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Monitoring VLBI Instrumentation for Accurate Terrestrial Reference Frames

Karine Le Bail, Masafumi Ishigaki, Tobias Nilsson, and Rüdiger Haas

Abstract

The International Terrestrial Reference Frame (ITRF) is realized by a global network of stations representing the four space geodetic techniques of VLBI, GNSS, SLR and DORIS. The technique-specific networks are combined using constraints such as local ties at colocation sites, and the assumption that station velocities and seasonal variations are identical for all techniques at a given site. Station motion is modeled primarily with linear trends to represent tectonic motion and glacial isostatic adjustment, complemented by post-seismic deformation models where necessary and applicable. Discontinuities are introduced to capture reference point changes associated with maintenance activities, including rail replacements at VLBI telescopes or equipment changes for GNSS and DORIS.

The ITRF2020 revealed a systematic drift in the intrinsic VLBI scale, with the VLBI legacy S/X station in Ny-Ålesund contributing roughly 50% of the effect. The remaining causes are currently being investigated by an International VLBI Service for Geodesy and Astrometry (IVS) working group, whose mandate covers several potential contributors to the drift; one of its specific areas of focus concerns station- and network-level effects. Missing or unmodeled discontinuities in station time series have the potential to degrade both the accuracy and the long-term stability of the terrestrial reference frame.

This study underscores the importance of detailed monitoring of VLBI instrumentation and demonstrates the impact of unmodeled equipment changes on scale accuracy. Using four VLBI legacy S/X stations (Tsukuba in Japan, Matera in Italy, Wettzell in Germany, and Zelenchukskaya in Russia) that underwent major repairs not represented in the ITRF2020 processing, we show that an additional 20% of the VLBI scale drift can be explained when these discontinuities are applied.

These results highlight that achieving the Global Geodetic Observing System (GGOS) goals, 1 mm accuracy and 0.1 mm/yr stability for the terrestrial reference frame, requires precise documentation and modeling of instrument behavior during maintenance and repair activities.

Keywords

ITRF2020 · Scale · Station monitoring · VLBI

K. Le Bail (✉) · R. Haas
Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, Onsala, Sweden
e-mail: karine.lebail@chalmers.se; rudiger.haas@chalmers.se

M. Ishigaki
Geodetic Department, Geospatial Information Authority of Japan, Tsukuba, Ibaraki, Japan
e-mail: ishigaki-m96bd@mlit.go.jp

T. Nilsson
Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, Onsala, Sweden

Lantmäteriet, Gävle, Sweden
e-mail: jan-tobias.nilsson@lm.se

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1 Introduction

The International Terrestrial Reference Frame (ITRF) is realized by a combination of the four space geodetic techniques: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). In ITRF2020 Altamimi et al. (2023), station motion is represented through an augmented modeling approach that includes piecewise linear functions, annual and semi-annual terms, and post-seismic deformation (PSD) models for sites affected by major earthquakes. Discontinuities are introduced to account for potential changes in station positions and/or velocities arising from maintenance or equipment interventions. Linear velocities and seasonal terms are constrained except when a nonlinear motion is detected.

A systematic drift in the VLBI scale identified in ITRF2020 prompted the International VLBI Service for Geodesy and Astrometry (IVS) to establish a dedicated Task Force to investigate its origin. The group found that most of the drift observed in the ITRF2020 VLBI scale after 2013.75 could be attributed to a combination of factors, including different deformation modeling approaches and various changes in VLBI equipment at several stations within the IVS network (see Le Bail et al. 2025, Ishigaki et al. 2025). In October 2024, this effort transitioned into IVS Working Group 9 (WG9), and the investigation continues.

The present study aims to support the refinement of future ITRF realizations by identifying missing discontinuities and potential changes in station velocities within the IVS network. This work directly contributes to the Global Geodetic Observing System (GGOS) goals of achieving a terrestrial reference frame accuracy of 1 mm and long-term stability at the 0.1 mm/year level.

