Geophysical Journal International

Geophys. J. Int. (2016) **204,** 480–487 doi: 10.1093/gji/ggv455

GJI Gravity, geodesy and tides

Impacts of GNSS position offsets on global frame stability

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Accepted 2015 October 16. Received 2015 October 15; in original form 2015 August 24

SUMMARY

While it has been known for some time that offsets in the time-series of Global Navigation Satellite System (GNSS) position estimates degrade station velocity determinations, the magnitude of the effect has not been clear. Using products of the International GNSS Service (IGS), we assess the impact empirically by injecting progressively larger numbers of artificial offsets and solving for a series of long-term secular GNSS frames. Our results show that the stability of the IGS global frame datum is fairly robust, with significant effects at the formal error level only for the R_x (and Y-pole) and R_z rotational orientations. On the other hand, station velocity estimates are more seriously affected, especially the vertical component. For the typical IGS station, the mean vertical rate uncertainty is already limited to 0.34 mm yr^{-1} for the current set of position discontinuities. If the number of breaks doubles, which might occur using newer detection schemes, then that uncertainty will worsen by ∼40 per cent to 0.48 mm yr^{-1}. This error source is generally a more important component of realistic velocity uncertainties than any other, including accounting for temporal correlations in the GNSS data. The only way to improve future GNSS velocity estimates is to severely limit manmade displacements at the tracking stations.

Key words: Time-series analysis; Satellite geodesy; Reference systems; Sea level change; Earth rotation variations; Plate motions.

1 INTRODUCTION AND BACKGROUND

Continuously operating Global Navigation Satellite System (GNSS) tracking stations (observing mainly Global Positioning System or GPS satellites) are being deployed ever more widely and the data processing is increasingly automated. For instance, the Nevada Geodetic Laboratory alone reports daily positions for more than 13 000 globally distributed GPS stations (at geodesy.unr.edu). One of the enduring obstacles to full automation has been the detection of discontinuities in time-series of station positions, which can be caused by natural (e.g. earthquakes) and human (e.g. equipment changes) events. Failing to account for such offsets in the data analysis will obviously bias velocity estimates, a key GNSS product for many user applications, such as for geodynamics.

For context, in the second reprocessing by the International GNSS Service (IGS), at least 2090 position offsets were found among 1176 stations having >700 days of data each during 1994.0 till 2015.0, out of 1848 total stations (Rebischung *et al.* 2015). Of the average 1.8 discontinuities per station, 49 per cent were caused by documented equipment changes, 31 per cent by earthquakes and 20 per cent due to unknown causes. Algorithms and software tools to detect offsets in position time-series have proliferated and become impressively sensitive, depending on the background measurement noise, but blind tests by Gazeaux *et al.* (2013) showed that manual methods still almost always excel over automated schemes. P. Rebischung (private communication, 2015) confirmed that visual inspection was used for the final verification of all IGS 2nd reprocessing discontinuities.

In fitting long station position time-series to determine secular rates in a global reference frame solution, a known discontinuity is accommodated by estimating a 3-D position offset at the break epoch while normally assuming that the velocity before and after the offset is unchanged. (The latter assumption is invalid, for example, in the near field of strong earthquakes where more sophisticated models are required.) Williams (2003) characterized the inflationary impact of the extra offset parameters on estimated station velocity uncertainties, depending on the power-law noise type in the GNSS measurements. Undetected (hence unmodeled) offsets in the time-series, usually too small to be reliably distinguished from noise, contribute a random walk error to the GNSS time-series, which are otherwise dominated by flicker noise (Santamaría-Gómez *et al.* 2011). Williams (2003) concluded with a plea for station operators to minimize any tampering with GNSS equipment while faithfully logging all local changes. That appeal has been largely ignored, as there seems to be little concern with position offsets because data analysts routinely estimate them. As just one example, the important IGS reference and International Terrestrial Reference Frame (ITRF) colocation station WES2 lists

