Evaluation of ITRF2014 Solutions

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Introduction

For the most recent International Terrestrial Reference Frame (ITRF) realization three insitutions have provided solutions. They significantly differ in the way how they have been generated and in their parametrizations:

- Deutsches Geodätisches Forschungsinstitut at TU Munich (DGFI-TUM, Germany), (Seitz et al. 2016)
  DTRF2014: based on a classical modelling of time series by station coordinates and linear velocities (after correcting for loading effects)
  DTRF2014L: corrections for atmospheric pressure loading and hydrological effects are reapplied
- Institut national de l'information géographique et forestière (IGN, France) (Altamimi et al. 2016)
  ITRF2014: based on coordinate, linear velocities, and empirical post-seismic deformation corrections (together with annual/semi-annual periodic functions in the background)
  ITRF2014P: periodic functions recovered
- Jet Propulsion Laboratory (JPL, USA) (Wu et al. 2015)
  JTRF2014: based on a filter approach

Coordinate sets for all days between 2000 and end of 2014 have been established following the instructions of all TRF solutions.

Background on the Data Processing

In 2015, a reprocessing effort of the GNSS data from 1994 to 2015 has been carried out at AIUB (Sušnik et al. 2016) in the frame of the EGSIEM project (European Gravity Service for Improved Emergency Management, Jäggi et al. 2015). The modelling of the GNSS data is consistent with the processing standards of the CODE analysis center (Center for Orbit Determination in Europe, Dach et al. 2016) of the IGS (International GNSS Service, Dow et al. 2009) hosted at AIUB as they were used in summer 2015.
The solution considers all active GPS satellites over the entire time period and the GLONASS satellites starting from 2002. Since about 2008, a global coverage of GLONASS tracking network has been achieved.
The station selection is the same as used by CODE for the IGS repro2 solution (Steigenberger et al. 2014). Because the reference frame solutions are based on IGS repro2 for their GNSS stations, 90 to 95% of the stations are included in the reference frame solutions. An example is shown in Figure 1.

