Volker Tesmer et al.: Impact of Analysis Options on the TRF, CRF and Position Time Series Estimated from VLBI,
IVS 2006 General Meeting Proceedings, p.243–251
http://ivscc.gsfc.nasa.gov/publications/gm2006/tesmer

Impact of Analysis Options on the TRF, CRF and Position Time Series Estimated from VLBI

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Abstract

This paper compares estimated TRF, CRF and position time series of different solutions in terms of systematic differences, scale, annual signals and station position repeatabilities. Several analysis options are investigated: various tropospheric parameterisations, atmospheric loading, thermal deformation and a refined stochastic model of VLBI observations, which mainly consists of elevation dependent re-weighting. All solutions were computed at DGFI using OCCAM 6.1 and the DOGS-CS software with VLBI data from 1984 till 2005.

1. Introduction

When computing geodetic solutions, an analyst has to choose between many options to set up the solution. Some of these options are obviously preferable to others and/or subject to conventions, like the IERS Conventions ([15]), or technique dependent conventions proposed by the technique services (e.g. see [16]). But, neither can all options be judged objectively right or wrong, nor are the effects of all options on geodetic target parameters known in detail.

2. Solution Setup

All solutions compared in this investigation used the VLBI observations of 2699 daily sessions between 1984 and 2005 with 49 radio telescopes observing 1954 sources. In a first step the data were processed with the VLBI software OCCAM 6.1 ([14]), setting up normal equations for each single session using the least-squares adjustment algorithm of OCCAM. Unknown parameters are station positions and velocities, source positions, the EOP (polar motion and rates, UT1 and LOD, nutation), tropospheric zenith delays (ZD) mapped with the VMF1 (Vienna Mapping Function 1, [4]), horizontal gradients and station clocks.

In a second step, the tropospheric and clock parameters, and all EOP were (pre-)reduced in all 2699 datum free single session normal equations, using the software DOGS-CS ([2]). All normal equations were then accumulated (stacked) to one big equation system, solely containing the parameters of the reference frames (station positions and velocities, and source positions). To remove the datum deficiencies of VLBI solutions, no-net-translation (NNT) and no-net-rotation (NNR) condition equations were added to the coordinates and velocities of 25 radio telescopes w.r.t. ITRF2000 ([1]), as well as NNR conditions for 199 stable sources ([5]) wrt ICRF-Ext1 ([7]). Inverting such an equation system yields a completely undeformed and fully consistent terrestrial (TRF) and celestial (CRF) reference frames (see also [12]) .

As step three, station position time series were derived by session-wise solutions with NNR and NNT conditions w.r.t. the TRF that was computed with exactly the same solution setup. This strategy guarantees station position time series as homogeneous and least noisy as possible, because position time series will get noisier the less similar the TRF (used as basis for the daily NNR+NNT conditions) is to the TRF implied by the solution setups. This approach is comparable to carrying out a 6-parameter similarity transformation, which theoretically requires normal distribution of the residual station positions w.r.t. the TRF used as basis for the transformation. The similarity is especially critical in case of single VLBI sessions, because networks with few (4-8) stations are not robust in that respect.

3. Comparison I: Solution Approaches "Tropospheric Parameterisation Options"

In this section, results from a solution **"usual"** (estimating hourly tropospheric ZD, no a priori values for the horizontal gradients, using surface met data to derive the a priori hydrostatic ZD), are compared with three solutions, each changing only one option w.r.t. the **"usual"** setup:

- **"2hour"**: estimating ZD every two hours,
- **"aprgr"**: using constant a priori tropospheric gradients (courtesy of GSFC, DAO 90-95),
- **"zdcon"**: using constant a priori ZDs (in this investigation, most of them were computed at the height of nearby GPS antennas following [3] and [10]).

3.1. CRF Differences

Figure 1 shows the differences between CRF (declination, DE) from the solution setup **"usual"** as reference and the **"2hour"**, **"aprgr"** and **"zdcon"** solutions. While **"usual"** − **"2hour"** seems to be more or less scattered around zero, **"usual"** − **"aprgr"** is a very distinct function. This function has a similar form and sign as the one described in [6], where the authors compare CRF solutions with and without estimating tropospheric horizontal gradients. However, the maximum value found by [6] was much larger (0.5 mas compared to 0.055 mas for **"usual"** − **"aprgr"**). This behaviour of DE is likely due to the pseudo-observations (constraints), which are added to the observation equations with an empirically derived formal error (here 0.5 mm). These constraints stabilize the gradient estimates towards their a priori values. The differences **"usual"** − **"zdcon"** also show a similar behavior but smaller in size (-0.02 mas).