Section 2 describes the data used and outlines the combination strategy applied with the CATREF software. Section 3 examines the case of the Ny-Ålesund VLBI station, while Sect. 4 investigates four legacy S/X stations whose unmodeled repairs may affect the VLBI scale.

2 VLBI Data and Scale Factor Estimation Strategy

The VLBI data used in this study are the official IVS contribution to ITRF2020 provided by the IVS Combination Center (Hellmers et al. 2022). The data set comprises 6,228 session-wise files delivered in SINEX format, spanning the period 1979.00–2021.00.

To derive the scale factor time series, we adopted the same general strategy as the ITRS Center for ITRF2020 and processed the data using the CATREF software (Altamimi et al. 2023). Our analysis is restricted to a single-technique solution, based solely on the IVS combined SINEX files. Within CATREF, a minimally constrained combination strategy was applied, imposing standard no-net-translation (NNT) and no-net-rotation (NNR) datum conditions on station positions at the reference epoch, realized through the selected core stations. These core stations are selected based on long-term stability, data continuity, and the absence of known unmodelled discontinuities. The list of core stations defining the datum, shown in the map in Fig. 1, along with the station discontinuity information and the post-seismic deformation (PSD) models used in this study, were taken from the official ITRF2020 input files; PSD corrections consistent with those used in ITRF2020, based on models derived from GNSS time series at the affected sites, were applied where required. Station positions, velocities, and seasonal signals were estimated. This yielded an intrinsic IVS VLBI-only solution.

For each session-wise VLBI solution, we then estimated the seven Helmert transformation parameters relative to this intrinsic solution, using the set of core stations defining the session datum. The scale factors discussed in this study are obtained from these transformations.

Each ITRF realization provides station position and velocity discontinuities in SINEX format. These discontinuities reflect a variety of causes, including instrumental interventions, equipment changes, structural adjustments, or detected nonlinear motion. In this study, we used both the ITRF2020 (Altamimi et al. 2022) and ITRF2020-u2023 discontinuity files (Altamimi et al. 2024), which we further modified to incorporate additional discontinuities identified in our analysis. Using these updated inputs, we computed the corresponding scale-factor time series and evaluated the scale drifts over the interval 2013.75–2021.00.

As a reference case, we first reproduced the ITRF2020 processing strategy with CATREF (top panel of Fig. 2) and estimated the drift over 2013.75–2021.00 (Table 1). This case serves as a reference against which subsequent tests are compared.

Because this study relies exclusively on VLBI SINEX files, the results represent the behavior of VLBI alone. They cannot be directly compared with the final multi-technique ITRF2020 realization, which incorporates GNSS, SLR, and DORIS data as well as additional constraints such as local ties. All results presented herein therefore reflect the VLBI-only contribution.

For clarity, all CATREF-derived scale factor time series are presented in Fig. 2, and the corresponding drift estimates for the period 2013.75–2021.00 are summarized in Table 1. Dates referring to station events follow the ITRF convention of year and day of year, and are expressed throughout this manuscript in the format YYYY–DOY.