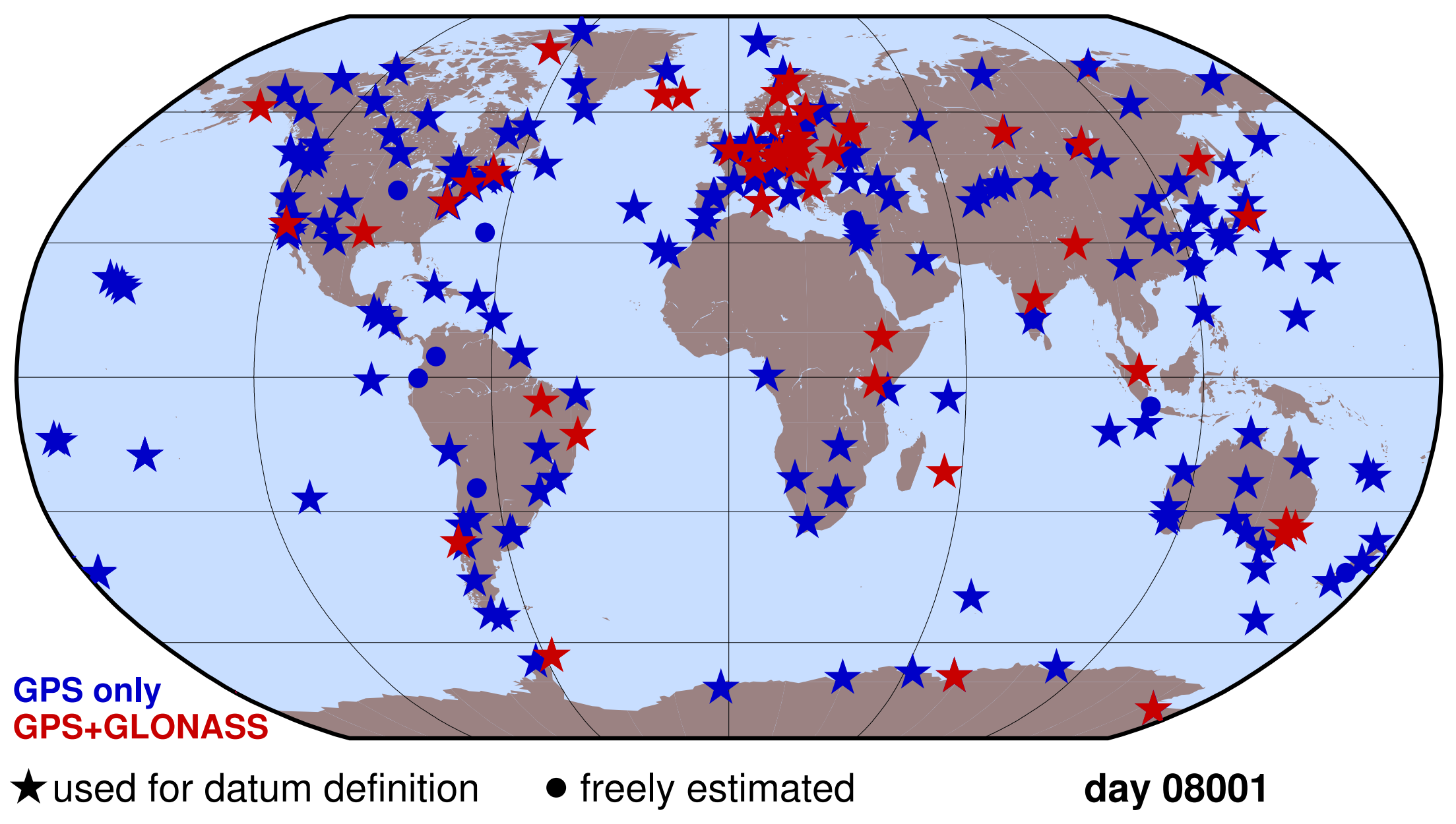

Figure 1: Example of the geographical distribution of the stations (shown for January 1st, 2008) where the reference stations of the DTRF2014 solution are shown as an example.

As in repro2, the IGS08-ANTEX antenna phase center corrections were used, providing a scale for the solution that is consistent to the repro2 solution of the IGS and therefore with the reference frame solutions. The main difference is the additional estimation of twice-per revolution empirical accelerations along the direction satellite-Sun for the GNSS satellites orbits according to Arnold et al. (2015), introduced as ECOM2 (Empirical CODE orbit mode, version 2).

Description of the Solution

All solutions are based on one and the same set of daily normal equations to ensure full consistency regarding the GNSS processing. The following parameters are estimated:

- station coordinates with a minimum constraint solution applying a NNR and NNT condition (no-net-rotation and no-net-translation) to all stations with given coordinates in the particular reference frame,
- troposphere zenith path delays with 2h-resolution using the VMF1/ECMWF model (Böhm et al. 2006), as well as troposphere gradients with a daily resolution (using the model from Chen and Herring 1997),
- Earth rotation parameters (X- and Y-pole offset and rate as well as LOD; 1st UT-values taken from the C04 product), and
- GNSS satellite orbits with 7 dynamical orbit parameters according to the ECOM2 description (see Arnold et al. 2015) and three empirical velocity changes of the satellites at noon as described in Beutler et al. (1994).

Due to the NNT-condition the center of mass (relevant, e.g., for the satellite orbit modelling) is forced to coincide with the origin of the reference frame solution – as typically done for the processing within the IGS. If the deviation of the center of mass from the origin is taken into account in the solution by estimating a translation vector (geocenter coordinates), the coordinates and GNSS orbits result in the same solution geometry – the differences can be fully absorbed by three translation and three rotation parameters. These solutions contain the usual pattern in the Z-component of the geocenter parameters (which is dominated by the orbit modelling). This solution is labeled datum-free solution and is used for comparisons.

Station Coordinates

In the datum-free solution the station network geometry is exclusively defined by the GNSS measurements. As soon as the center of mass of the solution is forced into the origin by applying a no-net-translation condition without estimating a geocenter vector, the network may become distorted.
Any potential distortions may be verified for the five different reference frame solutions by a seven parameter Helmert transformation with respect to the datum-free coordinate solution. The magnitude of the network distortions is expressed by the RMS of the residuals which is displayed for the full time series in Figure 2. The RMS is typically below 1 mm which confirms only a marginal deformation of the station network geometry by this effect.

