A Review of Space Geodetic Technique Seasonal Displacements Based on ITRF2020 Results

Xavier Collilieux, Zuheir Altamimi, Paul Rebischung, Maylis de La Serve, Laurent Métivier, Kristel Chanard, and Jean-Paul Boy

Abstract

The new release of the International Terrestrial Reference Frame, ITRF2020, differs from ITRF2014 by the addition of parametric functions describing annual and semi-annual displacements for every station. ITRF2020 coordinates are now described with piece-wise linear functions, occasional exponential and logarithmic functions modelling post-seismic displacements and the newly provided seasonal parameters. The paper first shortly presents the ITRF2020 seasonal parameters provided both in the Center of Mass (CM) and in the Center of Fig. (CF) frames. The station-specific seasonal displacements determined by the four space geodetic techniques (DORIS, GNSS, SLR, VLBI) are then reconstructed from the ITRF2020 results in the CF frame. The estimated seasonal signals are shown to agree generally within their uncertainties at co-location sites if a realistic noise model is considered.

Keywords

ITRF2020 · Non-tidal loading displacements · Seasonal displacements · Space geodetic techniques · Terrestrial reference frame

1 Introduction

The International Terrestrial Reference Frame (ITRF) is widely used for societal and science applications. It is composed of the coordinates of a primary network of stations that sample the Earth's surface. These coordinates are monitored by space geodetic techniques, namely Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI). The official ITRF products are computed by combining altogether the coordinates estimated from these four techniques. The homogenization of their reference frames is carried out in this process by estimating Helmert parameters (Altamimi et al. 2023). The estimation of these parameters is made possible by adding the relative position vectors of the instrument reference points at co-location sites that host several techniques, the so-called local ties. For the combination to be optimal, it is essential to monitor how coordinates of co-located stations agree at those fundamental sites.

Seasonal displacements at ITRF co-location sites have been investigated in various studies in the past, based on ITRF2008 input data (Collilieux et al. 2007; Altamimi and Collilieux 2010) or homogeneously reprocessed series (Tesmer et al. 2009). While attempts were made to evaluate the error introduced by reference frame alignment, the so-called network effect, no specific methodology was carried out to mitigate it. Indeed, in order to compute coordinates from a network of stations in a well-defined reference frame,

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it is necessary to apply a Helmert transformation which includes transformation parameters (translation, rotation and scale). The coordinate time series derived with this method suffer from periodic errors which depend on the network distribution and on the magnitude of periodic displacements in the time series (Collilieux et al. 2012). It is thus of utmost importance to mitigate these errors for the purpose of comparing seasonal displacements observed by the different space geodetic techniques.

In the scope of the ITRF2014 processing (Altamimi et al. 2016), seasonal coordinate variations were estimated for each technique but not combined. A rigorous combination was proposed by Collilieux et al. (2017, 2018) in order to express seasonal parameters in the same reference frame and thus mitigate network effect errors. The availability of 6 years of additional data in ITRF2020 is an opportunity to revisit this comparison. Indeed, a larger set of co-location sites is now available with longer and more overlapping position time series.

For the first time, seasonal coordinate variations, rigorously combined, have been included in the ITRF2020 products (Altamimi et al. 2022, 2023). However, as will be explained in Sect. 2, they cannot be used to assess inter-technique agreement at co-location sites. In this paper, we propose in Sect. 3 a method to compute technique-specific seasonal displacements in the ITRF2020 Center of Fig. (CF) frame. Then, we compare them while accounting for the time-correlated nature of the noise processes in station coordinate time series. The results are introduced in Sect. 4 and discussed in Sect. 5.

2 Input Data

2.1 ITRF2020 Seasonal Parameters

The original data used in this study are those submitted for ITRF2020 (Moreaux et al. 2023; Rebischung 2022; Hellmers et al. 2022; Pavlis and Luceri 2022) by the International Association of Geodesy (IAG) technique services: the International DORIS Service (IDS), the International GNSS Service (IGS), the International VLBI Service for Geodesy and Astrometry (IVS) and the International Laser Ranging Service (ILRS). Station coordinate time series with their full variance-covariance information have been combined during the ITRF2020 computation to estimate station positions at the reference epoch (2015.0), velocities and seasonal coordinate variations in addition to Earth Orientation Parameters (Altamimi et al. 2023). Thus, constant annual and semi-annual displacements along each component (East, North and Up) have been estimated for each station over its whole data span. The amplitudes of the cosine and sine terms at these two frequencies are hereafter referred to as "seasonal parameters".