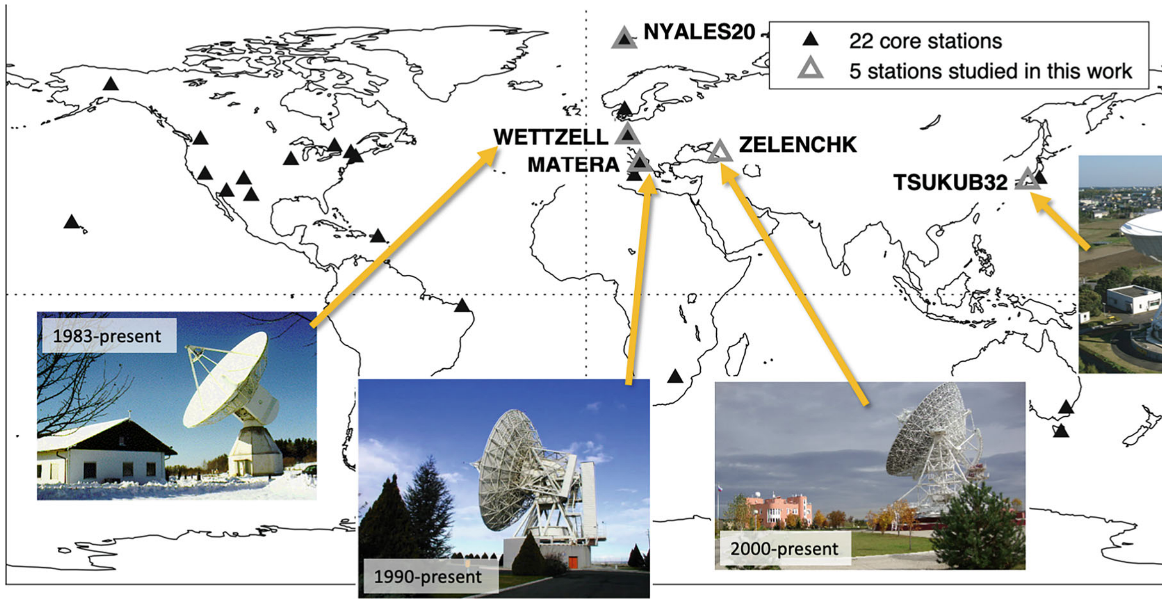

Fig. 1 Geographical distribution of the 22 core stations used in CATREF (black filled triangles). The five legacy S/X VLBI stations analyzed in this study (NYALES20, TSUKUB32, MATERA, WETTZELL, and ZELENCHK) are highlighted; ZELENCHK and TSUKUB32 are not part of the core station set. Photographs are courtesy of the IVS Annual Reports

3 Consistency Analysis of VLBI Station NYALES20 and Colocated GNSS Station NYA1

The VLBI antenna NYALES20 is colocated with several GNSS stations at the geodetic site in Ny-Ålesund, Svalbard, Norway including the well-monitored station NYA1. Figure 3 illustrates the relative positions of the two instruments. To evaluate the internal consistency of the ITRF2020 modeling at this site, we compared the ITRF2020 positions and velocities of NYALES20 with those of NYA1.

In the ITRF2020 realization, NYA1 is represented by three velocity segments, whereas NYALES20 is modeled with a single constant velocity over its full operational period. For NYA1, a position discontinuity is introduced at epoch 1999–153 to reflect an antenna change affecting only the reference point. Two subsequent velocity changes, at epochs 2004–186 and 2016–233, account for nonlinear behavior identified in the GNSS residuals. The resulting vertical velocities for the three NYA1 intervals are 10.32 ± 0.46 mm/yr, 10.25 ± 0.10 mm/yr, and 12.77 ± 0.31 mm/yr. By contrast, NYALES20, which has been operational since October 1994, is modeled in ITRF2020 with a single vertical velocity of 10.55 ± 0.09 mm/yr (Table 2).

To ensure consistency between the colocated techniques, we introduced two position discontinuities for NYALES20 at the same epochs as the non-linearities modeled for NYA1 in ITRF2020, namely 2004–186 and 2016–233. Using CATREF, we re-estimated the NYALES20 velocities without constraining continuity across these epochs. The resulting three vertical velocities are 9.82 ± 0.13 mm/yr, 9.99 ± 0.09 mm/yr, and 11.25 ± 0.49 mm/yr (Table 3 and Fig. 4). These values are statistically consistent with the corresponding NYA1 velocities within the standard deviation.

The resulting scale factor time series and the drift estimate for 2013.75–2021.00 are shown in Fig. 2 and Table 1. Introducing the two discontinuities for NYALES20 reduces the scale drift from 0.618±0.064 mm/yr to 0.330±0.061 mm/yr. This finding aligns with Kern et al. (2025), which identified NYALES20 as the dominant contributor to the VLBI scale drift. Previous studies have also emphasized the influence of present-day ice mass loss on geodetic sites in Svalbard; for example, Kierulf et al. (2022) proposed a piecewise linear model for the vertical component of NYALES20 to account for such effects.

