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Citation for the original published paper (version of record):
Ishigaki, M., le Bail, K., Nilsson, T. et al (2026). Exploring reasons for the ITRF2020 VLBI scale drift. Journal of Geodesy, 100. http://dx.doi.org/10.1007/s00190-026-02057-6

Journal of Geodesy (2026) 100:36
https://doi.org/10.1007/s00190-026-02057-6

ORIGINAL ARTICLE

Exploring reasons for the ITRF2020 VLBI scale drift

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Received: 7 February 2025 / Accepted: 16 April 2026

Abstract

In the recent realization of the International Terrestrial Reference System (ITRF2020), it was found that the VLBI scale parameter showed a positive drift after 2013.75. Although several possible reasons for this apparent VLBI scale drift are being discussed by the International VLBI Service for Geodesy and Astrometry community, a clear explanation for this issue has not yet been identified. In this study, we investigated the reasons for the apparent VLBI scale drift in the ITRF2020 using CATREF software, applying the same approach as that used for producing the ITRF2020. We estimated the impact of various models and methods used in the ITRF2020 on the VLBI scale drift, such as discontinuities applied to VLBI station positions and velocities, gravitational deformation models, and thermal deformation corrections. The analysis revealed that there is no simple explanation for the scale drift; however, the station position modeling of NYALES20 is one of the major contributors to it, and a combination of different deformation models and equipment changes for some stations can explain most of the drift observed in the scale parameter.

Keywords ITRF · VLBI · IVS combined solution · Scale

1 Introduction

The International Terrestrial Reference Frame (ITRF) is a global reference frame constructed by combining different space geodetic techniques: VLBI, GNSS, SLR, and DORIS. The ITRF2020 was released in 2022, which was updated from the previous version of ITRF2014 by stacking the time series of the four techniques all together and improving models of nonlinear station motions for seasonal variations and Post-Seismic Deformation (PSD) (Altamimi et al. 2023).

The ITRF has a solution for station positions, velocities, earth orientation parameters, and 14 transformation parameters between the new and past frames (translation vector, scale factor, and matrix containing rotation angles). The ITRF scale factor is defined by a combination of the selected VLBI sessions and weekly SLR solutions. For the first time in ITRF history, the selected VLBI sessions for ITRF2020 did not cover the entire International VLBI Service for Geodesy and Astrometry (IVS) observation time span, but comprised only sessions up to 2013.75. This selection was based on the detection of a drift in the scale factor time series of the VLBI CATREF-combined solution after 2013.75. For further details, please refer to Altamimi et al. (2023).

Several suggestions have been made regarding the causes of VLBI scale drift. One possibility is a problem at one or more stations. This could be either a technical problem with the antenna or receiver or nonlinear station motions not properly considered in the ITRF combination. For example, the VLBI station at Ny-Ålesund, Spitsbergen, Norway, experi-

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M. Ishigaki, K. L. Bail, T. Nilsson, M. Mouyen have contributed equally to this work, and R. Haas was involved in the conception of this work and in the discussion and interpretation of the results.

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ences nonlinear land uplift due to present-day ice melting (Kierulf et al. 2022). Because this was not considered in the ITRF2020 combination, it could have affected the ITRF2020 VLBI scale. The contribution of the station at Ny-Ålesund has been investigated in a recent study of Kern et al. (2025). Other possibilities could be problems with one or more of the models or constraints used in the VLBI data analysis.

Various studies (see Lindé (2022); Le Bail et al. (2023a, b); Nilsson et al. (2023), Le Bail et al. (2024a); Ishigaki et al. (2024); Le Bail et al. (2024b) have been conducted under the IVS Task Force on the VLBI scale, which was restructured into IVS Working Group 9 in October 2024. In this work, we explore potential causes of scale drift from multiple perspectives and assess the impact of each, building on the findings of these previous studies.