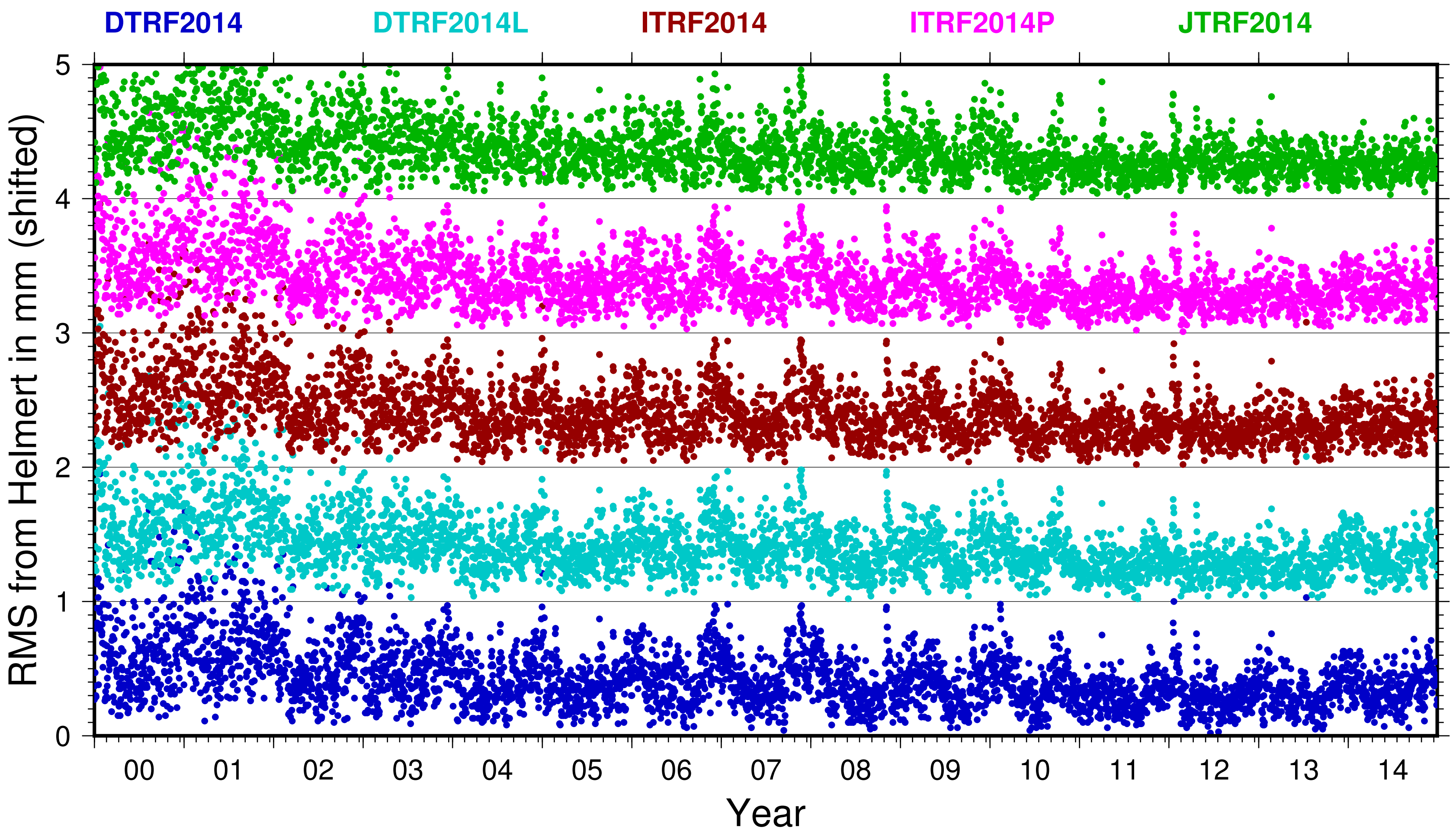

Figure 2: RMS of the seven parameter Helmert transformation between the solutions fixed on the respective origin of the reference frame solutions and the datum-free solution; the datasets are shifted by 1 mm for plotting.

Looking at the residuals of the Helmert transformation in a histogram for each day (as shown for one example in Figure 3), all solutions look very similar. Nevertheless, for most of the days an order of the solutions with increasing RMS was found: JTRF2014, DTRF2014L, ITRF2014P, ITRF2014, and DTRF2014. In the same order the magnitude of the annual variations in the total RMS as visible in Figure 2 is decreasing.

