the four space geodetic techniques contributing to the realisation of the reference system, we compared the official ILRS-A solution (ASI Combination Centre) to both ITRF2014 and DTRF2014 by means of weekly seven-parameter similarity transformations. The translation parameters, ΔX, ΔY, and ΔZ, as well as the scale Δs are shown in Fig. 3, where rotations were not included given the loose constraints of the SLR solutions. The direction of the computed Helmert transformations is ILRS-A$\rightarrow$XTRF2014, that is, the parameters shown are

[1]ASI, BKG, DGFI, ESA, GFZ, GRGS, JCET, and NSGF (https://ilrs.cddis.eosdis.nasa.gov/science/analysisCenters/index.html).

those required to map the weekly ILRS-A coordinates onto ITRF2014 and DTRF2014. For clarity, we also plot the difference between the Helmert parameters computed between the ILRS-A coordinates and each frame.

Regarding the translation components, no long-term differences of any import can be seen in the time series. Over the 15 years of analysis, the agreement between ILRS-A and both TRFs, and by implication between the reference frames themselves, exceeds the GGOS requirement of 0.1 mm/year. Perhaps only in the last three years, after 2010–2012, a slight trend can be appreciated in the X and Z components of the translations, in particular when the Helmert transformation is computed using all stations instead of only the core sites, but this was not tested for significance nor investigated any further.

As hinted to in previous sections, it is in the scale parameters where a substantial difference is evident. The scale of ITRF2014 is on average 0.6 ppb greater than the ILRS-A solution, over the period 2000–2015 (only core sites taken into account). Contrariwise, essentially no scale change is observed between ILRS-A and DTRF2014 (-0.04 ppb on average in 2000–2015). Attending to the difference between the two, the scale factor in 2010.0 after a linear fit is 0.70 ppb. This finding follows from the decision to define the scale of ITRF as the arithmetic average of the scales of the VLBI and SLR subnetworks. The scale difference between these was computed in ITRF2014 to be 1.37 ppb at epoch 2010.0, double the difference found here, as expected if one of the compared set of coordinates shows no difference to the input time series. This is a significant result that clearly must respond to different (fundamentally, even) approaches adopted for the computation of the combined reference frames.

It is not within the remit of this author to pass judgement on whatever different strategies, principles, or philosophical approaches underpin the production of the TRFs tested here. What we may examine is the goodness of the final result, restricted to the SLR subnetwork, on the basis of a few developments in the analysis and modelling of SLR data that have occurred since the publication of ITRF2014 and DTRF2014. These developments cast some light over the relative merits of these two products regarding their adopted scales.

Mitigation of SLR systematic errors

Since the definition of the ILRS standard products, a great deal of efforts have been devoted within the ILRS Analysis Standing Committee to minimise, identify, and rectify the presence of errors in the laser ranging observations. Other than constant monitoring of the data for quality control purposes (Otsubo et al., 2018), these efforts involved periodic reanalyses of the SLR solutions to detect potential problems, providing to and obtaining feedback from the tracking stations, as well as maintain-