It is worth noting that the update frequency of the ITRF has recently increased, and ITRF2020 is now scheduled for annual updates. The most recent version, ITRF2020-u2023, was released in December 2024 as the first official update. It follows the same methodology as the original ITRF2020 but incorporates an additional three years of data, covering the period from 2021.0 to 2024.0. The VLBI scale drift observed in ITRF2020-u2023 is currently under discussion within IVS Working Group 9. While this study contributes to that broader dialog, it focuses specifically on the original ITRF2020 solution.

In this paper, Sect. 2 describes the data used in this study, Sect. 3 presents the impact of each potential cause on the VLBI scale factor, and Sect. 4 concludes the paper and provides perspectives for future work.

2 Data

We analyzed two sets of data: (a) the IVS contribution to the ITRF2020 and (b) a single Analysis Center VLBI solution, both described hereafter. The IVS combined solution is the final VLBI contribution of the IVS considered in the calculation of the ITRF2020 (Hellmers et al. 2022). For the IVS contribution to ITRF2020, sessions containing 24-hour VLBI observations from 1979 to the end of 2020 were reprocessed by 11 different Analysis Centers and submitted to the IVS Combination Center. The IVS combined solution consists of session-wise SINEX files, which include datum-free normal equations for station coordinates, source positions, and Earth Orientation Parameters (EOPs). Further details are provided in Hellmers et al. (2022). We used the Combination and Analysis of Terrestrial REference Frame (CATREF; Altamimi et al. 2016) software to estimate scale factors we are interested in, applying the same analysis strategy used by the ITRF team for the ITRF2020 production (Altamimi et al. 2023). CATREF is the software used for the construction of ITRFs, combining solutions from VLBI, GNSS, SLR, and DORIS. This study focuses on VLBI data and inputs only VLBI data into the CATREF analysis. We put the SINEX files of 6,246 sessions of the IVS combined solution into the CATREF software, using the same PSD models and discontinuity lists as used in ITRF2020 production, applying No-Net-Translation and No-Net-Rotation, minimum constraints on the translation and rotation parameters, and internal constraints on the scale parameter. Internal constraints preserve instrinsic long-term parameters when stacking time series, whereby the offset and trend of the VLBI scale time series over the entire period is constrained to zero. Further details are provided in Altamimi et al. (2023). Note that CATREF calculates not only the scale parameters, which are the main focus of this study, but also the station coordinates, since the IVS combined solution provides session-wise, combined, datum-free normal equations for the ITRF realization.

Figure 1 shows the scale time series with respect to ITRF2020 obtained from our analysis, using all stations as fiducial points in sessions where more than three stations participated. The scale drift estimated after 2013.75 is 0.50 ± 0.07 mm/yr (Case-0 in Table 1), which is consistent with that obtained in Altamimi et al. (2023). This data set (a) is used for the analyses of Section 3.1, 3.2, and 3.3.

The second set of data analyzed in this paper corresponds to the VLBI solution calculated operationally by the OSO VLBI Analysis Center. We analyzed high-quality 24-hour geodetic VLBI sessions with four or more stations from the period Jan. 1990 – Jan. 2022, for a total of 5351 sessions. Only legacy S/X sessions were included in the dataset. The analysis was performed with the ASCOT software (Artz et al. 2016), using the settings and models recommended for ITRF2020. We applied gravitational deformation models for 10 telescopes, using the models provided by the IVS Analysis Coordinator in January 2023 (containing models for four additional telescopes, compared to those used in ITRF2020). The coordinates of the International Celestial Reference Frame 3 (ICRF3, Charlot et al. 2020) defining sources were fixed at their ICRF3 values, whereas the other radio source coordinates were estimated for each session. Non-tidal atmospheric loading was corrected using the atmospheric loading product provided by the Vienna University of Technology (Wijaya et al. 2013). After analyzing this OSO solution, the drift derived from the scale factor time series after 2013.75 is 0.60 ± 0.08 mm/yr, which is larger than that with the IVS combined solution (Case-3 in Table 1). This data set (b) is used for the analyses of Section 3.4.