The ITRF2020-u2023 update Altamimi et al. (2024), released in 2024, extends the ITRF2020 series by three years and introduces several new discontinuities, including two earthquakes (impacting, among others, ZELENCHK at epoch 2023–037 and KP-VLBA at epoch 2010–094), a 2020 discontinuity affecting both FD-VLBA and OV-VLBA at epoch 2020–267, a 2016 data-gapdiscontinuity

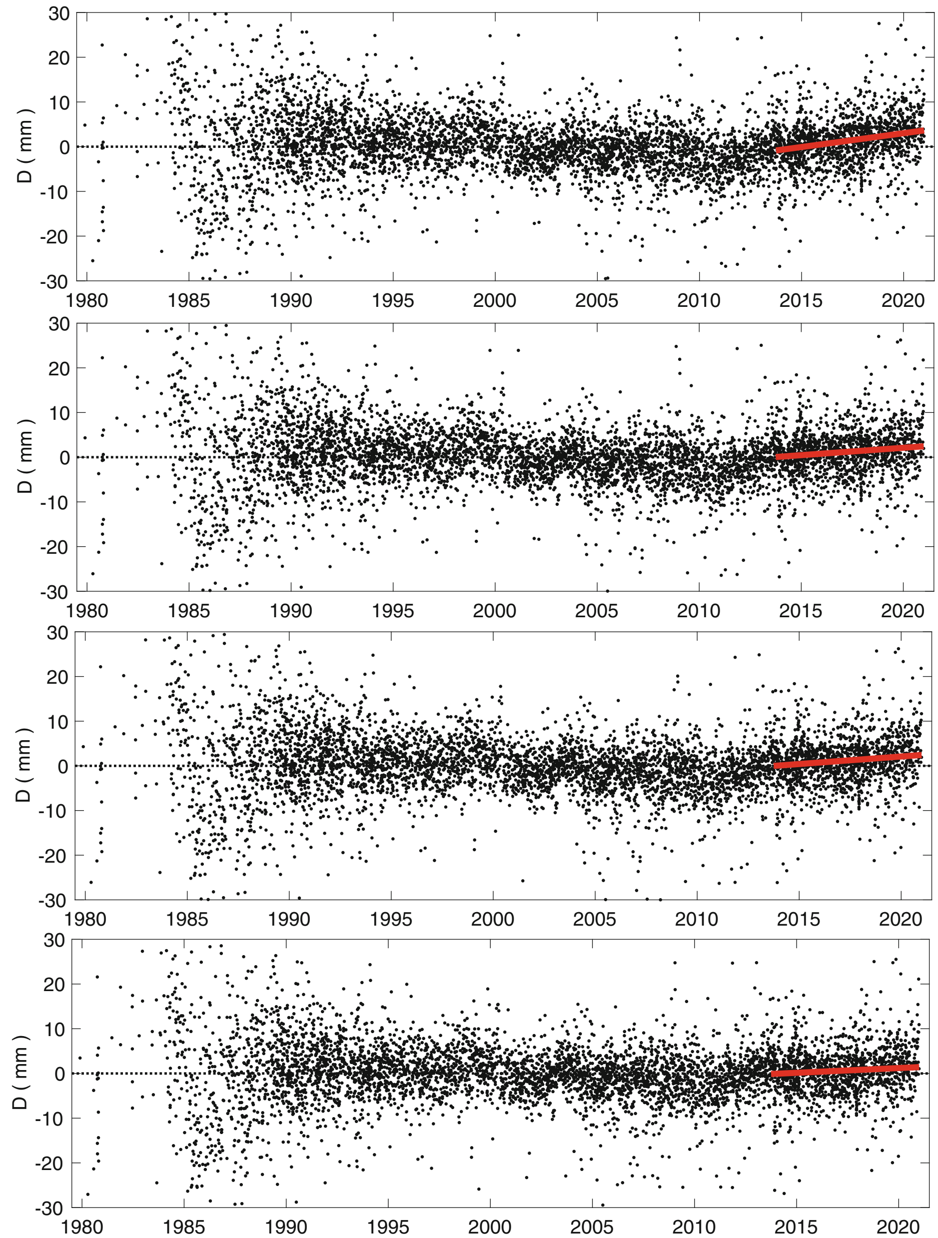

Fig. 2 Scale factor time series for the period 1979.00–2021.00 derived from the IVS Combination Center contribution to ITRF2020. The four panels (top to bottom) show CATREF solutions using: (1) the original ITRF2020 discontinuity list; (2) the ITRF2020 list supplemented with two additional discontinuities for the VLBI station NYALES20 (see Sect. 2); (3) the original ITRF2020-u2023 discontinuity list; and (4) the ITRF2020-u2023 list supplemented with seven additional discontinuities identified in Sect. 3