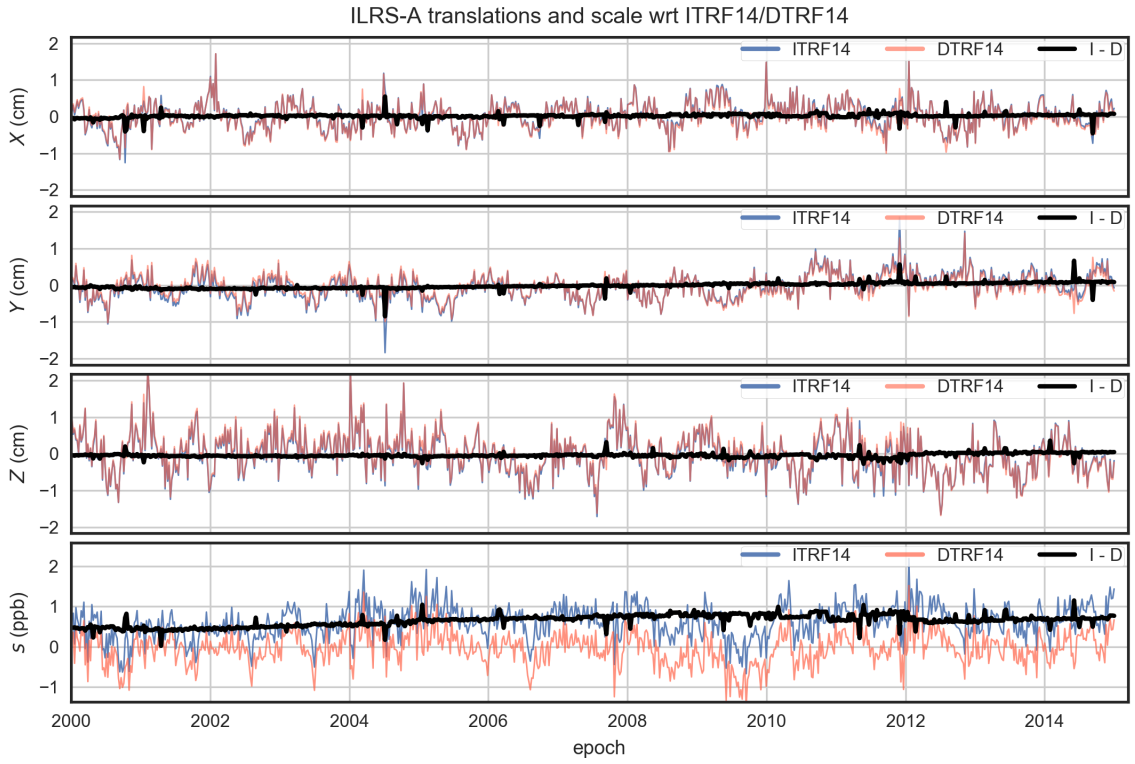

Fig. 3: *Weekly translation and scale parameters between the official ILRS-A combined solution and: ITRF2014 (blue); DTRF2014 (red). In black, the differences between these two, approximately equivalent to the transformation parameters between both frames, in the direction DTRF2014→ITRF2014.*

ing a database of known issues together with instructions for analysts about how to handle them (Luceri et al., 2019). Unfortunately these practices do not guarantee the detection of all problems, especially long-term issues below the level of perhaps 3–4 cm. Thus, the ultimate accuracy of the technique is achieved with simultaneous estimation of observation errors along the rest of parameters of interest (Appleby et al., 2016). These kinds of solutions are the basis for a new ILRS product currently under development, seeking to ensure that station coordinates are as free as possible from any potential systematic errors (Luceri et al., 2019). It must be noted the diverse nature of the systematic errors that may affect the data, from actual observation errors at the station level, inaccurate survey of calibration targets, and several modelling deficiencies. For instance, recent work on the computation of centre of mass corrections for several spherical geodetic satellites shows that a significant proportion of the errors previously estimated have their cause in inaccuracies in the modelling of centre of mass corrections for spherical geodetic satellites (Rodríguez et al., 2019).

Of immediate interest for the present discussion are the several results, obtained by all the ILRS ACs that have produced solutions with simultaneous coordinates and systematic error estimation, which found an average increase of about 0.7 ppb in the scale of the SLR network relative to previous determinations. The ILRS contribution to ITRF2014/DTRF2014 included only error estimation for a very limited number of sites known to be problematic during certain periods, and therefore did contain systematic errors in the site coordinates that would eventually find their way into the final combined terrestrial reference frames. However, as seen in the previous section, the scale of ITRF2014 is on average (2000–2015) 0.6 ppb greater than the input ILRS-A solution, so it appears that this frame is a more accurate representation of the scale of the SLR network.