25 receiver updates and 15 antenna swaps during its 22.5-yr lifetime (ftp.igs.org/pub/station/log/wes2_20150326.log). Many of the receiver mods were to revise firmware but 15 involved hardware changes. As a result, there are seven official discontinuities for WES2, due to receiver and antenna changes in 1994, 1997, 1998, 2000, 2001, 2002 and 2013. Even seemingly benign configuration changes can cause observable displacements, as Wyatt & Agnew (2005) showed using GPS and conventional survey data from a close pair of long-running stations, each outfitted with ultra-stable drilled-braced monuments and thorough local documentation. Following Wyatt & Agnew (2005), operators of sites most used in the global reference network could do well by installing two or three well-monumented stations nearby (within 100 m). This could provide a means for tracking offsets at the reference station, which could be applied instead of purely empirical offset parameters when estimating velocities. Unfortunately, the results are not always straightforward to relate to geocentric positions which usually depend differently on observables and propagation calculations, as is the experience at Wettzell (Steigenberger *et al.* 2010).

We return to this problem with two new goals. First, we aim to assess the magnitude of the existing level of discontinuities on IGS products. While Williams (2003) computed the functional dependence of station velocity uncertainties on the number of offsets added (for different assumed background noise types), he did not determine the actual magnitude of current impacts. Second, we want to evaluate the consequences of local position offsets on the overall stability of the global terrestrial reference frame itself. A position discontinuity at any given station can be estimated in a long-term linear reference frame solution only if there are sufficient numbers of other stations observing simultaneously that do not suffer breaks at the same time. Obviously, as the number of offsets increases, there must be some negative effects for the global frame stability. If, in the most extreme case, all stations experienced breaks at the same time, there would be no way to relate the global frames before and after such a catastrophic event. That circumstance partially arises sometimes (Tregoning *et al.* 2013) because some major earthquakes cause widespread displacements (e.g. Peru 2001, Alaska 2002, Indonesia 2004, Chile 2010, Japan 2011). In addition, a similar situation can arise when operators of national or large-scale networks sometimes opt to change all their station configurations at nearly the same time. One expects there should be some smooth degradation of the overall frame stability with increasing station offsets, and that we seek to quantify.

2 ANALYSIS APPROACH

We adopt a purely empirical approach to assess the effects of GNSS offsets by starting with the regular operational time-series of IGS global frames, each including observations for one week. They cover the period from 1994.0 till 2013.8, which includes the first IGS reprocessing until its end at 2007.9 followed by consistent regular operational products afterward (igscb.jpl.nasa.gov/pipermail/igsmail/2011/006393.html). A total of 1134 stations has been considered, with an average data span of 8.2 yr (standard deviation 6.1 yr) and an average uninterrupted span per station of about 3 yr. Geocentric station coordinates for each week and polar motion values for each day are included, together with full variance–covariance information in SINEX-format files (igscb.jpl.nasa.gov/igscb/data/format/sinex_v210_proposal.pdf). Similar procedures as for ITRF (Altamimi *et al.* 2011) have been followed to form a secular global reference frame (see chapter 4 of Petit & Luzum 2010) by stacking the weekly IGS solutions assuming generally linear (i.e. tectonic) station motions. The result is a set of global geocentric regularized station coordinates aligned to ITRF2008 at epoch 2005.0, their velocities and consistent daily polar motion values. The long-term stacking process adjusts the Helmert alignment of each weekly IGS input frame allowing for net rotations, origin translations and scale (radial) changes to achieve the most linear motions and smallest station residuals. The official set of station position discontinuities has been applied. These amount to about 0.9 offsets per station overall and about 0.6 offsets for each of the well distributed core IGS stations used for frame alignment (Rebischung *et al.* 2012). Fig. 1 shows how the breaks are distributed over time in the IGS reference network. We have used the CATREF software (Altamimi *et al.* 2002, 2007, 2011) and verified that the official IGS accumulated frame solution up to epoch 2013.8 was reproduced. This initial IGS-like stacking formed our baseline frame solution against which later solutions were compared.