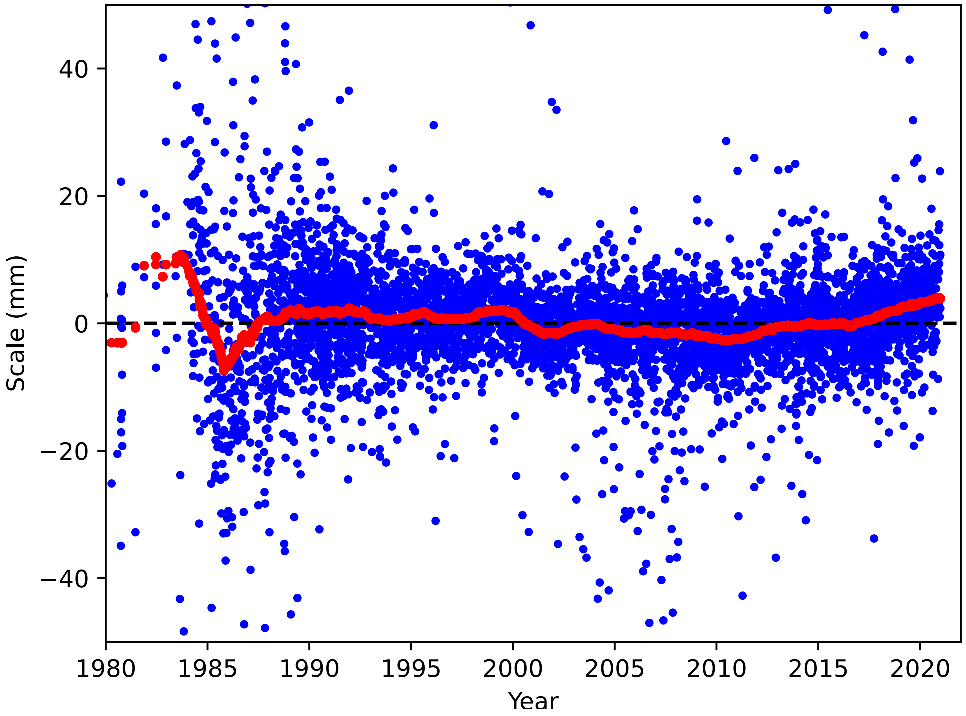

Fig. 1 Time series of scale factors with respect to ITRF2020 obtained in our analysis using the same models and method as those for the ITRF2020 construction shown in blue dots. The smoothed time series weighted median over ±1 year is shown in red

Table 1 Comparison of scale drift after 2013.75 with various models using IVS combined solution

	Solution		Scale drift (mm/yr)
0	Original data	(IVS combined solution)	0.50 ± 0.07
1	Velocity modeling applied to	NYALES20	0.31 ± 0.07
2	Discontinuities applied to	NYALES20	0.26 ± 0.07
		WETTZELL	0.49 ± 0.07
		MATERA	0.48 ± 0.07
		ONSALA60	0.45 ± 0.07
		TSUKUB32	0.49 ± 0.07
		ZELENCHK	0.46 ± 0.07
		all the six stations	0.15 ± 0.07
3	Different models	(a) Standard	0.60 ± 0.08
		(b) No Gravitational deformation	0.60 ± 0.08
		(c) Gravitational deformation for six stations	0.60 ± 0.08
		(d) No Thermal def	0.63 ± 0.08
		(e) Temperature from GPT2	0.62 ± 0.08
		(f) IERS 2010 mean pole model	0.53 ± 0.08
		(g) No pole tide correction	0.60 ± 0.08
		(h) Loading from IMLS	0.62 ± 0.08
		(i) Source coordinates from ICRF2	0.67 ± 0.08
		(j) DTRF2020 PSD models	0.50 ± 0.08

3 Results and discussion

3.1 Evaluation of the IVS combined solution

The first step was to investigate the Up-component time series of each of the IVS stations and extract possible offsets and trend changes that were not considered as discontinuities in the ITRF2020. To detect these, CATREF was run without estimating scale factors over the time span 2000.0–2021.0. Sessions conducted before 2000 were not included in this analysis, because including old sessions caused halt of CATREF calculation due to too large scatters of data in this period, when fixing scale factors. We selected stations with more than 500 sessions during the period 2000–2021. Based on this criterion, 19 stations were chosen; however, station GILCREEK was excluded from the following discussion because it has not participated in any sessions since 2006. Among the remaining 18 stations, six IVS stations (NYALES20, WETTZELL, ONSALA60, TSUKUB32, MATERA, and ZELENCHK) showed an upward trend in the time series of their Up-component offsets (see Fig. 2), exceeding 0.5 mm/year from 2013.75 onward. Table 2 shows details of the six stations. These stations have participated in many IVS sessions over a long period, and are expected to have a significant impact on ITRF2020.