The better average agreement between ITRF2014 and the new solutions produced by ILRS ACs, following the latest strategy for mitigation of systematic errors, is not completely consistent at the level of individual stations. We show in Fig. 4 two examples of time series of station heights, with coordinates taken from ILRS-A, an independent NSGF AC solution with range bias estimation (simultaneous with coordinates), and the site heights modelled by ITRF2014 and DTRF2014. While the ITRF2014 height for station 7839 GRZL (Graz, Austria) is closer to the newer estimates that take into account the presence of systematic errors (such as NSGF RB in the plot), this is not true at all epochs; the first years after 2000 show a similar disagreement between ITRF2014/DTRF2014 and the heights obtained in the solution with bias estimation. The second example in Fig. 4 shows the opposite behaviour (to what is generally the norm), i.e. a better agreement between

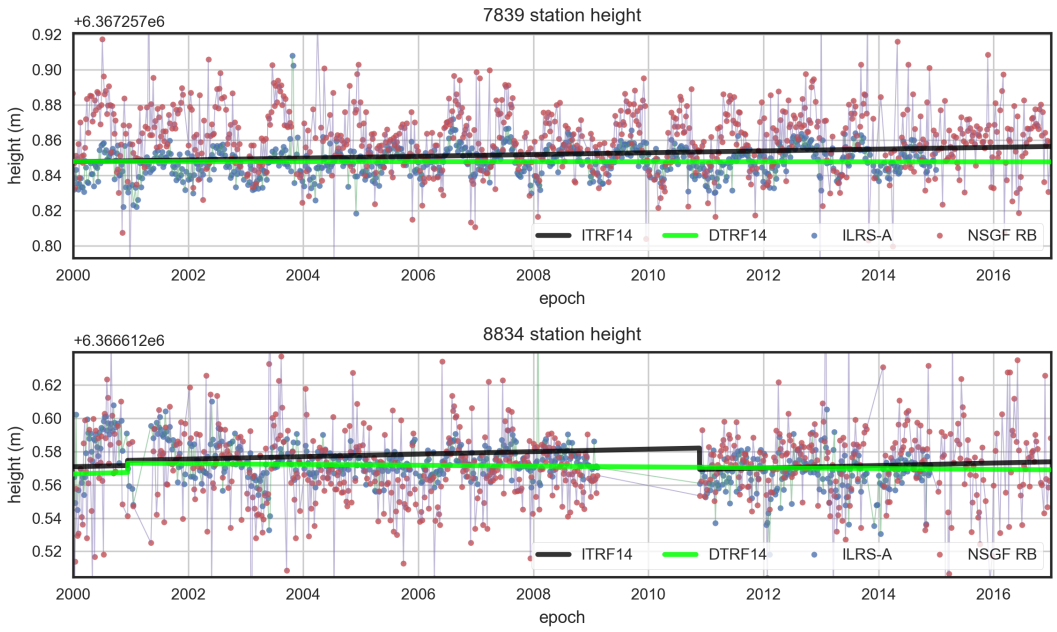

Fig. 4: *Time series of weekly heights for stations 7839 GRZL (Graz, Austria) and 8834 WETL (Wettzell, Germany), from: ILRS-A solution (blue dots); NSGF solution with RB estimation (red dots); ITRF2014 (black line); DTRF2014 (green line).*

DTRF2014 and the coordinates estimated taking into account range biases. Station 8834 WETL (Wettzell, Germany) is one of the few cases where negative average biases have been found during some periods of its operation. The effect of these negative biases is an overestimation of station heights in some years of the solutions submitted for the ILRS contribution to ITRF2014/DTRF2014. Since ITRF2014 heights are on average greater than those from ILRS-A, stations with negative biases will tend to show worse agreement between ITRF2014 and the latest estimates than what is the case with DTRF2014.

Residual trends

The aforementioned solutions obtained with simultaneous estimation of biases and station coordinates have been thoroughly tested (Appleby et al., 2016) and replicated by all ILRS ACs. But for the avoidance of any doubts about the conclusions drawn regarding the increase of the scale of the SLR network that these solutions indicate, we discuss here independent evidence of inaccurate modelling of station heights in ITRF2014 and DTRF2014, which shows equivalent findings.