Subsequently, additional artificial position offsets have been inserted at the midpoint of each continuous data segment and the stacking process repeated. These artificial offsets are inserted by adding offset parameters. Their magnitudes are not prescribed and have no impact on the results described below concerning the impact of estimating the offset parameters themselves; they are estimated from the data as is done with real disruptions. Note that according to Williams (2003), station velocity estimates are most strongly affected by midpoint (or nearly so) offsets if the background data noise is white or flicker, but does not depend on placement for random walk noise. This process was iteratively repeated with increasing numbers of discontinuities and shorter continuous data segments. Each iteration yielded geodetic results that were compared with the starting baseline solution that used the official set of IGS position discontinuities and their differences computed. This effort was very computationally challenging, with parameters for each iteration for up to 48 288 regularized station coordinates, an equal number of station velocities, 36 190 daily polar motion coordinates, 7238 weekly transformation parameters and the empirical offsets for all positional discontinuities. No new velocity discontinuities were introduced beyond those in the official IGS stacking.

To fill in trends more completely, rather than to consider only a doubling of offsets with each iteration, intermediate points were obtained by averaging two subsolutions. To illustrate how this was done, let us consider the intermediate point between the baseline (iter = 0) solution and that from the first full iteration (iter = 1), where the number of positional breaks doubled. The full network was used for both subsolutions. For the first of the two subsolutions in this case, positional breaks were introduced at the midpoint of the data spans in iter = 0 for half of the stations, randomly chosen. For the second subsolution, midpoint breaks were introduced for the other stations. The intermediate point (iter = 0.5) was computed by averaging the results from the two subsolutions between iter = 0 and iter = 1. Likewise, for the subsequent intermediate points (e.g. iter = 1.5, 2.5, 3.5, . . . , 15.5).

Motivated in part by the work of Williams (2003), our approach was chosen assuming that the quantitative impacts of the added artificial discontinuities would follow reasonably well-behaved forms that could be fit to the results. In this case, it should be possible to extrapolate to zero discontinuities to evaluate the size of the effects due to currently recognized offsets as well as to larger numbers in view of ongoing improvements in detecting previously unrecognized breaks (such as in the second reprocessing results).

Figure 1. The distribution of data and position offsets for the stations in the IGS list of IGb08 reference frame stations as a function of time. Each row displays a different station. Light red indicates that the site has data while light blue means there are data and the site is a 'core' IGS station with valid reference coordinates. Reference coordinates become invalid for different reasons, but typically it happens because a discontinuity occurred following the release of IGb08. Black dots mark epochs of discontinuities.

3 RESULTS FOR FRAME ORIGIN AND SCALE STABILITY

Fig. 2 shows the change in the weighted root-mean-squared (WRMS) differences of the weekly origin translation and scale parameters, compared to the baseline solution using the IGS official set of discontinuities, as a function of the average number of offsets per station per decade. The leftmost point in each panel ($x_{\rm now} = 0.898$ offsets per station per decade) is the baseline solution case and therefore all the WRMS changes are zero for that point. Each panel also shows the individual fit parameters for trends of the form $(a + b\sqrt{x})$ where x is the plot abscissa. This is the functional type one expects for random walk behaviour, which fits the empirical results reasonably well except less so for the scale changes. Even for extreme numbers of artificial position offsets, the impacts on the frame origin and scale stabilities remain rather minor.

It is important to note here that there is no obvious theoretical basis for fitting a square-root function to the WRMS changes for the transformation parameters (Fig. 2). In examining the plots visually, one might conclude that a linear function is more appropriate. Of course, there is also no obvious theoretical basis for a linear functional form either. In any case, we tested a linear fit (not shown) and found that the impact on the results is insignificant. The fit is slightly better for T_x and slightly worse for T_y, T_z and scale.

The y-intercept values for each square-root fit in Fig. 2 can be interpreted as the shift in results for the ideal situation if no offsets at all were present in the IGS time-series compared to the baseline solution case. That is,

$$(a + b\sqrt{x_{\rm now}}) - (a + b\sqrt{0}) = b\sqrt{x_{\rm now}}$$

gives the impacts of the current level of discontinuities. For the frame origin and scale, those impacts are insignificant at about the 1-sigma level of the formal errors: 0.09 ± 0.07 mm for T_x, 0.09 ± 0.05 mm for T_y, 0.08 ± 0.05 mm for T_z and 0.02 ± 0.02 ppb for scale.