In the following subsections, we discuss the potential contribution of each station to the scale drift. First, we evaluated the deformation models for NYALES20 to express the nonlinear motion of the station, and then we investigated station events found at six stations: NYALES20, WETTZELL, ONSALA60, TSUKUB32, MATERA, and ZELENCHK. Note that the results presented in Sections 3.2, 3.3, and 3.4 are independent of one another. The effects investigated in Section 3.2 are not related to those in Section 3.3, and the same applies to Section 3.4.

3.2 Velocity modeling of NYALES20

In the case of NYALES20, an uplift trend has been detected by GNSS stations in recent years in the region around the Svalbard Archipelago (Kierulf et al. 2022). Kierulf et al. (2022) showed that this region is affected by two types of loading effects caused by glacier mass changes: (1) glacial isostatic adjustment, which is a long-term linear motion, and (2) present-day ice melt (PDIM), which is a short-term nonlinear motion. The recent uplift is explained by the PDIM effect. The increased PDIM in recent years has also led to differences between long-term and recent station velocities. In the ITRF2020 production, the VLBI station at Ny-Ålesund was not modeled with nonlinear functions but only with one linear function. Conversely, the GNSS station NYA1 at Ny-Ålesund was modeled with three different velocities as shown in Table 3. Therefore, the station position model for the Ny-Ålesund VLBI station potentially lacks the effect of the PDIM. We applied this velocity modeling of the GNSS to VLBI in CATREF to improve the fitting of the uplift of Ny-Ålesund. The results are summarized in Table 1 Case-1. The scale drift decreased to 0.31 ± 0.07 mm/yr. For comparison, we also checked the Up-components of the velocities of NYALES20 when the same discontinuities as those for NYA1 were applied but the velocities were not constrained. The velocities are listed in the last column of Table 3, which are comparable to those of NYA1. This indicates that the station velocities derived from NYALES20 VLBI data are consistent with those of the GNSS station NYA1.

The result suggests that the velocity of NYALES20 can be modeled more accurately using piecewise linear functions with multiple velocity components, rather than the single linear functions applied in ITRF2020. Further investigation is needed to develop more accurate models using nonlinear functions that quantitatively account for the PDIM model.

Recently, Kern et al. (2025) reported an independent study on the contribution of NYALES20 to scale drift. Instead of CATREF, the authors used the combination software VieCompy. Their approach is similar to the analysis presented in this section, as they evaluated the impact of PDIM by introducing discontinuities in the NYALES20 time series, but focused exclusively on this station. They demonstrated that the discontinuity strategy applied in this paper yields the best results, compared to (i) assuming no discontinuity as in ITRF2020 and (ii) applying the four discontinuities proposed in Le Bail et al. (2023b). Although the epochs of discontinuities in Kern et al. (2025) differ from those examined here, both studies show a comparable reduction in scale drift.

The impact of NYALES20 on the scale parameter was also investigated in the study by Lindé (2022). In their analysis, the stations NYALES20, SEJONG, YEBES40M, and the stations of the Very Long Baseline Array (VLBA) were excluded during processing. Excluding SEJONG and YEBES40M alleviated the scale drift, whereas excluding NYALES20 and the VLBA stations had nearly the opposite effect. This result contrasts with the findings of the present study, suggesting that NYALES20 has a negative impact on scale drift. As discussed in Lindé (2022), this can be explained by the fact that NYALES20 participated frequently in IVS sessions over a long time span, and removing the station may destabilize the network. It should also be noted that their study was based on the estimation of Helmert parameters between the session-wise OSO solutions and ITRF2014, which was used as the reference frame for comparison.