Let us remind ourselves of what the effect of biases and incorrect site heights have on the range residuals after a least squares adjustment of the satellite orbits. If the observations of a given station have a constant, positive range bias during a given arc, the estimated site height in solutions with no range error estimation will be lower than the “true” value (station coordinates accommodate the bias in the UP component, mainly). Furthermore, the amount by which the estimated station height

will be biased towards lower values is greater than the magnitude of the constant bias. This simply arises from the observation geometry; although a 1:1 ratio between bias/Δh obtains for zenithal observations, low elevation ones drive the estimated height in the negative direction. The point at which the sum of squared residuals is minimised is somewhere between the value of the bias and what would result if only low elevation observations were present. The exact bias/Δh ratio depends on the specific distribution of angular elevations for each station and arc. For perfectly distributed observations between 25 and 90 degrees of elevation, the excess Δh can be computed to be approximately 33% for zenithal passes. Taking into account actual, typical elevation distributions suggest greater ratios (approaching 1.5), confirmed empirically by our geodetic solutions. The result of this effect is that the observation residuals of stations with a height that is lower than the correct value will show a pattern with zenith distance, where high elevation residuals will tend to be negative (observed ranges lower than the computed ones), and will become positive at low satellite elevations. The opposite will be true for sites with overestimated station heights (positive residuals at the zenith, negative in the horizon).

With the above considerations in mind, we show in Fig. 5 the average post-fit residuals of the same two stations displayed in Fig. 4, aggregated by zenith distance, obtained from solutions where only orbits were adjusted and employing ITRF2014 and DTRF2014 to model station coordinates. The aggregated residuals for station 7839 GRZL during the first three years of the analysis (2000–2003), where both ITRF2014 and DTRF2014 underestimated the height of this station (because of the underestimation already present in the input ILRS-A solution), show an evident positive trend with zenith distance. Focusing on the last three years (2014–2017), where the ITRF2014 height approaches the values obtained in solutions where biases are taken into account, show no trend with zenith distance for the residuals obtained with this frame. On the other hand, as DTRF2014 follows closely the height for 7839 GRZL in the ILRS-A solution, a positive trend in the post-fit residuals is still present in the later period. Repeating this exercise for the second site shown, 8834 WTZL, leads to the same conclusions mentioned in the previous section, i.e. ITRF2014 appears to incorrectly overestimate the height of 8834 WTZL during years 2006–2009. This can be concluded from the negative residual trend in the latter period, as opposed to the flat residuals in 2001–2004, and from the flat profile in both periods for the residuals obtained with DTRF2014.

Without resorting to bias estimation, the information contained in the observation residuals can be effectively visualised and interrogated to identify the presence of inaccurate site heights. This kind of analysis, resting solely on geometric considerations, is feasible in SLR because