4 RESULTS FOR FRAME ORIENTATION AND POLAR MOTION

Fig. 3 shows analogous results for the three weekly frame rotation components. Since rotations about the x and y axes are indistinguishable from corresponding (negative) shifts of the polar motion coordinates, Y-pole and X-pole respectively, the latter WRMS changes are also included. It can be seen that the two measures of frame orientation change are nearly identical, as they should be (though the frame rotations refer to weekly integrations while the polar motions are daily). For the R_x and R_z rotations, the fits are robust, which is not true for R_y. We assume that the insensitivity of R_y rotations (and X-pole) to increasing numbers of station position offsets is caused by relatively lesser land area (and hence IGS tracking stations) near the orthogonal x–z plane (namely, west Europe and west Africa), which can be seen visually using the map at webigs.ign.fr/en/tfcc/station/map/. On the other hand, R_x (and Y-pole) respond to stations scattered across North and South America as well as much of Asia. This difference in behaviour of the two components is consistent with the similar well-known disparity in geophysical excitation of polar motion, for like reasons of land/ocean distribution. The R_z dependency is especially robust since all stations not close to either pole can have an impact.

Following the same reasoning as for the frame translations and scale, the impact of current position offsets on the IGS frame rotations (and polar motion) are significant for two of the three components: 1.46 ± 3.34 µas for R_y/X-pole, 3.56 ± 1.98 µas for R_x/Y-pole and 4.06 ± 1.95 µas for R_z. Recall that 1 mm of horizontal displacement at the Earth's equator corresponds to 32.34 µas of rotation. So, while significant, the R_x and R_z effects are nonetheless small. However, the formal errors of the IGS polar motion estimates are only slightly larger (about 5 µas). So we find that even the current level of position offsets is a marginally significant source of systematic polar motion error for at least its Y component. (Larger sources of systematic polar motion error are described by Ray *et al.* 2014.)

5 RESULTS FOR STATION VELOCITY ESTIMATES

Fig. 4 shows how station velocity estimates are affected as the number of artificial position offsets increases. The functional fits are excellent for all three—east, north and up—local components. Based on increases over the y-intercepts of each component fit, the impact of the current number of IGS position offsets is significant, on average, for all three velocity components: 0.09 ± 0.02 mm yr^{-1} east, 0.09 ± 0.03 mm yr^{-1} north and 0.34 ± 0.10 mm yr^{-1} up. For reference, compare these impacts with the mean IGS formal velocity uncertainties: 0.14 mm yr^{-1} east, 0.14 mm yr^{-1} north and 0.26 mm yr^{-1} up. The vertical velocity impact is especially notable and significant.

6 DISCUSSION OF RESULTS

The present level of position discontinuities in the IGS operational products (about 0.9 offsets per station per decade and an average continuous data span of about 3 yr) does not appear to pose a serious threat to the stability of the IGS global terrestrial frame datum. Only the R_x (and Y-pole) and R_z orientations are significantly affected, at the level of their formal uncertainties. If the next IGS update leads to a doubling of the recognized position offsets, as is potentially possible based on the refined break detection methods used in the preliminary 2nd reprocessing results that have 1.8 offsets per station overall (Rebischung *et al.* 2015), the IGS frame stability will not be much worse except that the R_x and R_z rotational scatters will increase by 40 per cent. This mostly fortunate circumstance for the IGS is probably a direct result of the very large number of continuously operating GNSS stations available and their reasonably good global coverage.

The situation is much less benign for station velocity estimates. The horizontal velocities are hardly being affected by the current discontinuities, at a level smaller than their average formal errors. But if the number of breaks doubles, then the impact will approximate the horizontal velocity formal errors. The greatest concern, though, is the excess scatter in the vertical velocities due to the present breaks, at about 0.34 mm yr^{-1} on average and 30 per cent larger than the mean formal error. That would increase by 40 per cent to 0.48 mm yr^{-1} too if the future number of offsets doubles.

An earlier caveat should be repeated. Adding extra offsets at the midpoints of continuous data segments, as we have done, maximizes their impact (Williams 2003). If the actual distribution for any given station is highly unequal, then a better estimate of the velocity uncertainty might be obtained by considering the impact for the longest uninterrupted segment alone. At WES2, for instance, there were no breaks during its last 11 yr of data but 7 in the 8.8 yr before that.