In the ITRF2020 computation process, the estimated seasonal parameters have been equated within co-location sites at the 0.1 mm level except where seasonal displacements of the different techniques were found to be inconsistent. In this case, they were only loosely equated as described in (Altamimi et al. 2023). This explains why different seasonal parameters have been published for certain pairs of co-located stations in ITRF2020, but also why they are generally equal. In any case, this does not mean that the coordinate residuals of the ITRF2020 combination are not free from seasonal variations.

The ITRF2020 seasonal parameters have been estimated in the Center of Mass (CM) frame as estimated from SLR data. However, the averaged station displacements in the CM frame is non-zero due to geocenter motion. Thanks to the seasonal geocenter motion model estimated by Rebischung et al. (2022), the ITRF2020 seasonal parameters could also be brought to the CF frame (Blewitt 2003). As no net translational motion exists in the CF frame, this frame is the most relevant for the seasonal displacement comparisons presented in this paper. Indeed, leaving geocenter motion included in the seasonal displacements would artificially increase their level of agreement.

2.2 Station Selection

Only stations with sufficient data span will be discussed, since short position time series are known to yield unreliable seasonal displacement estimates (Blewitt and Lavallée 2002). Thus, stations with at least 150 points for DORIS (weekly), SLR (weekly) and VLBI (daily sessions) have been investigated. With this criterion, all selected VLBI series span longer than 3 years. Moreover, the SLR station coordinates estimated before 1993.0 – without Lageos II observations – were excluded since they exhibit significantly larger scatter. This led to the complete exclusion of only one SLR station: the older Arequipa station (7907). As GNSS solutions are provided by the IGS on a daily basis, a minimum of 1000 points has been considered for GNSS stations. The selection of stations used in this study is shown in Fig. 1. It includes 180 GNSS, 121 DORIS, 45 SLR and 45 VLBI stations distributed over 111 distinct co-location sites. 20 sites include three techniques or more. A few vast co-location sites were split into two sub-sites when inter-station distances were exceeding 2 km and at least one GNSS station was available for every sub-site. Besides, remote GNSS stations (>2 km) were excluded if a closer GNSS station was available.