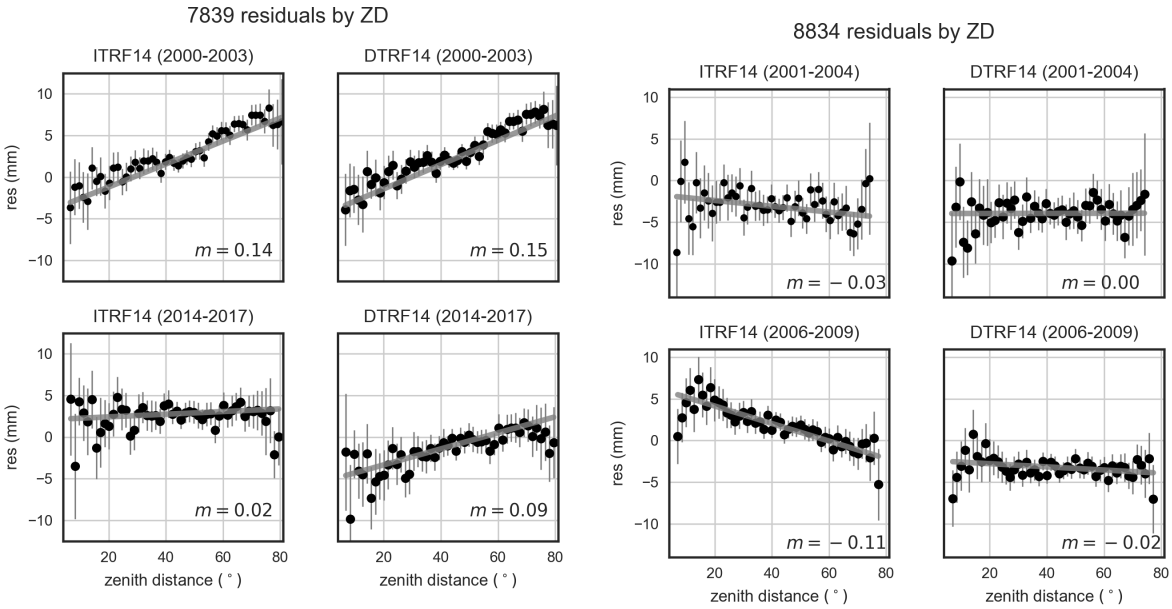

Fig. 5: *Average LAGEOS post-fit residuals, in mm, of stations 7839 GRZL and 8834 WTZL, aggregated by zenith distance of the observations at bins of 1.5 degrees, employing ITRF2014 and DTRF2014 station coordinates (fixed). Error bars represent the 95% CI of the each average value. Solid line: linear fit (slope noted in each subplot)*

there are very few parameters that could absorb mismodelled heights and mask the presence of systematic errors (e.g. no clocks or tropospheric delays are estimated in SLR).

Conclusions

Following a comparison of orbital solutions of satellites LAGEOS and LAGEOS-2, using the reference frames ITRF2014 and DTRF2014 to model station heights, we find in general limited differences in the basic statistics of the post-fit residuals. The performance for sites affected by earthquakes, again rather crudely assessed by the RMS values of the residuals obtained with both frames, is with few exceptions also similar (although some of the differences will tend to be magnified in the extrapolation period, post-2015). The single, greatest difference found in this work between these two TRFs is the scale disagreement of the SLR network. While in ITRF2014 the scale of the frame is computed as the arithmetic average between VLBI and SLR, DTRF2014 follows the scale of the input official ILRS solution. In light of what is known today regarding the presence of unaccounted for systematic errors in past SLR contributions, and exclusively in view of the practical, final results, the conclusion is that the strategy followed in the production of ITRF2014 (and previously ITRF2008) proved to be of merit. On average, the scale of ITRF2014 agrees better with the scale of future ILRS solutions, which will introduce strategies for systematic error mitigation and use more recent models to correct the range observations. The

conclusions regarding mismodelled site heights, for both frames, are derived from results computed with estimation of systematic errors, as well as independently from the direct examination of observation residuals, whose trends, if present, reveal inaccuracies (and their sign) in station heights.