It has long been recognized that the true accuracy of geodetic velocity estimates is not well represented by their formal errors

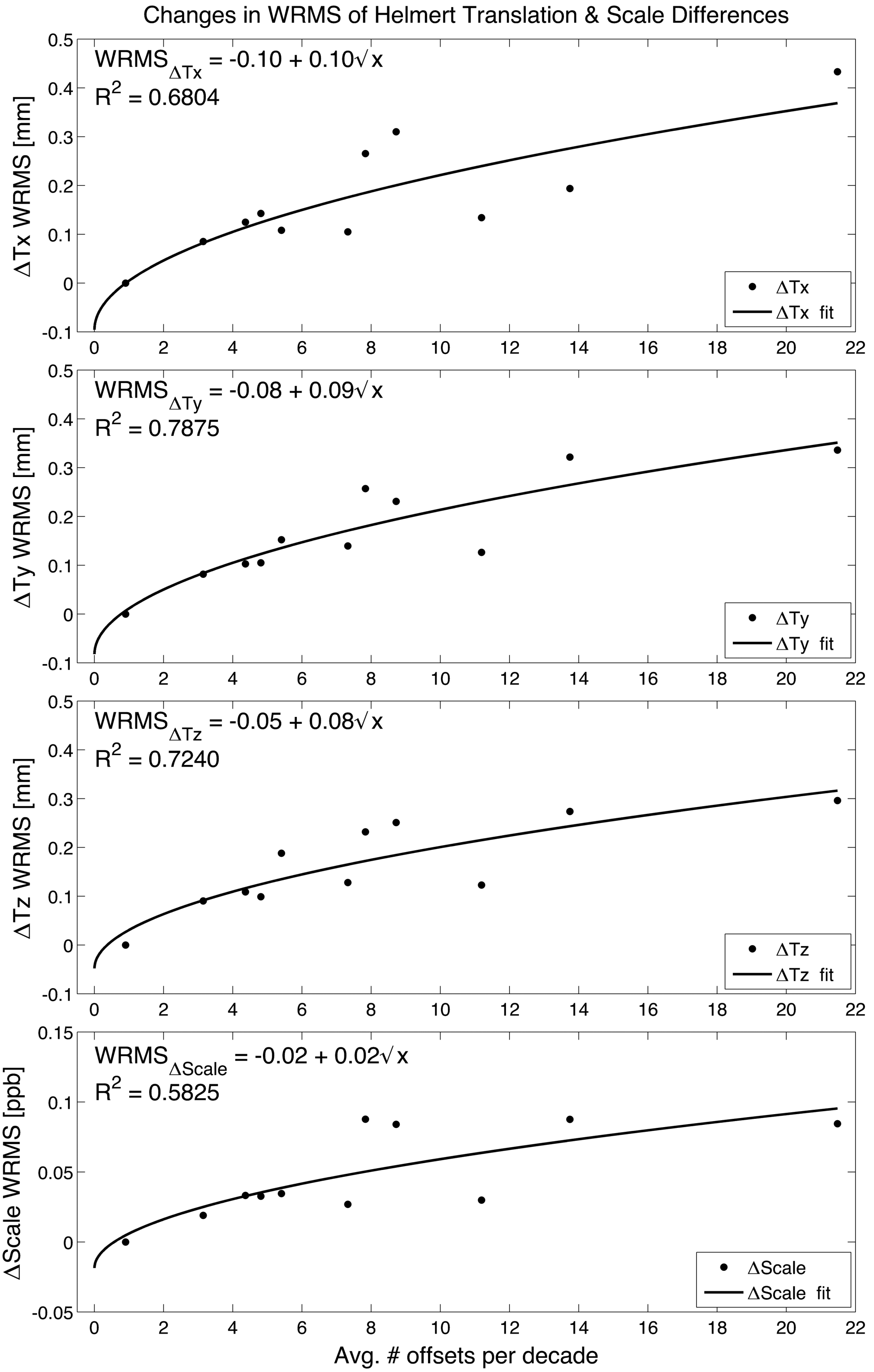

Figure 2. The variation in the scatter of weekly frame origins and scales as a function of increasingly numerous position discontinuities. From the top, panels show the behaviour for translation of the origin in the *x*-direction, in the *y*-direction and the *z*-direction, respectively. The bottom panel shows the corresponding growth in scatter of the weekly frame scales. Respective curve fit information is given in the top left plot corner for each Helmert component.