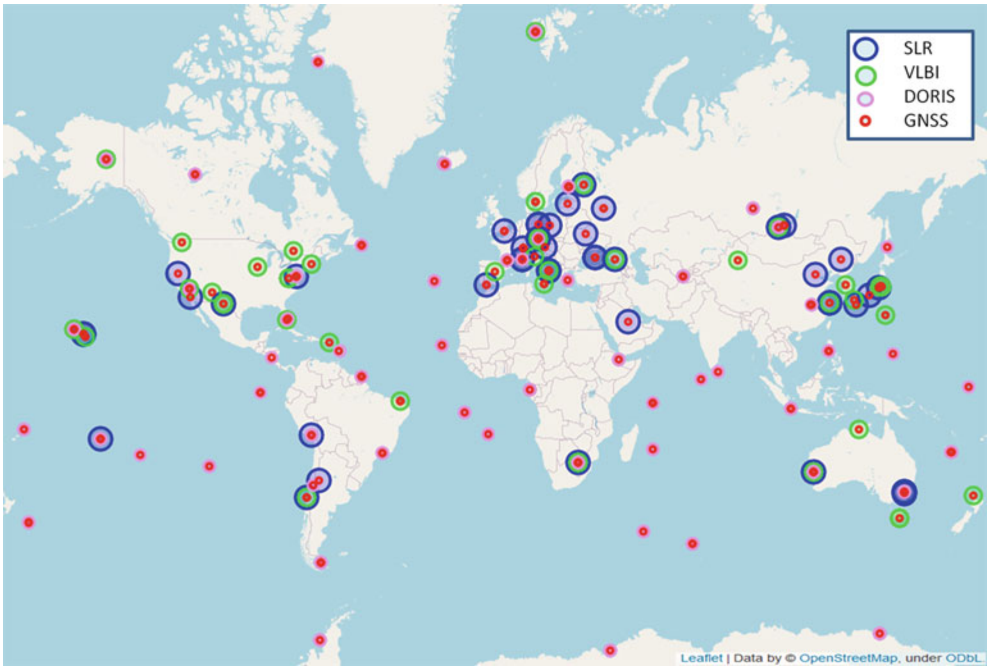

Fig. 1 Network of stations used in this study

For comparison with seasonal coordinate variations of geodetic stations, the non-tidal loading deformation model computed by Boy (2021) has been considered. It is based on ERA5 atmospheric pressure (Hersbach et al. 2020), TUGO-m induced barotropic ocean response to pressure and winds (update of Carrère and Lyard 2003), and on ERA5 soil-moisture and snow loading. Daily average displacements have been computed over the period 01/01/1994 to 01/01/2021.

3 Methodology

In order to obtain station-specific seasonal parameters expressed in a common frame from the ITRF2020 results, three steps were followed:

1. Estimation of annual and semi-annual variations in the ITRF2020 residual time series of each individual station. In this process, possible outliers may have been filtered out.
2. Addition of ITRF2020 seasonal parameters (in the CF frame) to the residual seasonal variations from step 1.
3. Re-evaluation of seasonal parameter formal errors.

The advantages of this three-step method are that it is easy to carry out, and ensures that the obtained station-specific seasonal variations are expressed in the same reference frame by benefiting from the ITRF2020 combination carried out by Altamimi et al. (2023). Indeed, the published ITRF2020 seasonal parameters are expressed in the same reference frame and the residual seasonal signals estimated in step 1 are free from residual translation, rotation and scale components since the ITRF2020 combination model includes transformation parameters.

In order to carry out step 3, a station- and component-specific noise model, composed of variable white noise and power-law noise (Williams 2003), has been adjusted to each ITRF2020 residual coordinate time series. The variable white noise variance factor, as well as the power-law noise variance factor and spectral index were estimated by restricted maximum likelihood following Gobron et al. (2021) and de la Serve et al. (2023). The estimation model also included annual and semi-annual signals, of which the a posteriori formal errors were extracted and will be used in the following as estimates of the precision of the station-specific seasonal parameters from step 2. Correlations between cosine and sine terms are neglected in the following but are smaller than 0.1 (absolute value) in 99% of cases.

Figure 2 shows the ratio between the formal errors of the annual cosine terms under variable white noise + power-law noise assumption and under variable white noise only assumption. In average, the ratio is larger than 1.0 for the four techniques. GNSS estimated parameters are the most impacted with a median value close to 4.0 (3.9 for East and 4.2 for North and Up components) but also with significantly larger differences between stations. SLR, VLBI and DORIS formal error changes are more homogenous while there are still differences on station by station basis. The median values for the three techniques lie between 1.2 and 1.5 for the horizontal components. It is 1.9 for the SLR vertical

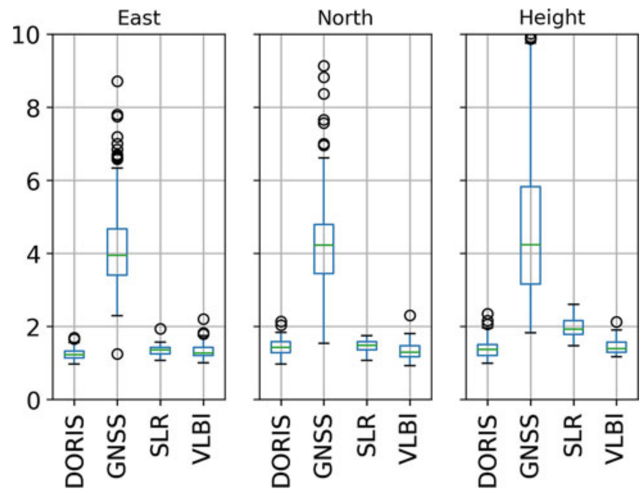

Fig. 2 Ratio between the formal errors of the estimated annual cosine terms under variable white noise + power-law noise assumption and under variable white noise assumption only, for the East, North and Up components. The boxes extend from the ratio quartile values, with lines at the medians

component against 1.4 for DORIS and VLBI. Looking at these numbers, it is clear that accounting for time-correlated noise in coordinate series analysis impacts inter-technique coordinate series comparison.