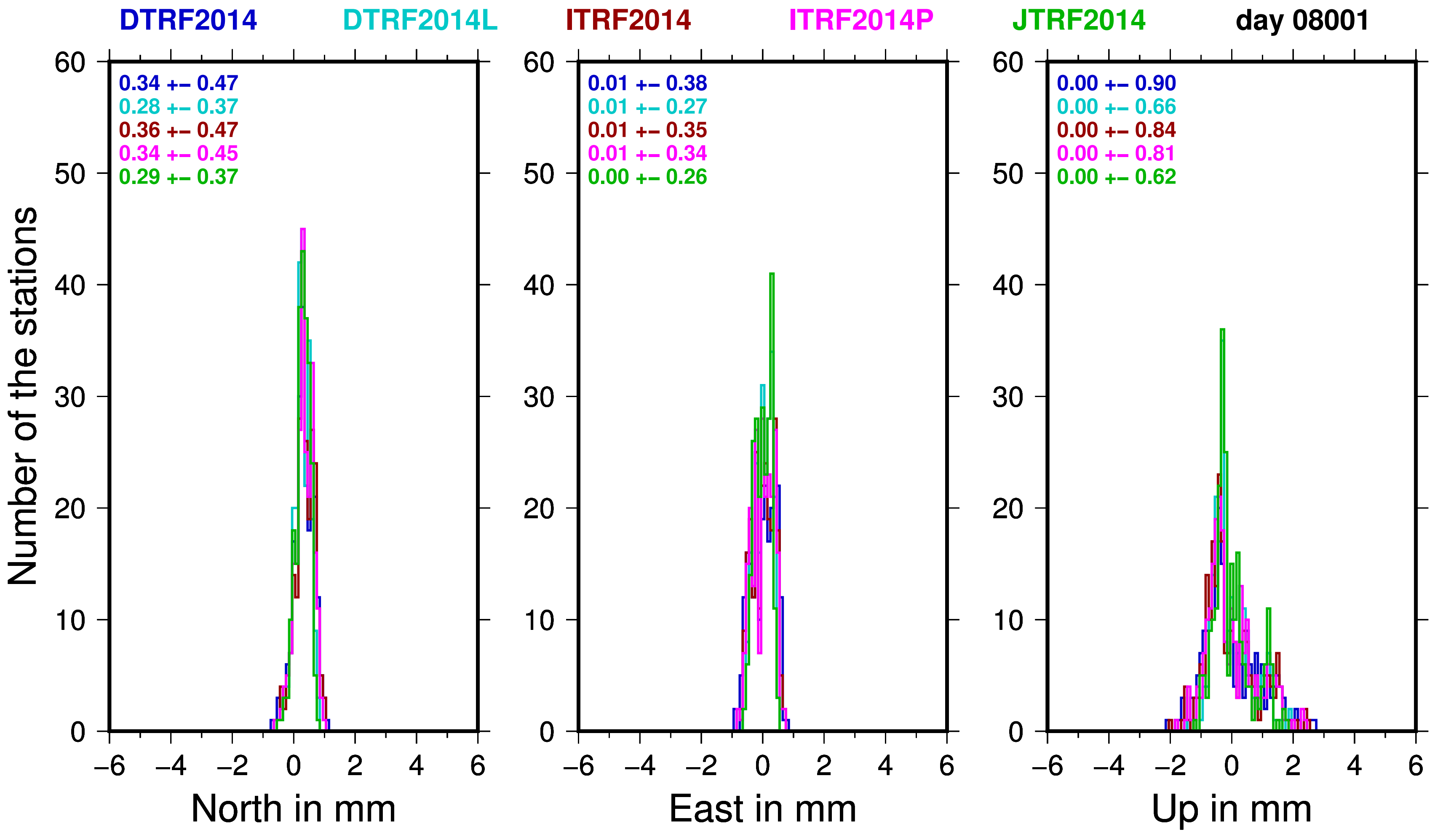

Figure 3: Typical example for a histogram of the residuals after a seven parameter Helmert transformation between the solutions fixed to the origin of the reference frame solutions and the datum-free solution for one day (the mean and RMS values per component are given in mm in the legend).

In the JTRF2014 solution no deterministic model for the long-term coordinate time series representation was implemented. It can therefore follow the network geometry of the GNSS-data based coordinate time series best. On the other hand, with its coordinate and linear velocity parametrization the DTRF2014 solution shows the lowest flexibility. The solution DTRF2014L, where the loading effects are corrected based on models, got the second rank confirming the high quality of these background models. Of course, as stated above, the magnitude of these differences between the solutions is small.