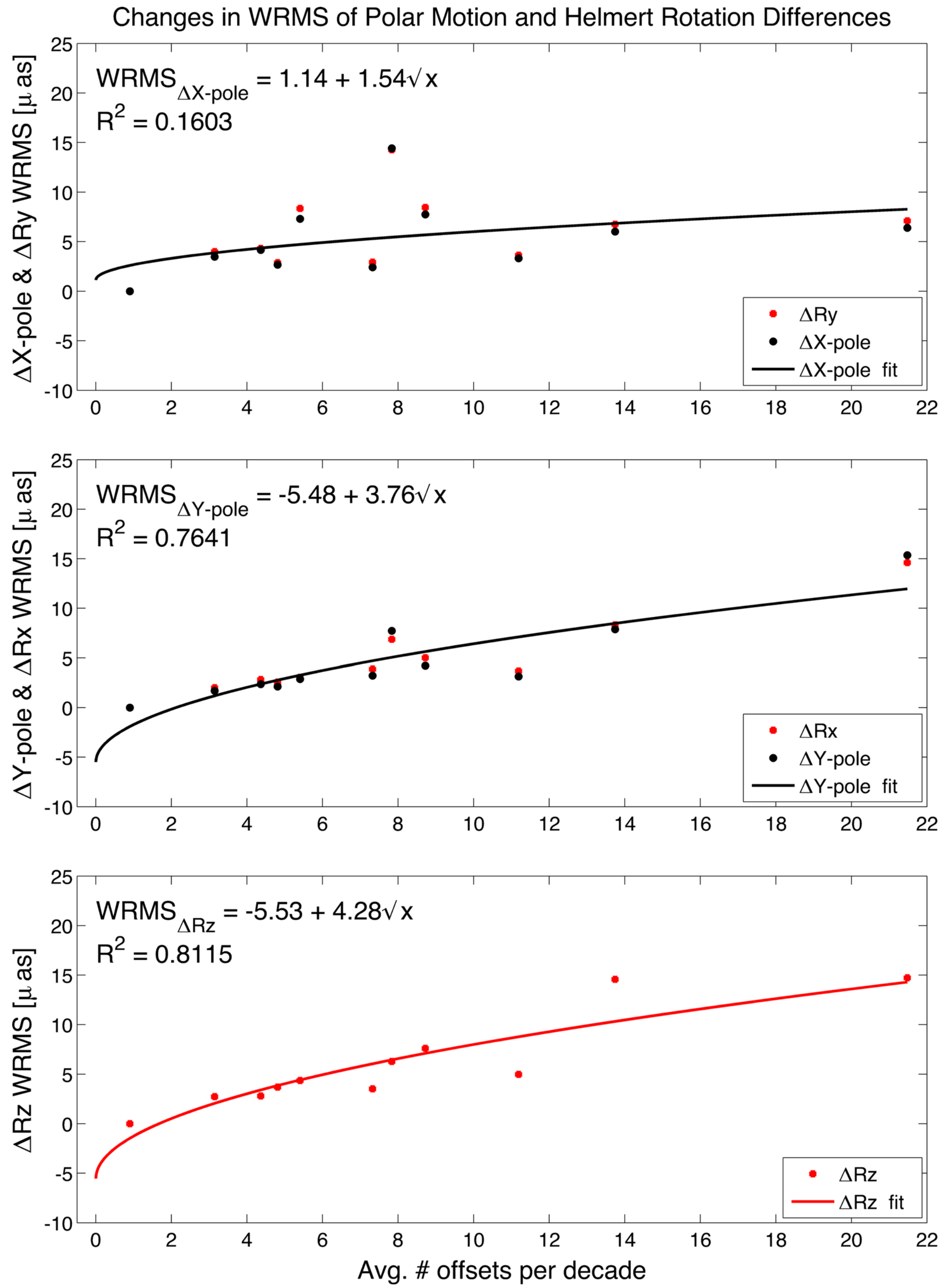

Figure 3. Analogous results as shown in Fig. 2 for the three components of frame rotation and the corresponding components of polar motion for the first two.