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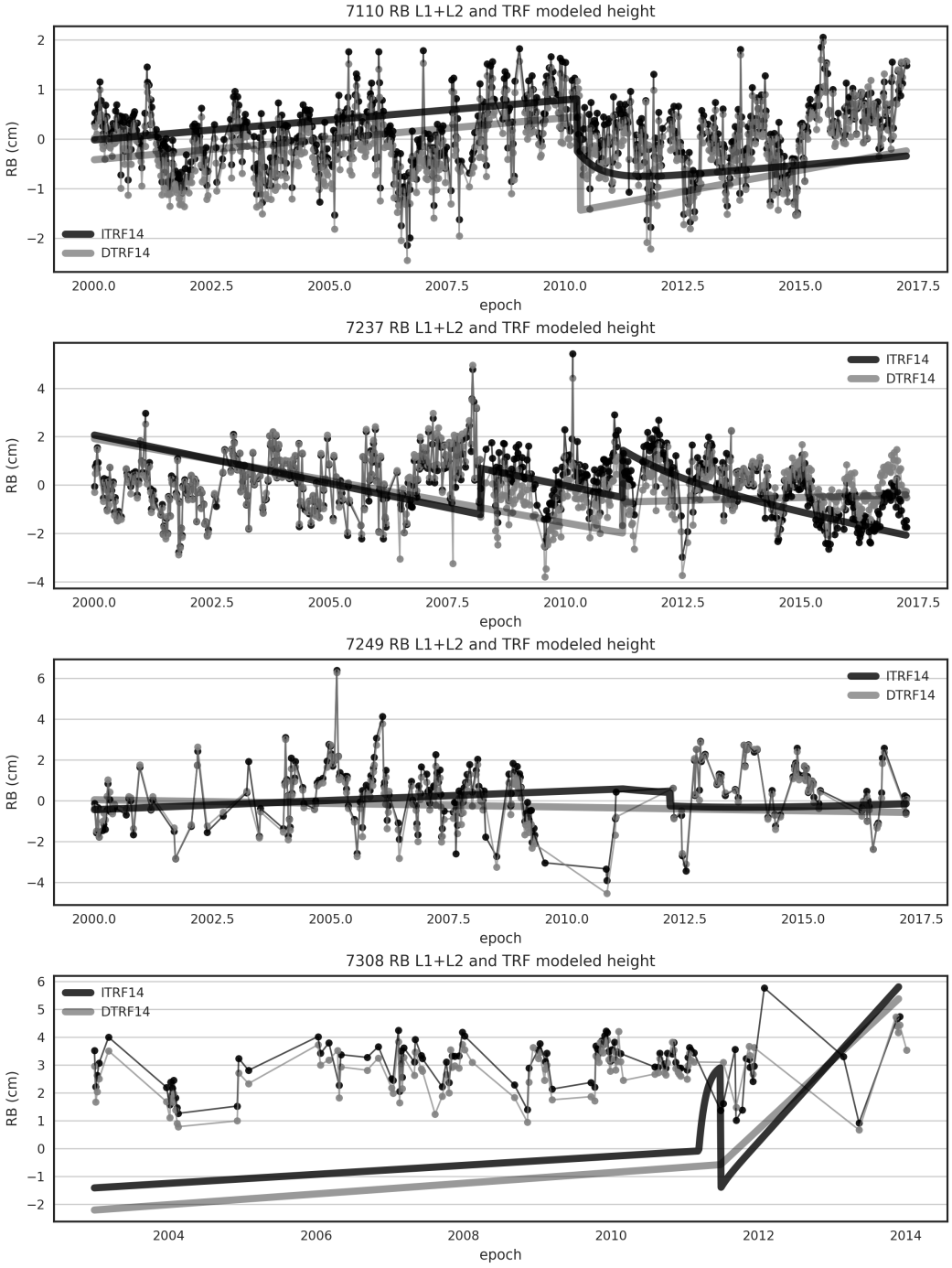

Fig. 6: *Time series of estimated biases for SLR sites affected by earthquakes, computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted.*