3.3 Station events related to technical issues

Most VLBI stations have undergone replacement, repair, and maintenance of equipment and antennas, which can cause

Table 2 Summary of six stations selected in the analysis which showed an upward trend in the time series of their Up-component offsets in the period from 2013.75

Station name	Latitude	Longitude	# of sessions in the IVS combined solution	Periods
NYALES20	78°55′44.4″	11°52′14.5″	2178	Oct. 1994 – Dec. 2020
WETTZELL	49°08′42.0″	12°52′38.6″	3844	Nov. 1983 – Dec. 2020
MATERA	40°38′58.2″	16°42′14.4″	1202	Oct. 1990 – Dec. 2020
ONSALA60	57°23′45.0″	11°55′34.9″	1037	Jul. 1980 – Dec. 2020
TSUKUB32	36°06′11.0″	140°05′19.0″	937	Jun. 1998 – Dec. 2016
ZELENCHK	43°47′16.1″	41°33′54.7″	604	Dec. 2005 – Dec. 2020

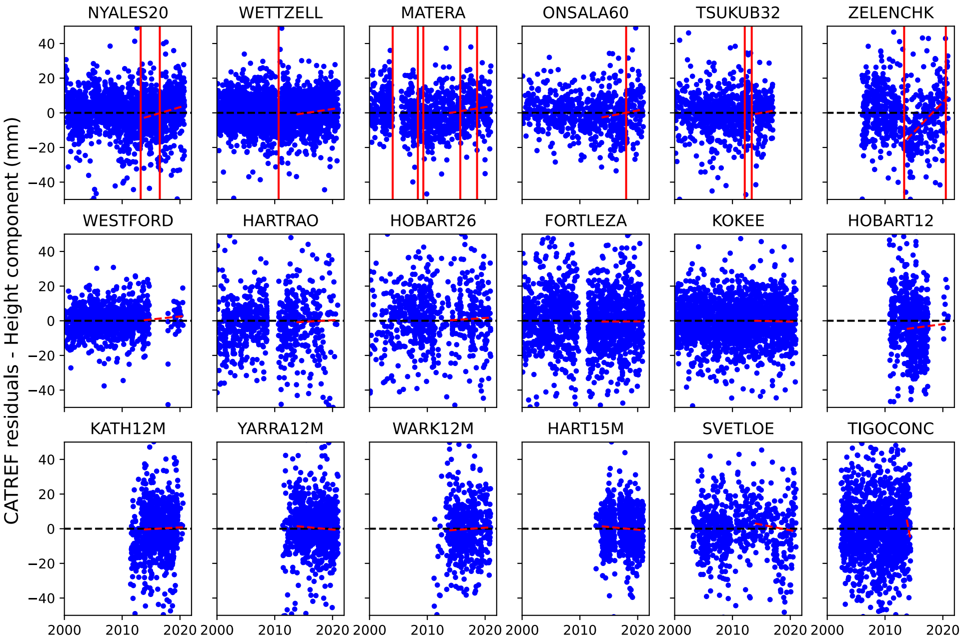

Fig. 2 Up-component CATREF-residuals w.r.t. ITRF2020 of 18 stations including NYALES20, WETTZELL, MATERA, ONSALA60, TSUKUB32, and ZELENCHK, which have more than 500 sessions in the period of 2000–2021. CATREF was run using the same strategy as that for the ITRF2020, except for scale factors estimation. The red dashed lines represent the least-squares regression line fitted for the plots in the period after 2013.75. The vertical lines indicate epochs for station events summarized in Table 4

Table 3 Up-component velocities for NYALES20 (VLBI) and NYA1 (GNSS) calculated from ITRF2020 (V_{up}) and those for NYALES20 (VLBI) in the analysis for comparison (V'_{up})

Data span	Station	V_{up} (mm/yr)	V'_{up} (mm/yr)
Whole period	NYALES20	7.92	-
Up to 04:186	GNSS NYA1	7.66	6.26
04:186-16:233	GNSS NYA1	7.63	7.44
After 16:233	GNSS NYA1	10.16	8.63

discontinuities in the position of the telescope reference point. This has a potential effect on the scale drift if it is not properly considered in ITRF2020. We examined the IVS annual and biennial reports of each station (https://ivscc.gsfc.nasa.gov/publications/annualreport.html) and checked whether any station events related to technical issues. A summary of the major station events for NYALES20, WETTZELL, MATERA, ONSALA60, TSUKUB32, and ZELENCHK is provided in Table 4.