that assume white data noise (Johnson & Agnew 1995). Temporally correlated errors are largely to blame. Langbein & Johnson (1997) found that the presence of power-law noise in two-colour electronic distance measurement networks significantly impacted rate-of-deformation estimates. Zhang *et al.* (1997) found that GPS position time-series possess flicker noise (power proportional to inverse frequency) with white noise only at the shortest periods. Seasonal and other periodic signals are also pervasive. Accounting for the time correlation of GNSS position residuals inflates realistic velocity uncertainties compared to white noise formal errors and the accuracy improves (for continuous data) only as the inverse of the data span rather than as the span to the −3/2 power. In their study of homogeneously reprocessed GPS data Santamaría-Gómez *et al.* (2011) found the median vertical velocity uncertainty to be 0.34 mm yr^{-1}, several times larger than for uncorrelated data. The mean 0.34 mm yr^{-1} vertical velocity error our results imply due to position offsets is the same size and it will not be reduced by longer observing spans as long as the occurrence of new breaks continues at the past rate. In more recent work, Santamaría-Gómez & Mémin (2015) point out that interannual surface pressure loading caused

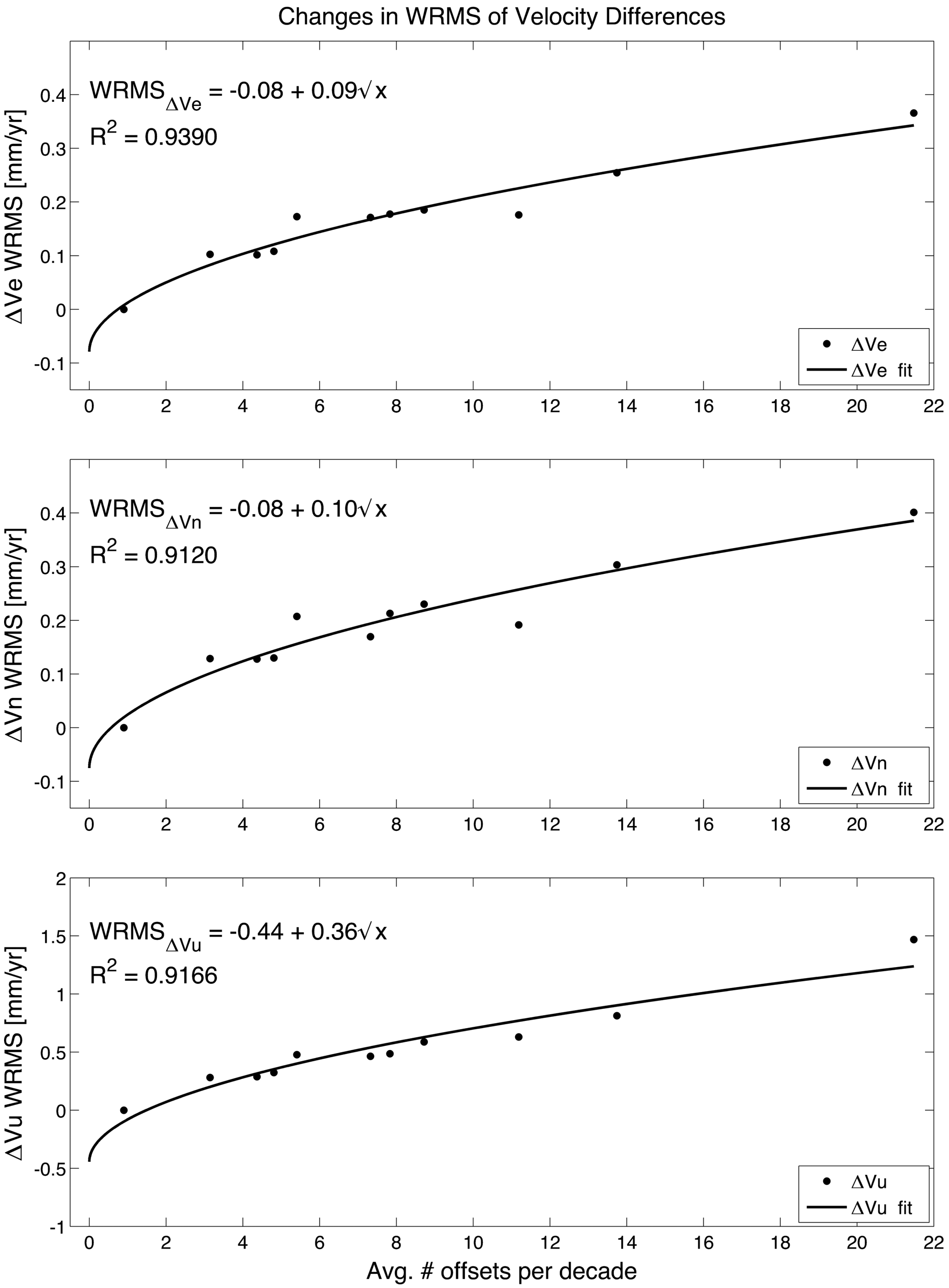

Figure 4. Similar to Figs 2 and 3, the average WRMS changes in station velocity estimates are shown for each local east (top) north (middle), up (bottom) component as a function of increasing numbers of position discontinuities.

by migration of geophysical fluids also biases vertical velocity estimates, depending on the length of the observing history. To reduce this effect below 0.4 mm yr^{-1} requires at least 4 yr of continuous data, on average. But in certain tropical areas, where hydrological loads are largest and most extensive, the required spans can reach 10 yr. Nevertheless, these errors do decrease as data accumulates, approximately as the inverse of the span, which is not true for the effect of position offsets.

The potential doubling of position offsets in the IGS 2nd reprocessing means that many jumps were undetected before and that ITRF2008 (Altamimi *et al.* 2011) and IGS08 (Rebischung *et al.* 2012) velocities could have been biased by some unknown amount due to those jumps. One may expect that accounting for the additional discontinuities would reduce the bias and result in more accurate velocities. However, the additional offset parameters will also inflate the velocity errors. In principle it might be possible to evaluate this trade-off between ignoring the smallest detectable offsets to avoid error inflation and risking a systematic velocity bias by using the random level shifts model of Williams (2003). It would require accumulating the occurrence statistics for the newly introduced offsets.