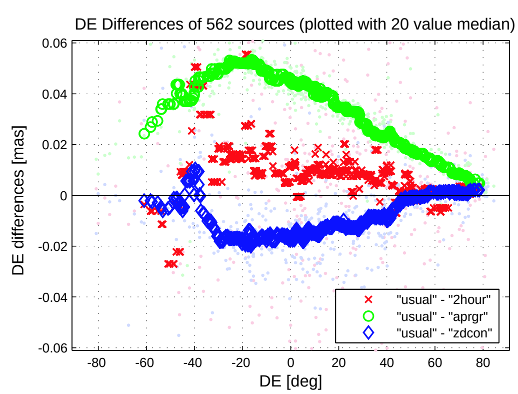

Figure 1. CRF declination differences: approach **"usual"** vs. **"2hour"**, **"aprgr"** and **"zdcon"**.

3.2. TRF Differences

Comparable to the CRF estimates, the TRF differences **"usual"** – **"2hour"** consist of random scatter only (see Figure 2). The differences **"usual"** – **"zdcon"** are of systematic nature, especially in the height component with a maximum value of −38 mm. This can be explained by the fact that a part of the hydrostatic zenith delay is mapped down with the wrong (wet) mapping function (as an example, +10 hPa error in the pressure used to compute the a priori hydrostatic ZD evokes about +2 cm error in the a priori hydrostatic ZD, resulting in a −0.4 cm error in the height estimate: for details please see [4]). As a consequence, the global scale for **"zdcon"** in this investigation differs by 0.2 ppb from the **"usual"** solution. The differences in the horizontal components for **"zdcon"** have a small shift of about +0.5 mm in north-south direction, which cannot be explained at the moment. The TRF differences **"usual"** – **"aprgr"** differ mostly in the horizontal components, where the a priori gradients evoke a clear north-south tilt up to −2 mm, probably because the a priori values for the gradients are constrained.

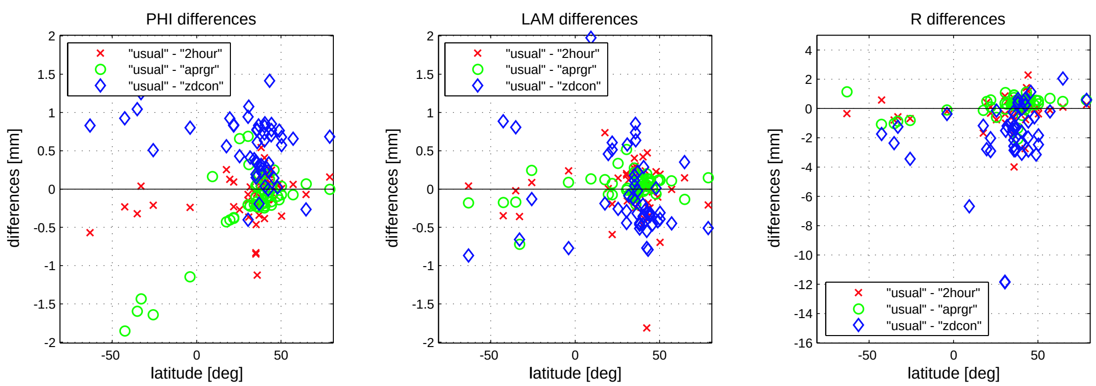

Figure 2. TRF position differences: approach **"usual"** vs. **"2hour"**, **"aprgr"** and **"zdcon"** (for reasons of clarity, the plots are zoomed—there are single values outside the visible boundaries, reaching up to −38 mm for R).

3.3. Station Position Time Series

Figure 3 illustrates the differences between station position time series of various solution approaches w.r.t. the **"usual"** solution. They show the differences for each single session w.r.t. the corresponding TRF (in light colored dots), as well as 70-day medians of these differences, computed every 7 days to better visualise periodic and annual parts of the differences.

NYALES20 (see Figure 3) is an extreme example for the strong influence of using **"zdcon"** on estimated height time series: there are very clear episodic signatures in the differences, superimposed by an annual part, altogether amounting to 4-5 mm.