4 Results

Figure 3 shows the obtained station-specific seasonal displacements together with their 95% confidence intervals within the co-location sites of our selection that host the four space geodetic techniques. A first visual inspection indicates a good agreement between the station-specific seasonal displacements when considering these confidence intervals. However it can be observed that the horizontal seasonal displacements of DORIS stations show larger amplitudes. The non-tidal loading model (black lines in Fig. 3) matches well the vertical seasonal displacements observed by the geodetic techniques at these four sites.

To quantify the level of agreement between station-specific seasonal displacements at co-location sites, the longest GNSS series at each site were arbitrarily taken as references. The RMS of the differences between the seasonal displacements of the other co-located stations and these references are reported in Table 1 for each technique and component.

As can be observed in Table 1, the best agreement between seasonal displacements of the longest GNSS series and the other techniques is found for VLBI, especially for the horizontal components. The RMS values are smaller

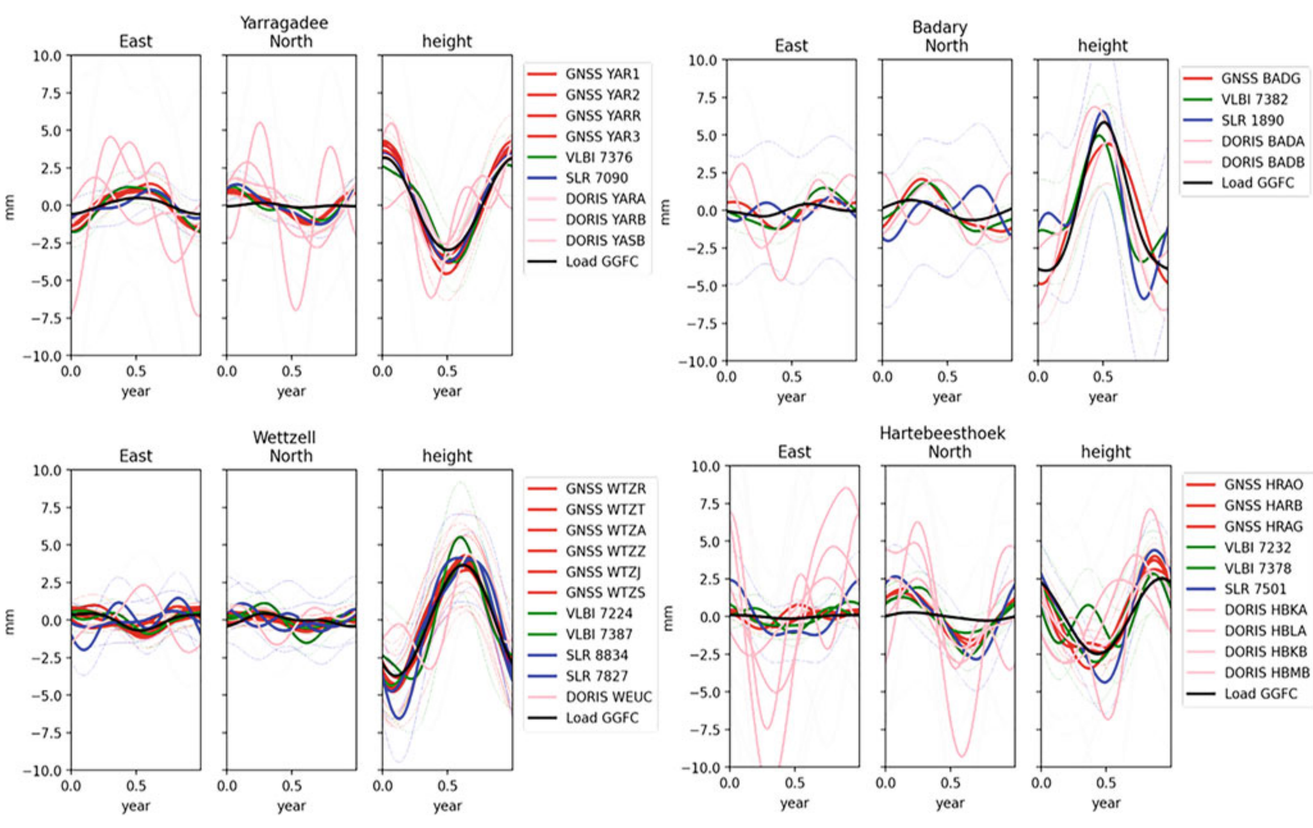

Fig. 3 Station-specific seasonal displacements (in the CF frame) within four co-location sites. The light curves represent 95% confidence intervals

Table 1 Median RMS and minimum/maximum RMS (between brackets) of the differences between (1) the seasonal displacements of the longest GNSS time series of each co-location site and (2) the seasonal displacements of other stations within the same co-location site or non-tidal loading model

	East (mm)	North (mm)	Up (mm)
DORIS	1.9 (0.4, 7.6)	1.7 (0.4, 5.9)	1.8 (0.3, 9.8)
SLR	1.0 (0.3, 9.0)	1.4 (0.3, 4.9)	1.6 (0.3, 7.3)
VLBI	0.5 (0.1, 1.2)	0.4 (0.1, 3.3)	1.4 (0.2, 5.7)
GNSS	0.3 (0.0, 2.8)	0.3 (0.0, 1.3)	0.6 (0.1, 3.3)