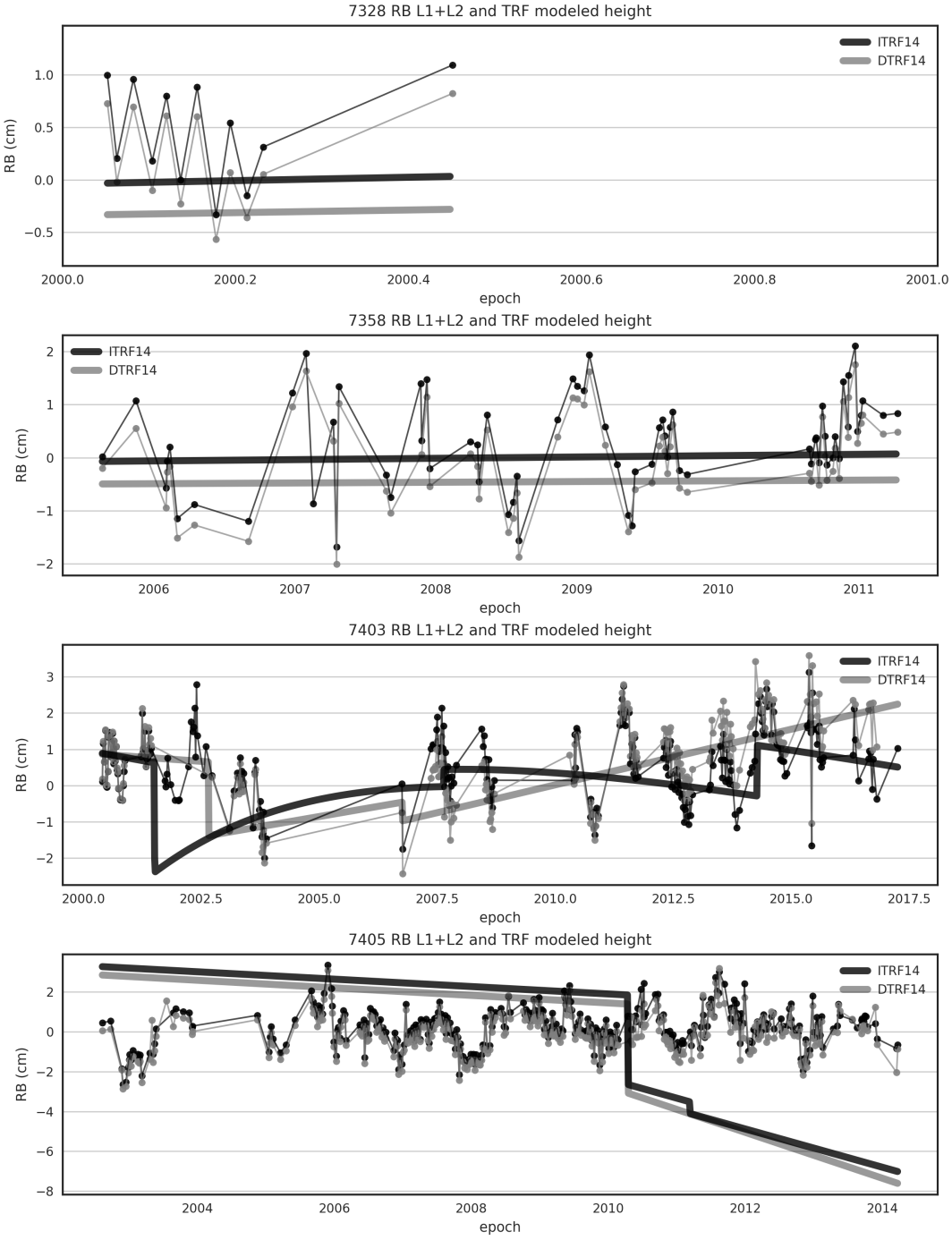

Fig. 7: *Time series of estimated biases for SLR sites affected by earthquakes, computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted (continued).*

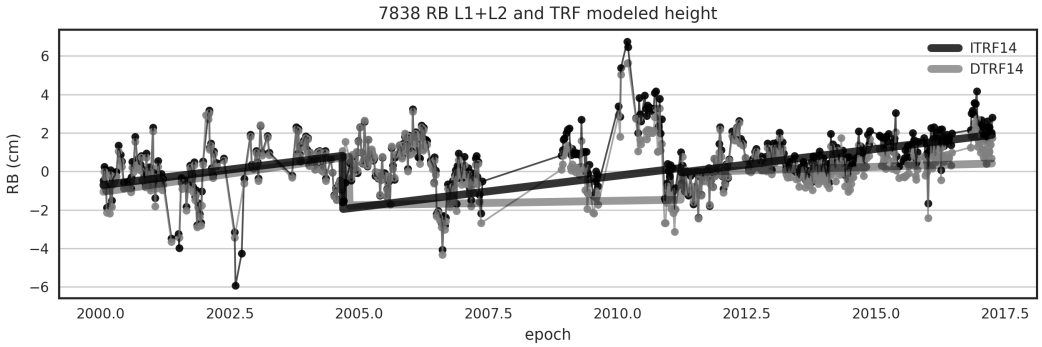

Fig. 8: *Time series of estimated biases for SLR sites affected by earthquakes, computed using coordinates from ITRF2014 and DTRF2014. For reference, the solid lines show the heights modelled by these two frames, to which the average ITRF2014 height has been subtracted (continued).*