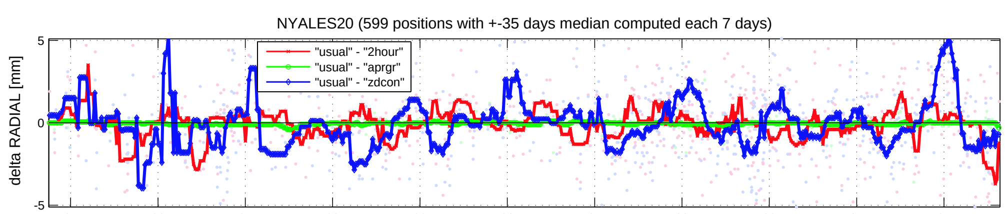

Figure 3. NYALES20 height time series differences: approach **"usual"** vs. **"2hour"**, **"aprgr"** and **"zdcon"**.

3.4. Station Position Repeatability

The station position repeatabilities were computed from the single session position estimates w.r.t. the corresponding TRF, with annual signals removed before computing the RMS and WRMS values. The RMS determined from all 2699 sessions between 1984 and 2005 for the **"usual"** solution setup were (PHI, LAM, R, all in [cm]) 0.50, 0.47, 1.09, the weighted RMS (WRMS) 0.27, 0.26, 0.49, respectively.

Generally, decreasing the temporal resolution of the estimated ZD from 1 hour to 2 hours leads to a degradation of station position repeatabilities by 2 to 3%. Using non-zero a priori gradients does not affect the station position repeatabilities. An amazing fact is that using constant a priori ZD instead of ZD derived from the measured surface met data leads to 2% better repeatabilities (up to 10% in WRMS for GILCREEK). This is probably due to errors in the surface pressure data taken for the solution, because other investigations with shorter time series show a clear advantage when using pressure data recorded at the sites ([4]).

4. Comparison II: Solution Approaches Using Atmospheric Loading, Thermal Deformation and a Refined Stochastic Model

In this section, results derived from a solution, in the following named **"usual"** (computed without atmospheric loading, without thermal deformation corrections and without using a refined stochastic model), were compared to the following solutions:

- **"atmos"**: with atmospheric loading correction ([8]),
- **"therm"**: with thermal deformation correction (see [9] and [16]),
- **"refst"**: using a refined stochastic model (elevation dependent re-weighting, see [11], [13]).

4.1. CRF Differences

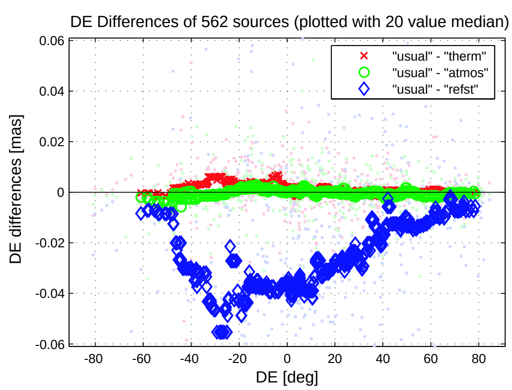

Figure 4. CRF declination differences: approach **"usual"** vs. **"atmos"**, **"therm"** and **"refst"**.

The only significant differences between CRF estimates occurred for the **"usual"** − **"refst"** comparisons (see Figure 4). The function that shows declination differences is very similar to the one that is evoked by using a priori non-zero horizontal tropospheric gradients (see Section 3.1) but having opposite sign: while for **"usual"** − **"aprgr"**, the maximum differences were 0.055 mas, the maximum for **"usual"** − **"refst"** is −0.050 mas. This is due to the fact that the gradient estimates were constrained to the a priori values. With the refined stochastic model, gradients have a smaller influence on the solution because observations at low elevations, which mainly define the gradient estimates, are slightly weighted down. Thus, the **"usual"** – **"aprgr"** differences are to a certain extent comparable to the ones of **"usual"** – **"refst"**.

4.2. TRF Differences

A comparable phenomenon also occurs for the TRF estimates: while the **"usual"** – **"aprgr"** TRF differences are tilted in north-south direction up to −2 mm (see Figure 2), the **"usual"** – **"refst"** ones are tilted in north-south direction up to +1.5 mm (see Figure 5). Differences in estimated heights using **"atmos"** or **"therm"**, which vanish in this investigation, could arbitrarily be evoked by the chosen reference temperature and pressure. The solution using the refined stochastic model has a scale that is larger by 0.1 ppb than the **"usual"** TRF.