(epoch 2016–288) and a 2021 nonlinearity (epoch 2021–001) for HART15M. Importantly, the update also applies to NYALES20 the same nonlinearity epochs as modeled for NYA1. When applying the ITRF2020-u2023 discontinuity file in CATREF, the resulting NYALES20 vertical velocities agree well with those obtained from our test using the two GNSS-based discontinuities (Table 3). The corresponding scale factor series and drift estimates are shown in Fig. 2 and Table 1.

Table 1 Estimated VLBI scale factor drifts (2013.75–2021.00) obtained from the four CATREF solutions presented in Fig. 2, each based on a different discontinuity file

Discontinuity file	Additional station events	Drift (mm/yr) 2013.75–2021.00
ITRF2020	None	0.618 ± 0.064
ITRF2020	NYALES20 (2)	0.330 ± 0.061
ITRF2020-u2023	None	0.337 ± 0.061
ITRF2020-u2023	4 STATIONS (7)	0.212 ± 0.060

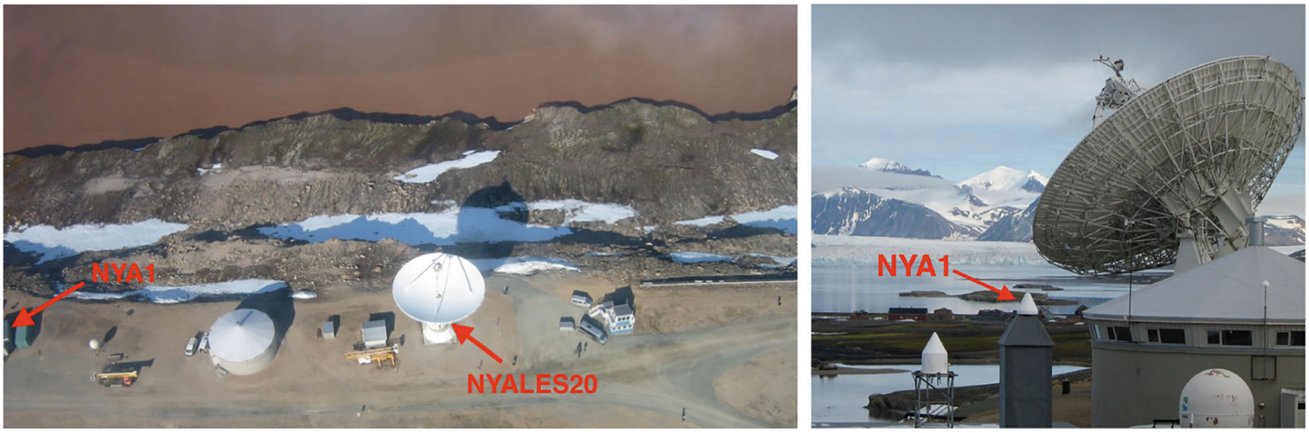

Fig. 3 Photos of part of the Ny-Ålesund geodetic core site, including the VLBI station NYALES20 (telescope with white dish in the middle of the picture on the left) and the GNSS receiver NYA1 (building on the left of the picture). Credit: R. Haas