NT-loading	0.4 (0.1, 1.9)	0.5 (0.1, 1.6)	1.2 (0.1, 4.1)

than 2.0 mm for 72% of the SLR, 68% of the VLBI stations and 57% of the DORIS stations for the vertical. However, such RMS values do not consider the uncertainties of the estimated seasonal displacements.

To quantify the level of agreement between station-specific seasonal displacements in a more statistically meaningful way, the ratios of the maximum absolute values of the seasonal displacement differences to their formal errors have been computed. The formal errors are based on the noise models adjusted to the ITRF2020 residual time series in step 3. Figure 4 shows the distribution of these ratios, hereafter referred to as "ratio statistics", for each technique and component. Values larger than 3.0 point to

Table 2 Percentage of "ratio statistics" larger than 3.0 at co-location sites. Between brackets: percentage of "ratio statistics" larger than 3.0 corresponding to RMS of seasonal differences larger than 2.0 mm

	East	North	Up
DORIS	11.6% (9.9%)	26.4% (15.7%)	8.3% (6.6%)
SLR	2.3% (2.3%)	0.0% (0.0%)	9.1% (6.8%)
VLBI	4.5% (0.0%)	11.1% (2.2%)	6.7% (6.7%)
GNSS	20.0% (1.5%)	15.4% (0.0%)	1.5% (0.0%)

significant inconsistencies between seasonal displacements in the longest GNSS series and in other co-located series.

As reported in Table 2, more than 90% of the SLR, VLBI and DORIS vertical seasonal displacements agree with GNSS within the 3σ level. The SLR and VLBI stations with ratio statistics larger than 3.0 in vertical are respectively Changchun (7237), Fort Davis (7080), Arequipa (7403), Tidbinbilla (7843) and Shanghai (7227), Chichijima (7347), Warkworth (7377). The DORIS stations with ratio statistics larger than 3.0 are Kitab (KIUB), Krasnoyarsk (KRAB), Cibinong (CIDB), Libreville (LIBB), Palmeira (SALB), Arta observatory (DJIA, DJIB), Goldstone (GONC), Fairbanks (FAIA) and Miami (MIAB).