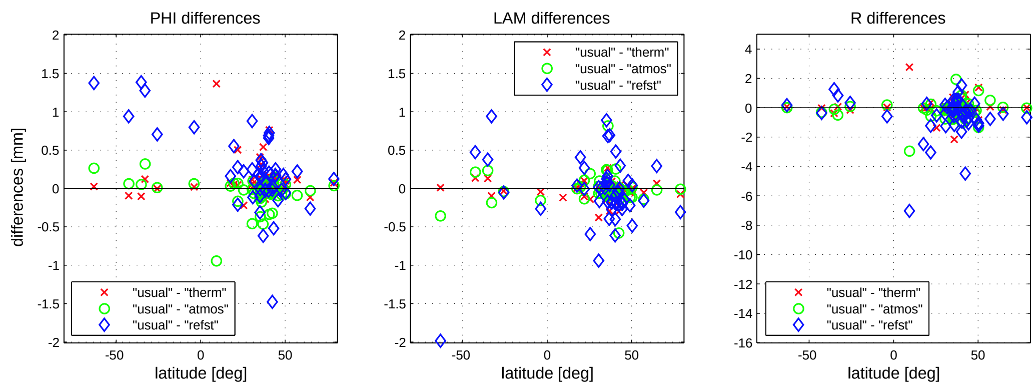

Figure 5. TRF coordinate differences: approach **"usual"** vs. **"atmos"**, **"therm"** and **"refst"** (for reasons of clarity, the plots are zoomed—there are single values outside the visible boundaries).

4.3. Station Position Time Series

The station position time series differences of the station GILCREEK are a good example to illustrate the influence of atmospheric loading corrections: Figure 6 shows the corresponding height differences due to atmospheric loading corrections, which obviously have an annual signal imposed with 5 mm amplitude. For GILCREEK, the thermal deformation correction is exactly out of phase compared to atmospheric loading, and has a smaller amplitude (2 mm). In the horizontal components (not shown here), both effects have annual signals with magnitude of about 0.7 mm.

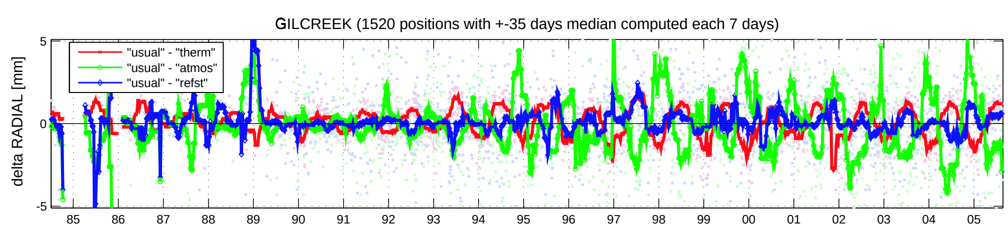

Figure 6. GILCREEK height time series differences: approach **"usual"** vs. **"atmos"**, **"therm"** and **"refst"**.

Another explicit example is the 46 m antenna ALGOPARK with a quite distinct annual thermal deformation signal in the height position time series of about 3 to 4 mm amplitude (Figure 7).

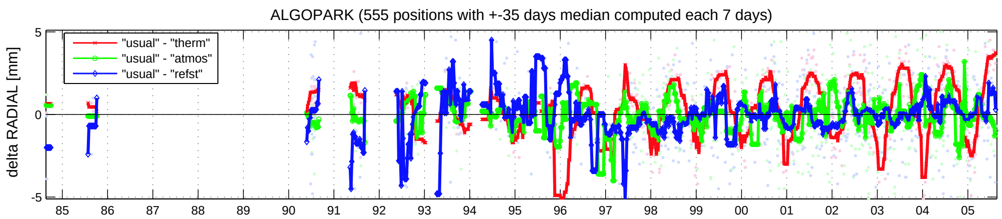

Figure 7. ALGOPARK height time series differences: approach **"usual"** vs. **"atmos"**, **"therm"** and **"refst"**.

4.4. Annual Signals in Station Position Time Series

Generally, the amplitudes of annual signals in station height time series are smaller than 5 mm (as illustrated in Figure 8) and smaller than 3 mm in the horizontal components (not shown here).