Finally, we note that strategies exist to estimate station velocities from position time-series using first differences without the need to identify discontinuities, such as the MIDAS estimator of G. Blewitt (private communication, 2015). But since this bypasses the station coordinates altogether, such approaches are not suited for global reference frame solutions that are by design intended to determine geocentric reference coordinates, including all the offset segments.

7 CONCLUSIONS

It is useful to put our new results into the larger context of user accuracy requirements. According to Plag & Pearlman (2009), the international geodetic community needs to achieve an ITRF accurate to 1 mm in its global datum and 0.1 mm yr^{-1} in its stability by the end of this decade in order to satisfy the demands for monitoring global change. While other factors block that goal at the moment, the instabilities to the ITRF datum caused by GNSS position offsets are not serious obstacles. However, rotational misalignments about the R_x (also Y-pole) and R_z axes reach about 0.12 mm already, which is small but significant, and they would increase if the number of future position offsets doubles.

The more important concern is the limit on vertical velocity accuracy, presently at 0.34 mm yr^{-1} on average (worse if future discontinuities increase). This becomes an error floor as long as position offsets continue to occur at historic rates. Of course, the impact on any given station velocity depends on the number of discontinuities for that particular point and their distribution in time, so it can be better or worse. This velocity error component is perhaps most relevant for GNSS stations such as those used to calibrate for land motions at nearby tide gauges to determine sea level change, which has a global long-term magnitude of only about 2 mm yr^{-1}. Likewise, the concern is similar for ground stations used to calibrate satellite altimeter drifts.

Clearly, a greater emphasis on strict configuration control at IGS reference frame stations is indicated. Perhaps national geodetic agencies could be convinced to take on this responsibility. Even with no further position offsets (which is not entirely achievable due to natural disruptions), though, it will take more than a decade of additional observations before the vertical velocity uncertainties begin to improve notably.

ACKNOWLEDGEMENTS

We thank Zuheir Altamimi for CATREF and for his help in using it for this study. Thanks also to Alvaro Santamaría-Gómez and Paul Rebischung for their review of an early draft of this paper. Their comments, as well as those of the editor and two anonymous reviewers, helped to improve this paper.

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