In the horizontal components, the DORIS seasonal displacements show higher proportions of significant discrep-

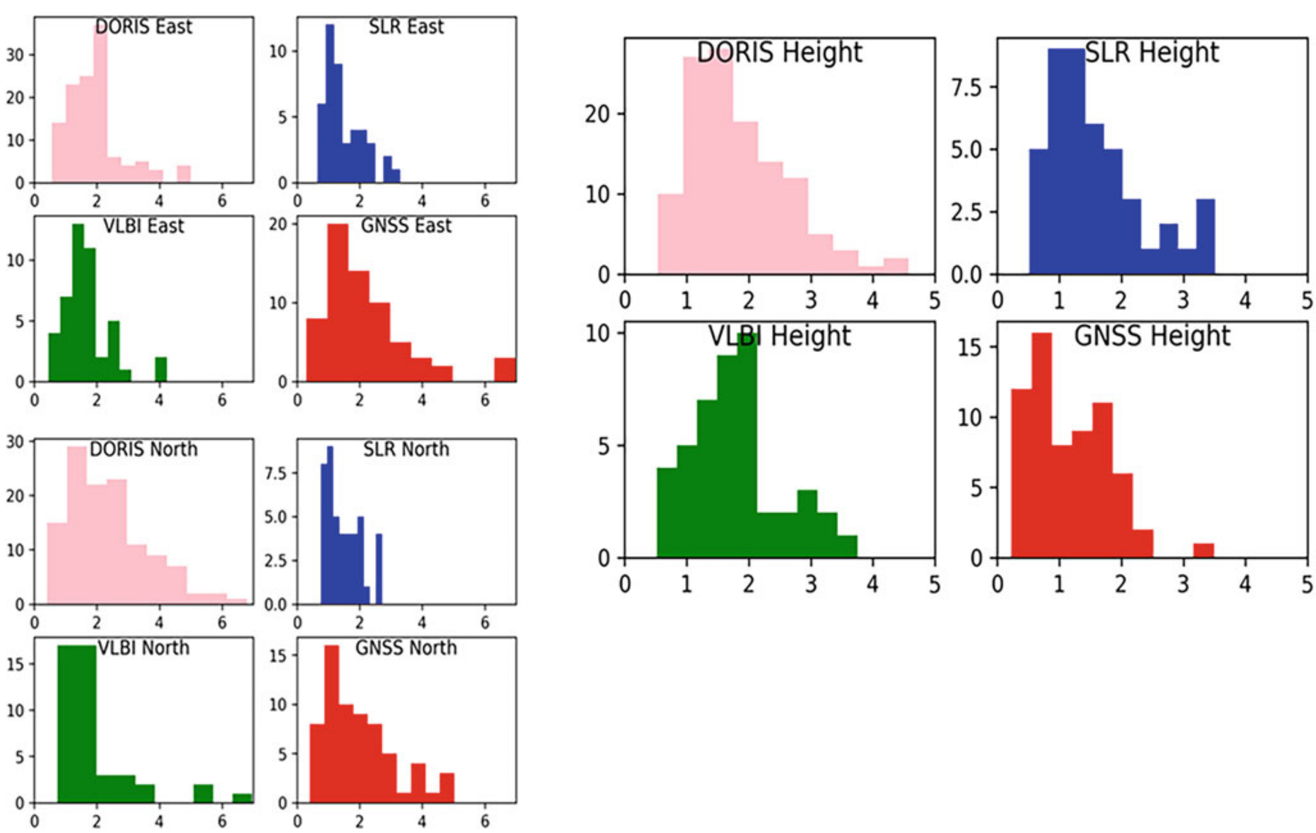

Fig. 4 Distributions, for each technique and component, of the "ratio statistics" introduced in the text

ancies with GNSS, especially along the North component. 15–20% of the selected co-located GNSS station pairs also have ratio statistics larger than 3.0, although the RMS of the corresponding seasonal displacement differences are smaller than 2.0 mm, except in Fairbanks (station pair FAIV/FAIR). The horizontal seasonal displacements of the Irkutsk SLR station (1891) and Warkworth VLBI station (7377) finally also differ by more than 2.0 mm RMS from the co-located GNSS stations.