GNSS Satellite Orbits

The GNSS satellite orbits obtained in the parameter estimation based on different reference frame solutions are compared based on satellite positions in the Earth fixed frame every 15 minutes. As for the station coordinates a seven parameter Helmert transformation is applied to compensate for differences in the datum between the different reference frame solutions. For each satellite the RMS of the residuals is computed per day.
There are some satellites with perticularly high RMS values because of the limited network geometry for GLONASS satellites during the years 2002 and 2007 or a reduced tracking of unhealthy satellites. To obtain representative values, the median and 75% quantile of the RMS values are computed and given in Table 1.

Reference		DTRF2014	DTRF2014L	ITRF2014	ITRF2014P	JTRF2014
DTRF2014	X		1.1 / 2.8	0.7 / 2.0	0.8 / 2.0	1.9 / 4.0
	Y		1.1 / 2.7	0.7 / 1.8	0.7 / 1.9	1.9 / 3.9
	Z		0.7 / 1.7	0.5 / 1.1	0.5 / 1.2	1.2 / 2.5
DTRF2014L	X	1.1 / 2.8		1.3 / 3.0	1.2 / 2.7	1.5 / 3.5
	Y	1.1 / 2.7		1.3 / 2.9	1.1 / 2.6	1.5 / 3.3
	Z	0.7 / 1.7		0.8 / 1.8	0.7 / 1.6	1.0 / 2.1
ITRF2014	X	0.7 / 2.0	1.3 / 3.0		0.3 / 0.5	1.6 / 3.6
	Y	0.7 / 1.8	1.3 / 2.9		0.3 / 0.5	1.6 / 3.6
	Z	0.5 / 1.1	0.8 / 1.8		0.2 / 0.4	1.1 / 2.2
ITRF2014P	X	0.8 / 2.0	1.2 / 2.7	0.3 / 0.5		1.4 / 3.4
	Y	0.7 / 1.9	1.1 / 2.6	0.3 / 0.5		1.4 / 3.3
	Z	0.5 / 1.2	0.7 / 1.6	0.2 / 0.4		0.9 / 2.1
datum-free solution	X	7.4 / 19.3	7.2 / 19.4	7.2 / 19.3	7.1 / 19.1	6.9 / 18.6
	Y	7.2 / 19.3	7.0 / 19.1	7.0 / 19.2	6.9 / 19.1	6.6 / 18.3
	Z	4.6 / 11.8	4.5 / 11.7	4.5 / 11.6	4.4 / 11.6	4.3 / 11.1

Table 1: RMS of the residuals after a Helmert transformation between the obtained GNSS orbits for each satellite per day in the Earth-fixed frame. The median and 75% quantil from all satellites/days are reported. The units are mm.

The RMS values in Table 1 show the expected relations between the orbits when different reference frame solutions are used. For instance correspond the GNSS orbits of DTRF2014 and ITRF2014 better to each other than with the other solutions because both use a parametrization that does not follow any short annual signals. The last line in Table 1 is the comparison of each reference frame solution with the datum-free solution. It shows significantly higher values. It means that the differences between the five reference frame solutions are much smaller than the distortion introduced into the solution by forcing the center of mass into the origin.
A validation of the GNSS orbits from these five GNSS-based orbit solutions using SLR data together with the coordinates from the SLR stations from the five reference frame solutions is planned. The differences in the SLR residuals can provide an insight on the consistency between stations related to different space geodetic techniques in the reference frame solutions.

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Earth Rotation Parameters

The Earth rotation parameters are an important result from the GNSS data analysis for geodynamical purposes. In Figure 4 the differences with respect to the ITRF2014 solution (arbitrarily chosen) are displayed.

In the X- and Y-component of the polar motion the magenta curve from the ITRF2014P shows, as expected, periodic differences with respect to the ITRF2014 solution. This is because also for the modelling of the station coordinate time series empirical periodic functions have been added. This confirms the sensitivity of the Earth rotation parameters on the stability of the reference frame solution regarding the orientation.

The JTRF2014 solution is based on a filter approach with a weak long-term stability in the orientation of the reference frame. This is clearly visible in the green curve of Figure 4. Even if this solution did coincide best with the coordinate estimates it has a disadvantage for the interpretation of the Earth rotation solution.

The differences between the DTRF2014 and DTRF2014L solutions (blue and cyan curves) may also be explained by adding the loading corrections. They do not show such a clean periodic behaviour like the differences between ITRF2014 and ITRF2014P. They are caused the applied loading corrections instead of estimating periodic functions as in the ITRF2014P solution.