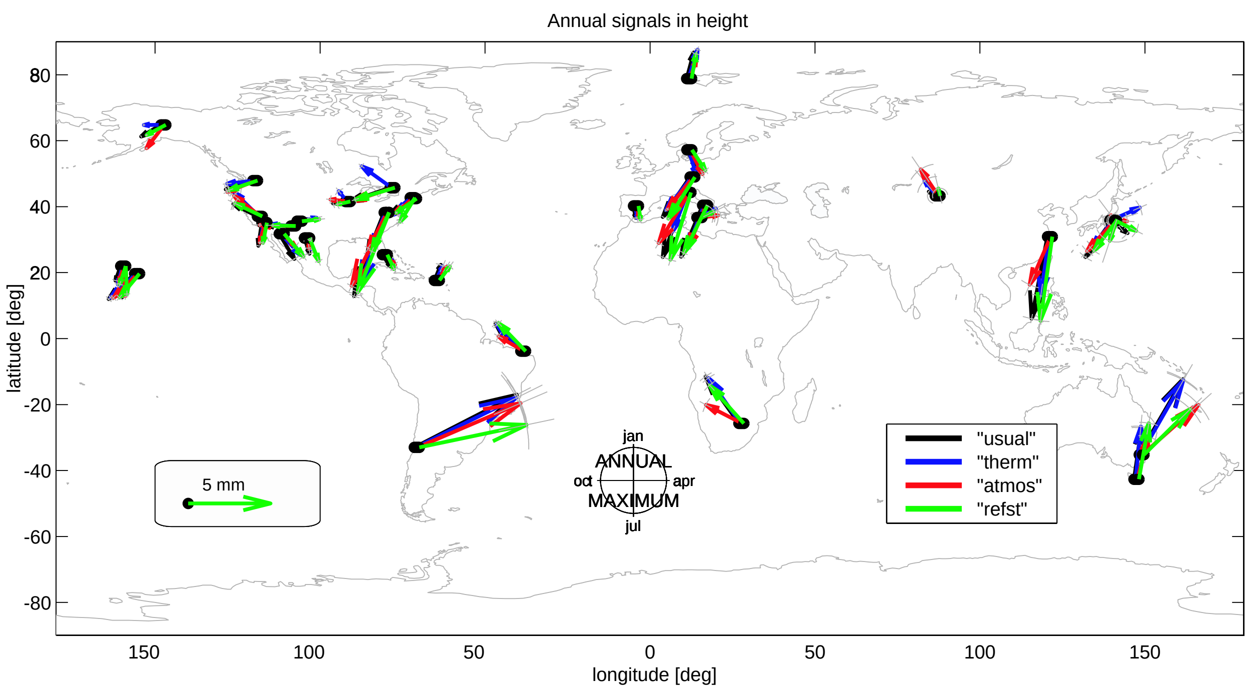

Figure 8. Annual signals in height time series: approach **"usual"**, **"atmos"**, **"therm"** and **"refst"**.

Figure 9 shows the differences between the amplitudes of the annual signals in the horizontal and height components, comparing the **"usual"** solution approach to **"atmos"**, **"therm"** and **"refst"**. The biggest influence is obviously evoked by applying thermal deformation: the annual amplitudes are reduced by up to 0.7 mm in height and 0.4 mm in the horizontal components. Using the atmospheric loading correction ([8]) also reduces the amplitudes of annual signals in height by up to 0.7 mm, but not in the horizontal components. The refined stochastic model does not significantly affect the annual signals.

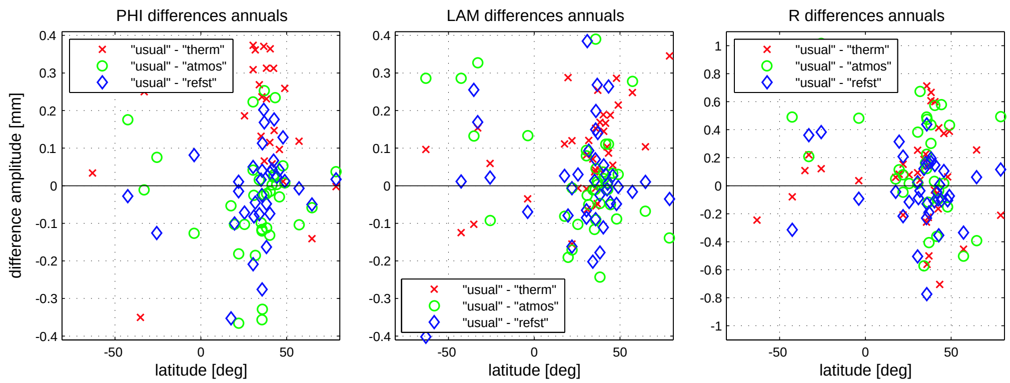

Figure 9. Differences of annual amplitudes in position time series: approach **"usual"** vs. **"atmos"**, **"therm"** and **"refst"** (for reasons of clarity, the plots are zoomed—there are single values outside the visible boundaries).