5 Discussion

We reported an overall good agreement between technique-specific seasonal displacements, and pointed out co-location sites where the seasonal displacements sensed by the different techniques are statistically inconsistent. However, as previously mentioned, constant seasonal displacements were estimated, whereas the Earth's deformations are not strictly periodic, such as the deformations caused by non-tidal loading effects. Moreover, space geodetic data are not regularly sampled. For example, the SLR technique is weather-dependent, while VLBI observation sessions are not continuous. Besides, the observation periods of co-located stations do not necessarily overlap since new instruments can be installed after others are decommissioned. Differences between the constant seasonal displacements adjusted to the series of co-located stations with different time spans are thus expected.

We evaluated the magnitude of this "sampling effect" by performing simulations based on the non-tidal loading model introduced above. The RMS of the differences between seasonal displacements estimated from continuous loading time series over the full time interval 01/01/1994 to 01/01/2021 and seasonal displacements estimated from loading time series re-sampled at the same epochs as the space geodesy observations have been computed and reported in Table 3. The largest differences have been found for SLR observations. This could be explained by the weather dependent availability of SLR data, which causes a coordinate bias related to atmospheric loading, the so-called blue sky effect (Otsubo et al. 2004). Differences between the vertical seasonal displacements are always smaller than 1.0 mm RMS except for the Mendeleevo SLR (7814) station (1.5 mm RMS). Only 13% of the SLR stations and 11% the VLBI stations show seasonal displacement differences larger than 0.5 mm RMS (6% for DORIS and 2% for GNSS). Differences between the horizontal seasonal displacements are generally smaller than 0.1 mm RMS. Overall, the evaluated magnitude of the "sampling effect" is much smaller than the differences between station-specific seasonal displacements reported in Sect. 4, see values in Table 1. This indicates that these differences are likely mainly due to errors in the space geodetic station position time series.

Only a small number of sites was found with statistically significant differences between seasonal displacements (i.e., ratio statistics larger than 3.0). Our re-evaluation of the seasonal parameter formal errors based on time-correlated noise models adjusted to the ITRF2020 residual time series likely contributes to this result. While we expect these models to provide more realistic formal errors than the white noise model used in the past by Collilieux et al. (2017, 2018), further work is needed to improve the modelling of space geodetic technique noise.

The overall good consistency of technique-specific seasonal displacements supports the choice made to equate them in the ITRF2020 combination – except in case of notable discrepancies – and ensures good confidence in the published ITRF2020 seasonal parameters. In particular, the good agreement between SLR and GNSS seasonal displacements made it possible to transfer reliably the SLR origin to the ITRF2020 seasonal parameters of GNSS stations and thus express them in the CM frame.

Table 3 Median RMS, 95% quantile and maximum RMS between seasonal time series estimated from continuous load time series (Boy 2021) [a] over the time interval 01/01/1994 to 01/01/2021 and estimated from sampled time series [a] by space geodesy

	East	North	Up
DORIS	0.03, 0.08, 0.13	0.03, 0.10, 0.19	0.17, 0.51, 0.93
SLR	0.03, 0.09, 0.16	0.03, 0.10, 0.13	0.17, 0.76, 1.51
VLBI	0.03, 0.07, 0.11	0.04, 0.07, 0.09	0.20, 0.57, 0.67
GNSS	0.01, 0.05, 0.13	0.01, 0.05, 0.11	0.09, 0.31, 0.65

[a] Computed from daily load values

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References

Altamimi Z, Collilieux X (2010) Quality assessment of the IDS contribution to ITRF2008. Adv Space Res 45(12):1500–1509. https://doi.org/10.1016/j.asr.2010.03.010

Altamimi Z, Rebischung P, Métivier L, Collilieux X (2016) ITRF2014: a new release of the International Terrestrial Reference Frame modeling nonlinear station motions. J Geophys Res 121(B8):6109–6131. https://doi.org/10.1002/2016JB013098

Altamimi Z, Rebischung P, Collilieux X, Métivier L, Chanard K (2022) ITRF2020 [Data set]. IERS ITRS Center Hosted by IGN and IPGP. https://doi.org/10.18715/IPGP.2023.LDVIOBNL

Altamimi Z, Rebischung P, Collilieux X, Métivier L, Chanard K (2023) ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions. J Geod 97:47. https://doi.org/10.1007/s00190-023-01738-w