We added these events to the discontinuity file and ran CATREF again. In this analysis, we conservatively assume that the velocity remains constant before and after each discontinuity, as some intervals between discontinuities are too short to allow for individual estimation. The values of the scale drift after 2013.75 for several cases are shown in Table 1 Case-2. NYALES20 again had the largest impact on scale drift among the six stations. This can be explained by the possibility that the impact of the PDIM discussed in the previous section is compensated by adding discontinuities to NYALES20.

This study doesn't conclude that the discontinuities shown in Table 4 are all or only the cause of the scale drift, but this is a case study which shows the impact of individual stations on the scale parameters and imply the importance of selecting an appropriate set of discontinuities. The result in this study indicates that the impact of individual stations on the scale parameter can be large, especially for stations which have long histories and experienced large number of sessions, which can be due to the limited number of stations in the current VLBI network. The validity of applying discontinuities

Table 4 Summary of station events at NYALES20, WETTZELL, MATERA, ONSALA60, TSUKUB32, and ZELENCHK presented in IVS annual and biennial reports

Stations	Periods	Events
NYALES20	2013-03-14	gear box replaced
	2016-07-04	broken AZ gear
WETTZELL	2010-09-01	gear wheels repair and new elevation bearings + re-adjustment dish surface
MATERA	2004-01-01	repair of the concrete pedestal
	2008-05-12	AZ wheel replacement
	2009-04-23	AZ wheel replacement
	2015-09-15	complete rail replacement
	2018-08-10	AZ wheel replacement
ONSALA60	2018-01-01	subreflector control electronics replaced + new pointing model
TSUKUB32	2012-02-15	repair of subreflector supporting structures
	2013-05-01	repair of antenna base
ZELENCHK	2013-04-22	center sector of the antenna subreflector replaced
	2020-07-07	heavy repairs (rail track + foundation - sag by 2-3 mm)

in the ITRF must be discussed based on a careful evaluation of each station event, and station events should be considered in the parameterization of a station only if their impact on the station position time series is significant and clearly identifiable. On the other hand, station events are often poorly recorded, so examining deviations from the ITRF model is one of the reasonable ways to detect possible discrepancies. The IVS Working Group 9 is currently investigating such events and will assess the impact of the stations considered in this study, along with others.

3.4 Different models

In the last subsection, we investigated the impact of different models on the VLBI scale. Using the ASCOT software, we calculated a number of alternative solutions to the standard solution using the OSO solution described in Sect. 2. In each case, one model was changed in the VLBI data analysis and compared with the standard solution. Table 2 lists the various models tested. The models we varied were gravitational deformation models (applied to ten, six, or no telescopes) (a)(b)(c), thermal deformation (applied or not applied) (d), temperature from data of the empirical GPT2 model (Lagler et al. 2013) (e), pole tide (models from different IERS Conventions or not applied) (f)(g), geophysical loading (applied or not applied) (h), celestial reference frame (ICRF3 or ICRF2) (i), and PSD models from ITRF2020, ITRF2014, and DTRF2020 (j). After calculating the VLBI solutions, the resulting SINEX files for all sessions were combined using CATREF. The station positions were parameterized in the same way in these solutions as in the standard solution.

For each alternative solution, we compared the scale time series with the standard solution. We examined possible differences in long-term drift, particularly after 2013.75, as well as other interesting differences such as annual variations. The scale differences between the three alternative solutions and the standard solution are shown in Fig. 3.