Table 2 Z-component velocities for VLBI station NYALES20 and GNSS station NYA1 at the Ny-Ålesund geodetic site (Svalbard), as published in the ITRF2020 discontinuity and solution files (Altamimi et al. 2024)

Data span	Station	VZ (mm/y)
00:000–00:000	VLBI NYALES20	10.55 ± 0.09
00:000–99:153	GNSS NYA1	10.32 ± 0.46
99:153–04:186	GNSS NYA1	10.32 ± 0.46
04:186–16.233	GNSS NYA1	10.25 ± 0.10
16.233–00:000	GNSS NYA1	12.77 ± 0.31

4 Impact of Legacy S/X Antenna Repairs on VLBI Scale Stability

The VLBI legacy S/X network includes some of the oldest operational antennas, several of which have been in service for several decades. Aging structural components, particularly azimuth rails and antenna foundations, have required major repairs that can induce shifts in the reference point. Such unmodeled changes have the potential to affect station positions, velocities, and ultimately the VLBI scale. In this study, we investigated four legacy stations that underwent significant rail or foundation repairs: TSUKUB32 (Japan, now dismantled), MATERA (Italy), WETTZELL (Germany), and ZELENCHK (Russia) (Fig. 1). Dates and descriptions of the repairs were extracted from IVS annual and biennial reports.

- TSUKUB32 (Japan). Data used cover the period 1998–176 – 2016–363. Two major events affected the antenna structure:
  1. April 1999 – Azimuth rail replacement. Structural failure of the original rail required installation of a new, heavier rail, leading to a documented +43.7 mm shift in the reference point height (see Fukuzaki (2001)). Because the initial operational period before the replacement was less than one year, we constrained the velocity to remain continuous across the event and introduced a position discontinuity at epoch 1999–091.
  2. May 2013 – Antenna base subsidence. Inspections revealed gaps beneath the rail sole plates causing measurable subsidence (up to 3.5 mm). The base was stabilized by re-grouting (see Wakasugi et al. (2014), Wakasugi (2013)). To reflect the possible subsidence effect, we introduce a discontinuity at epoch 2013–121, both in position and in velocity.
- MATERA (Italy) Data used cover the period: 1990–277 – 2020–364. The station experienced long-term rail degradation:
  - 2004–2015 – Detection of abnormal rail movement leading to complete rail replacement. Rail misalignment was detected in 2003, indicating structural issues with both the rail and underlying concrete (see Colucci et al. (2005)). Following progressive deterioration, the full rail system was finally replaced. Due to the fact of the misalignment of the rail and the total rail replacement, we introduced two discontinuities (position and velocity) at epochs 2004–001 and 2015–258.
- WETTZELL (Germany) Data used cover the period: 1983–320 – 2020–365.
  - September 2010 – Severe elevation bearing damage was discovered, requiring disassembly of the antenna, replacement of the bearings, and photogrammetric readjustment of the reflector surface (see Neidhardt et al. (2011)). This intervention likely altered the reference point geometry. We introduced a position and velocity discontinuity at epoch 2010–244.
- ZELENCHK (Russia) Data used cover the period: 2005–356 – 2020–339.