The most interesting feature is the long-term stability of the two solutions ITRF2014 and DTRF2014. Although both solutions are stable in the short-term by construction. At the same time, they show a systematic difference in the long-term stability as clearly shown by the blue curve in Figure 4. This implies that both reference frame solutions do rotate with respect to each other influencing the obtained Earth rotation parameters.

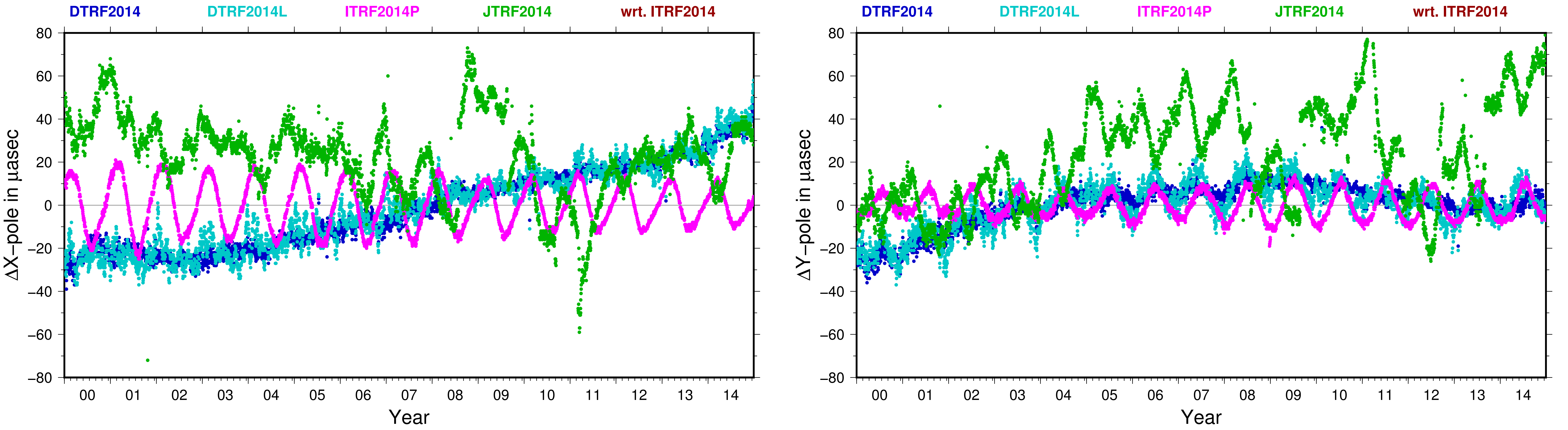

Figure 4: Difference between the obtained polar motion X- (left) and Y-components (right) for the reference frame solutions with respect to the arbitrarily chosen solution ITRF2014.

Assessing the Long-term Stability

Based on the comparison of the estimated Earth rotation parameters, it is only possible to observe differences in the long-term stability of the DTRF2014 and ITRF2014 solutions. A direct comparison of the coordinate sets from different epochs by evaluating the corresponding rotation angles in a Helmert transformation does not give a closer insight because the result will depend on the station selection.

Assuming that an external velocity field is free from rotations (e.g., the NNR-NUVEL 1A, DeMets et al. 1994), the coordinates from an epoch t_0 may be transformed to a second epoch $t_0 + 365\,\mathrm{days}$. These coordinates can be compared to those given in the corresponding reference frame solution for the epoch $t_0 + 365\,\mathrm{days}$. Of course, the coordinate series between the epochs t_0 and $t_0 + 365\,\mathrm{days}$ have to be checked for discontinuities due to equipment changes and tectonic events, e.g., by inspecting the parameter intervals in the reference frame solutions.

Because NNR-NUVEL 1A model considers only the motion of the tectonic plates but no local deformation effects, which may act on the GNSS tracking stations, the residuals of the Helmert transformation have to be screened rigorously. All stations with residuals exceeding 3 mm are not considered to determine the rotations of the reference frame solution with respect to the NNR-NUVEL 1A model. Due to this strong condition, about 60% of the stations pass the test and contribute to the rotation parameters.

In order to compensate for potential changes of the origin in the reference frame solution between the epochs t_0 and $t_0 + 365\,\mathrm{days}$, also translation parameters are set up in the Helmert transformation. The results of this experiment are shown in Figure 5.