Gravitational deformation models The VLBI telescopes are deformed by gravity, and these deformations affect the VLBI observables. If not corrected, this will cause error in the estimated station positions (mostly in the height component). For example, for the ONSALA60 telescope, the effect is about 5 mm in the vertical (Nothnagel et al. 2019). Thus, it is possible that gravitational deformation also affects the scale. However, for most telescopes the deformations have not been measured, hence no corrections can be applied. For the ITRF2020 analysis, models for six telescopes (EFLSBERG, GILCREEK, MEDICINA, NOTO, ONSALA60, and YEBES40M) have been included. Since then, a few more telescopes have been measured. For the standard solution, models for the telescopes KOKEE, NYALES20, WETTZELL and WETTZ13N were also included.

The top plot in Fig. 3 shows the difference between the solution without gravitational deformation models (b) in Table 1 and the standard solution which contains models of ten stations (a). As can be seen, the scale differences are small. We also calculated a solution using the same gravitational deformation (c) as in ITRF2020 (which contains models for six antennas). Also, the scale results with these solutions did not differ significantly from that of the standard solution. Hence, our results show that the application of gravitational deformation models does not cause scale drift.

Thermal deformation corrections VLBI telescopes are distorted by time-dependent temperature effects. Consequently, their reference points are displaced from a mean position,

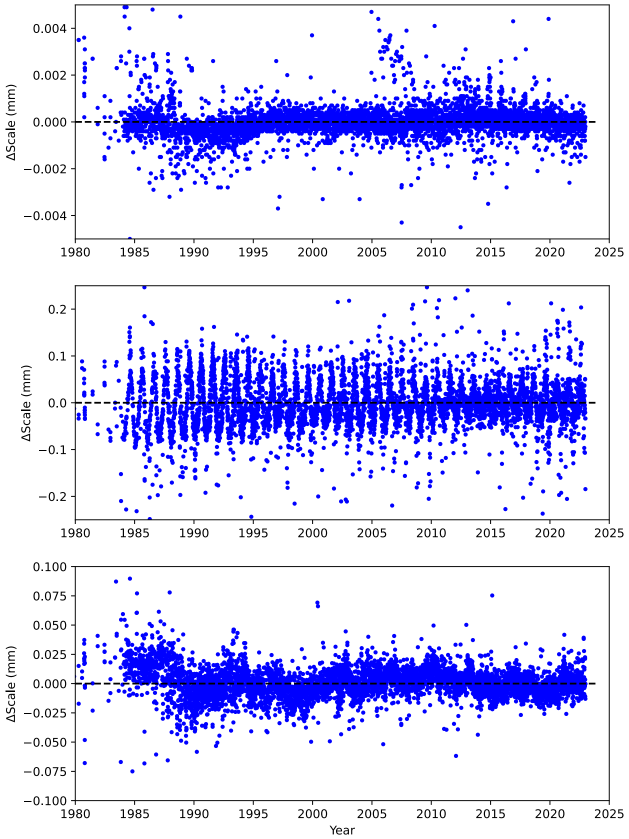

Fig. 3 Time series of the differences in scale between three alternative solutions and the standard solution. The upper plot shows the solution when no gravitational deformation models are applied, the middle plot shows the solution not using thermal deformation, and the lower plot shows the solution using geophysical loading from the IMLS

with the magnitude typically on the order of several millimeters (Nothnagel 2008). The middle plot in Fig. 3 shows the time series of difference in scale between the solution in which no thermal deformation corrections ((d) in Table 1) were applied and the standard solution. As shown, scale drift was not significantly affected. However, the difference in scale relative to the standard solution varies annually, with an amplitude of a few submillimeters. This can be explained by the following scenario. In the summer, when the temperature is high, thermal deformation causes telescopes to expand. If not corrected, it will cause an increase in the scale. Because most VLBI telescopes are located in the Northern Hemisphere, not correcting for thermal deformation will cause the scale factor to increase in summer in the Northern Hemisphere. We note that the amplitude of the annual variations seems to have decreased after 2012. One possible explanation for this is that more Southern Hemisphere stations have joined the VLBI network in recent years, as shown in Thomas et al. (2024). Another possible explanation is that the telescopes that have joined in recent years are small (VGOS-type telescopes) and thus experience less thermal deformation.