Table 3 Vertical velocities of the VLBI station NYALES20 at the Ny-Ålesund geodetic site, derived from VLBI-only intrinsic solutions computed with CATREF. The first row corresponds to the original ITRF2020 discontinuity file. The next three rows show the velocities obtained when adding two additional discontinuities associated with detected nonlinearities, modeled from NYA1. The final three rows present the results obtained using the ITRF2020-u2023 discontinuity file, also supplemented with the same two non-linearity discontinuities

Discontinuity files	Data span	Station	VZ (mm/y)
ITRF2020	00:000–00:000	VLBI NYALES20	10.55 ± 0.06
ITRF2020 + 2	00:000–04:186	VLBI NYALES20	9.82 ± 0.13
ITRF2020 + 2	04:186–16.233	VLBI NYALES20	9.99 ± 0.09
ITRF2020 + 2	16.233–00:000	VLBI NYALES20	11.25 ± 0.49
ITRF2020-u2023	00:000–04:186	VLBI NYALES20	9.83 ± 0.13
ITRF2020-u2023	04:186–16.233	VLBI NYALES20	10.02 ± 0.09
ITRF2020-u2023	16.233–00:000	VLBI NYALES20	11.33 ± 0.49

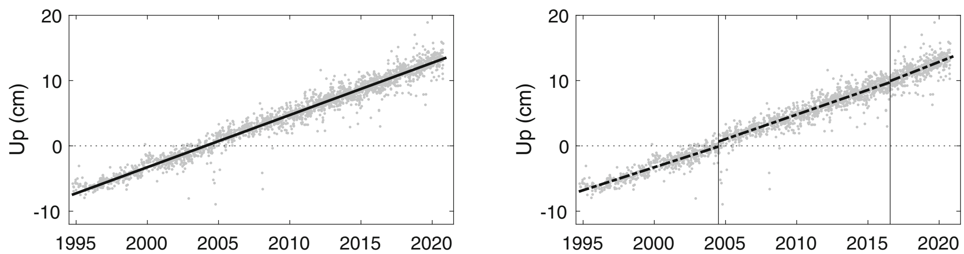

Fig. 4 The Up component (in cm) for NYALES20, derived from the CATREF analysis (ITRF kinematic model) over the period 1994.8–2021.0, is shown as gray dots. The vertical linear velocity estimated from VLBI-only intrinsic solutions computed with CATREF is shown as a solid black line in the left panel when the original ITRF2020 discontinuity file is used, and as three dashed black lines in the right panel when two additional discontinuities (indicated by solid black horizontal lines) are introduced to account for nonlinear behavior detected at the colocated GNSS station NYA1. Note that the values listed in Table 3 correspond to the Z-component in mm/yr, whereas the plots display the Up component in cm

– July–September 2020 – Rail and foundation repairs. Major repairs were carried out on the concrete foundation supporting two sections of the azimuth rail Ivanov et al. (2021). Structural degradation had resulted in 2–3 mm of rail sagging. The damaged concrete and embedded elements were replaced, and the rail was restored to its design height. A position and velocity discontinuity was introduced at epoch 2020–189.

To assess the cumulative impact of these repair-related events, we repeated the analysis using the ITRF2020-u2023 discontinuity file together with the seven additional discontinuities described above. The resulting scale-factor time series and drift estimates are shown in Fig. 2 and Table 1. Incorporating these seven events reduces the VLBI scale drift to 0.212±0.060 mm/yr, demonstrating that unmodeled structural changes at legacy S/X stations constitute a measurable and non-negligible contribution to the VLBI scale instability.

The improvement in the 2013.75–2021.00 drift, however, remains limited compared to the effect obtained when properly modeling NYALES20. This is expected, as most of the newly introduced discontinuities fall outside the interval over which the scale drift is estimated. Only a small number of events, one in 2013 for TSUKUB32, and one in 2015 for MATERA, occur within the drift-estimation window. As a result, their effect on the scale appears mainly through small adjustments to the overall network geometry across the full 1979.00–2021.00 period, rather than through a direct change in the scale trend during the shorter drift-estimation interval.