4.5. Station Position Repeatability

The effect of the solution options **"atmos"**, **"therm"** and **"refst"** on station position repeatabilities is as follows (please note that annual signals were removed from the position time series before computing the repeatabilities): As the thermal deformation correction does not improve the station position repeatabilities (less than 1% gain overall), one can assume that the present models are appropriate to describe the dominant annual part of this effect (see section 4.4). Atmospheric loading corrections improve the overall station height repeatability by 2% RMS and 4% WRMS, for some stations even between 5 and 10%. But, the repeatability of the horizontal components does not improve significantly. The biggest improvements concerning station position repeatabilities can be achieved using the refined stochastic model (mainly elevation dependent re-weighting), which yields an overall gain of about 3% RMS and 4% WRMS, for some stations even between 10 and 15%.

5. Summary

The results of VLBI solutions significantly depend on the solution setup, which can cause systematic effects. For all applications, like for geophysical studies or combination issues, these systematics must be considered thoroughly. The biggest influences due to the solution setups tested in this paper can be summarised as follows:

- The approach using (realistic) non-zero a priori values for the horizontal tropospheric gradients is sensible from a theoretical point of view and should yield more realistic results. But, compared to solutions where zero values are used, this approach influences the estimated declinations of radio sources by up to almost 0.055 mas. TRF estimates are mainly affected by a small tilt in north-south direction by up to -2 mm. These systematic effects are due to the common practice to stabilize gradient estimates towards their a priori values, because the gradients are sometimes weakly defined by the VLBI observations themselves.
- Using constant a priori ZD instead of ZD derived from surface met data can change the station heights of an estimated TRF to almost arbitrary values, because of the correlations between the estimated ZD and station height components. With the ZD data used in this

investigation, the station heights generally change less than 1 cm (the maximum is 38 mm), the overall scale is shifted by about 0.2 ppb. Periodic and annual signals in height position time series differences were found to reach up to ±4 mm.

- Decreasing the temporal resolution of the estimated ZD from 1 hour to 2 hours does not influence systematically any type of parameter investigated. It leads to episodic signals and noise in station position time series and degrades their repeatabilities by about 3%.
- Applying thermal deformation corrections reduces the annual amplitudes in station position time series by up to 0.7 mm in height and 0.4 mm in the horizontal components. Episodic signals reach up to ±3 mm in height and ±1 mm in the horizontal components. But this correction can only be used in VLBI solutions, computed for combination issues of the IVS or the IERS, if a clear and reasonable definition of the reference temperature exists. In the future, even local tie measurements from VLBI reference points to those of other techniques should comprise calibrated temperature measurements.
- The atmospheric loading corrections as proposed/provided by [8] generally reduce the amplitudes of the annual signals in height by up to 0.7 mm, but not in the horizontal components. Implied episodic differences in station position time series reach up to ±5 mm in height and ±1 mm in the horizontal components. Using this correction improves the overall station height repeatability by 2% RMS and 4% WRMS, for some stations even between 5 and 10%, whereas the repeatabilities of horizontal components do not change. Comparable to thermal deformation, a reasonable application to geodetic data analysis requires a well founded definition of the reference pressure.
- The last solution option under investigation was the refined stochastic model (mainly elevation dependent re-weighting as proposed by [13]). The effects on CRF and TRF are comparable to those evoked by using a priori non-zero horizontal tropospheric gradients, but with different sign: declination estimates are systematically changed by up to −0.050 mas, TRF estimates are tilted in north-south direction by up to 1.5 mm, the scale gets bigger by about 0.1 ppb. This is due to the fact that the "real" observations under low elevations (which mainly define the gradient estimates) are slightly weighted down using the refined stochastic model, and the gradient a priori values are constrained in VLBI solutions. Applying the refined stochastic model, the station position repeatabilities overall improve by 3% RMS and 4% WRMS in height and the horizontal components (which is the best improvement of the solution setup options analysed in this investigation). For some stations the gain is even between 10 and 15%.

Acknowledgement

This study made extensive use of VLBI-data provided by the International VLBI Service for Geodesy & Astrometry (IVS). Thanks to all IVS components.

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