Geophysical loading models The bottom plot of Fig. 3 shows the effect of using geophysical loading models ((h) in Table 1) (atmosphere, non-tidal ocean, and hydrology) from the International Mass Loading Service (IMLS, Petrov 2015) (the standard solution only uses corrections for atmospheric loading). We cannot see that this solution has a lower scale drift after 2013.75 (0.62 mm/yr) compared to the standard solution (0.60 mm/yr).

Other models In Case-3 in Table 1, the scale drift after 2013.75 is shown for the standard solution and for all the calculated alternative solutions. The scale drift was not significantly affected by any of the models, although some smaller impacts were noted. The largest reduction in scale drift (approximately 0.1 mm/yr) was observed when using the IERS 2010 mean pole model ((f) in Table 1) and the PSD models from DTRF2020 (Seitz et al. 2023; Seitz et. al., 2026) instead of those from ITRF2020 (j). Furthermore, an increase in the drift of approximately 0.07 mm/yr can be noted when using the radio source coordinates from ICRF2 instead of from ICRF3 (i). We also observed that some models affected seasonal variations in the scale. Apart from thermal deformation, not applying pole tide loading (g) also results in annual variation in scale. The model with temperature from observations from the empirical GPT2 (e) did not significantly affect the seasonal scale variations.

4 Conclusions

The results discussed in this study are summarized in Table 1.

In the CATREF analysis, the station position modeling of NYALES20 had a dominant impact on the VLBI scale drift after 2013.75 in ITRF2020. This can be explained by the uplift of the station caused by PDIM in the Ny-Ålesund region. The remaining reasons for the scale drift could be the combination of multiple factors, including discontinuities caused by station events in some of the major stations and various models used in the ITRF2020 construction.

This research outlines the importance of monitoring what happens at IVS stations and the changes in positions that can be due to changes in equipment, service, and maintenance events, but may also indicate the necessity to consider the impact of PDIM on station positions. This research further highlights the potential risk to the robustness of the VLBI network, showing that the reference frame obtained from VLBI could be affected by a small number of stations.

The next steps in this research are twofold. First, the objective is to identify and collect information related to station events that could potentially change the positions of the station reference point, and to test the impact of these station events with the help of the ITRF team by applying them to the ITRF. Such a list of station events must be maintained regularly over time within the IVS and communicated as a "logbook" and a standardized discontinuity file containing information of all the stations, which is essential for anyone involved in the investigation of VLBI-derived EOP time series, TRF or CRF solutions. The IVS Working Group 9 is currently collaborating with the IVS Network Coordinator and the IVS Analysis Coordinator to implement a logbook, consisting of a list of station events maintained by station staff, as well as a list of recommended discontinuities. These will be accessible online and updated regularly. Second, collaboration with geodynamics experts is required to understand the impact of PDIM and earthquakes on station positions worldwide. These suggestions are currently being discussed by the IVS Working Group 9 to further investigate the causes of VLBI scale drift using the updated version of ITRF2020.

Acknowledgements This study was conducted during Masafumi Ishigaki's visit to Chalmers University of Technology, supported by the Ministry of Education, Culture, Sports, Science and Technology. We are grateful to Zuheir Altamimi for giving us access to the CATREF software and to the IVS and IVS Combination Center for providing the VLBI data used in this work. We also thank Yudai Sato, Kensuke Kokado, Shinobu Kurihara, Basara Miyahara and Toshimichi Otsubo for supporting the collaborative work between Chalmers University of Technology and the Geospatial Information Authority of Japan and for helpful comments on this work.

Author Contributions Study conception and design were performed by all authors. CATREF analyses were performed by Masafumi Ishigaki. The station events were investigated by Karine Le Bail. Model comparison was performed by Tobias Nilsson. Velocity modeling was evaluated by Maxime Mouyen. The first draft of the manuscript was written by Masafumi Ishigaki, and all authors commented on previous versions of the manuscript. All the authors have read and approved the final version of the manuscript.

Data Availability The datasets generated in this study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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