5 Discussion

Our results show that several unmodeled station events, particularly equipment interventions and structural repairs, produce measurable changes in station velocities and directly affect the VLBI scale. For NYALES20, introducing discontinuities consistent with the colocated GNSS station NYA1, interpreted as a response to ongoing ice mass loss in Svalbard, reduced the VLBI scale drift by nearly half, demonstrating that this geophysical signal influences VLBI observations in the same way as GNSS. One possible explanation is the strategic role of this site within the VLBI core network, as one of the northernmost stations, where unmodeled vertical motions may propagate efficiently into global scale determination. Similarly, accounting for seven major repair events at legacy S/X stations further lowered the drift. These findings confirm that incomplete modeling of station behavior contributes significantly to the scale instability identified in ITRF2020.

Beyond individual stations, the comparison of VLBI-only solutions highlights the importance of monitoring geodetic core sites as integrated systems. Differences in modeled velocities between colocated instruments (VLBI, GNSS, SLR, DORIS) can reveal inconsistencies or unrecognized events, as demonstrated by NYALES20 and in previous multi-technique comparisons, e.g., De La Serve et al. (2023). Such discrepancies emphasize the need for coordinated interpretation of position time series and for updating deformation models, particularly in regions affected by post-seismic deformation or present-day ice mass changes.

Local ties also remain essential for ensuring consistency between techniques. Traditional survey methods and more recent innovative approaches, such as interferometric ties Niell et al. (2021), offer valuable information to strengthen the inter-technique geometry.

Overall, our analysis indicates that undocumented station-related changes can lead to unmodeled reference point position changes, which in turn propagate into the scale solution. Improving the operational and reporting framework is, therefore, necessary to avoid unmodeled discontinuities in future ITRF realizations.

However, identifying significant station events remains a major challenge. Maintenance actions, equipment interventions, or structural changes are not systematically reported, and valuable information is often lost. Within the framework of IVS Working Group 9 (WG9), we work closely with the IVS Network Coordinator to raise awareness among station managers and technical staff about the importance of documenting and reporting all station-related events, regardless of scale. Even minor interventions can alter the reference point and must be registered.

6 Conclusion

This study demonstrates that incorporating appropriate discontinuities, particularly those associated with equipment interventions and structural repairs, substantially improves the stability of the VLBI scale. Accurate identification and modeling of station events remain essential. This includes systematic tracking of VLBI equipment changes, careful evaluation of post-seismic deformation following major earthquakes, and continuous interaction with the ITRS Center to ensure that station-specific information is correctly implemented in future ITRF realizations.

Achieving the GGOS targets of 1 mm accuracy and 0.1 mm/yr stability requires systematic identification and reporting of station events. Regular local-tie surveys, continuous monitoring of deformation at core sites, and timely updates of post-seismic and non-linear motion models are essential components of this process. Particular attention must be given to regions where present-day ice mass changes introduce complex, irregular deformation patterns, such as Svalbard.

A key challenge is the consolidation of all relevant site information, technical reports, survey results, maintenance logs, and station event notifications, into a single, accessible platform. Treating a geodetic core site as an integrated system rather than a collection of independent instruments is essential for achieving the accuracy and long-term stability targeted by GGOS.

In this work, we focused on ITRF2020 and the IVS Combination Center contribution to assess the VLBI scale drift over 2013.75–2021.00. Further analysis (see Le Bail et al. (2024), Le Bail et al. (2025)) is ongoing to better understand modelling and processing aspects influencing recent ITRF update solutions. Continued cross-technique collaboration will be necessary to fully resolve the VLBI scale discrepancy.

The study also illustrates that scale estimates can be sensitive to how discontinuities and time-dependent station behavior are represented. Further inter-comparisons with other TRF realizations, such as DTRF (Seitz et al. 2023) and JTRF (Gross et al. 2023), would provide useful context for interpreting these effects, but are beyond the scope of the present contribution.

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The files used by CATREF in this study are available via the ITRF2020 resources at https://itrf.ign.fr/en/solutions/itrf2020. These include the core station list (datum definition), the discontinuity files, and the post-seismic deformation model parameter file.

The IVS Annual and Biennial reports are available on the IVS Coordinating Center website: https://ivscc.gsfc.nasa.gov/publications/annualreport.html.

Competing Interests The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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