Blewitt G (2003) Self-consistency in reference frames, geocenter definition, and surface loading of the solid earth. J Geophys Res 108(B2). https://doi.org/10.1029/2002JB002082

Blewitt G, Lavallée D (2002) Effect of annual signals on geodetic velocity. J Geophys Res 107:2145. https://doi.org/10.1029/2001JB000570

Boy J-P (2021) Contribution of GGFC to ITRF2020. Technical report EOST/IPGS. http://loading.u-strasbg.fr/ITRF2020/ggfc.pdf

Carrère L, Lyard F (2003) Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing - comparisons with observations. Geophys Res Lett 30:1275. https://doi.org/10.1029/2002GL016473

Collilieux X, Altamimi Z, Coulot D, Ray J, Sillard P (2007) Comparison of very long baseline interferometry, GPS, and satellite laser ranging height residuals from ITRF2005 using spectral and correlation methods. J Geophys Res 112(B12403). https://doi.org/10.1029/2007JB004933

Collilieux X, van Dam T, Ray J, Coulot D, Métivier L, Altamimi Z (2012) Strategies to mitigate aliasing of loading signals while estimating GPS frame parameters. J Geod 86:1–14. https://doi.org/10.1007/s00190-011-0487-6

Collilieux X, Altamimi Z, Rebischung P, Métivier L, Chanard K (2017) Analysis of the seasonal parameters estimated in the ITRF2014 processing. Presented at IAG-IASPEI Joint Scientific Assembly, Kobe

Collilieux X, Chanard K, Altamimi Z, Rebischung P, Métivier L, Ray J, Coulot D (2018) Comparison of the seasonal displacement parameters estimated in the ITRF2014 processing, what can we learn? Presented at 42nd COSPAR Scientific Assembly, Pasadena

de La Serve M, Rebischung P, Collilieux X, Altamimi Z, Métivier L. (2023) Are there detectable common aperiodic displacements at ITRF co-location sites? J Geod 97:79. https://doi.org/10.1007/s00190-023-01769-3

Gobron K, Rebischung P, Van Camp M, Demoulin A, de Viron O (2021) Influence of aperiodic non-tidal atmospheric and oceanic loading deformations on the stochastic properties of global GNSS vertical land motion time series. J Geophys Res 126. https://doi.org/10.1029/2021JB022370

Hellmers H, Modiri S, Bachmann S, Thaller D, Bloßfeld M, Seitz M, Gipson J (2022) Combined IVS contribution to the ITRF2020. In: International Association of Geodesy Symposia. Springer, Heidelberg. https://doi.org/10.1007/1345_2022_170

Hersbach H, Bell B, Berrisford P et al (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146:1999–2049. https://doi.org/10.1002/qj.3803

Moreaux G, Lemoine FG, Capdeville H, Otten M, Štěpánek P, Saunier J, Ferrage P (2023) The international DORIS service contribution to ITRF2020. Adv Space Res 72(1):65–91. https://doi.org/10.1016/j.asr.2022.07.012

Otsubo T, Kubo-oka T, Gotoh T, Ichikawa R (2004) Atmospheric blue sky effects on SLR station coordinates. In: Proceedings of 14th ILRS workshop, San Fernando, pp 69–74

Pavlis EC, Luceri V (2022) The ILRS contribution to ITRF2020. Tech. Rep. https://itrf.ign.fr/en/solutions/ITRF2020

Rebischung P (2022) The IGS contribution to ITRF2020. Tech. Rep. https://itrf.ign.fr/en/solutions/ITRF2020

Rebischung P, Altamimi Z, Collilieux X, Métivier L, Chanard K (2022). ITRF2020 seasonal geocenter motion model, presented at REFAG 2022, this meeting

Tesmer V, Steigenberger P, Rothacher M, Boehm J, Meisel B (2009) Annual deformation signals from homogeneously reprocessed VLBI and GPS height time series. J Geod 83:973–988. https://doi.org/10.1007/s00190-009-0316-3

Williams SDP (2003) The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. J Geod 76:483–494. https://doi.org/10.1007/s00190-002-0283-4