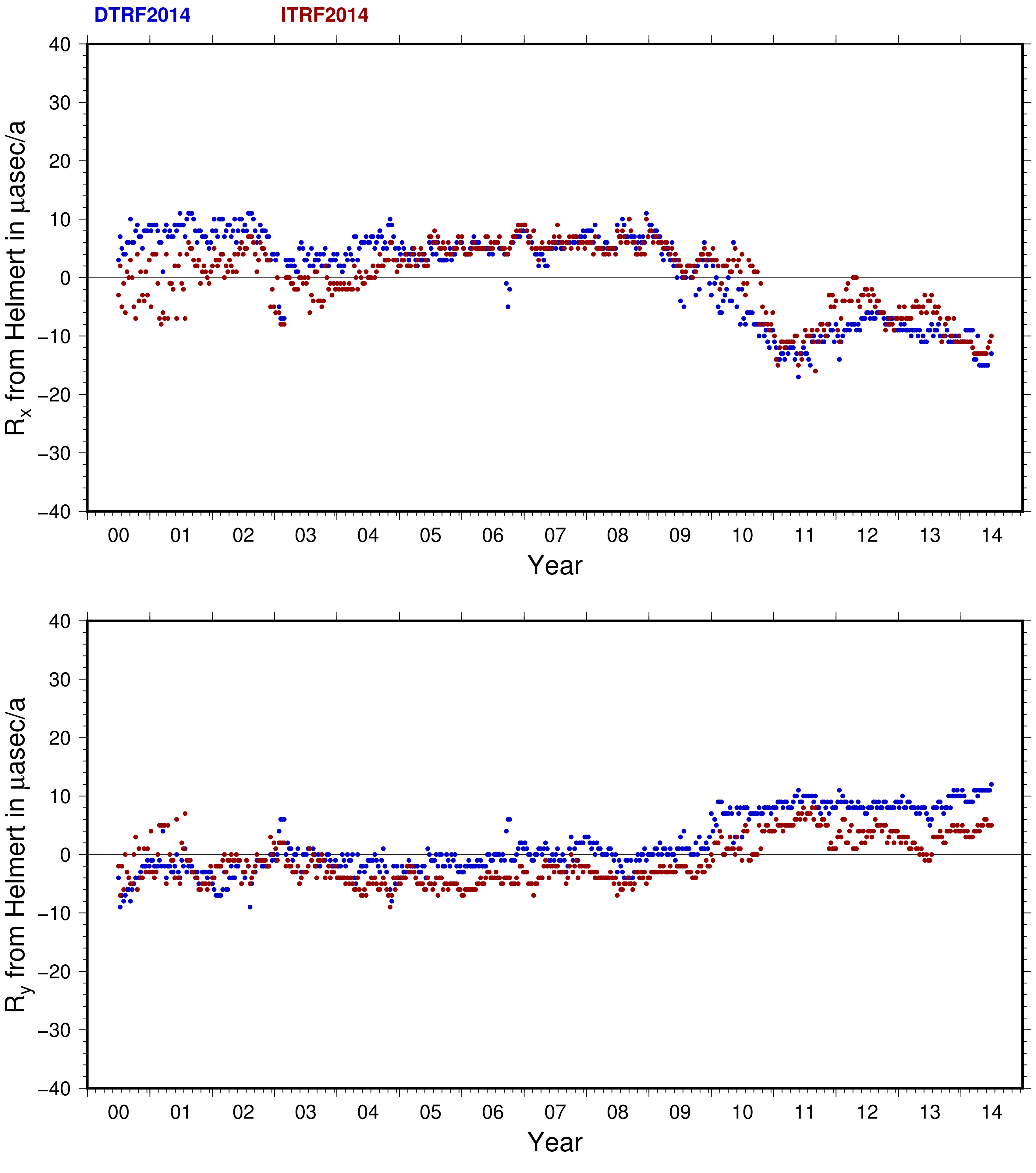

Figure 5: X- and Y-rotations during one year when comparing the coordinate differences over one year from the reference frame solutions with the NNR-NUVEL 1A velocity field (computed every 10 days, centered at the middle of the one year interval).

The rotations displayed in Figure 5 are expected to be zero if no torsion of the reference frame with respect to the NNR-NUVEL 1A model exists. In the case that the NNR condition in the plate tectonic model is not fully met the rotation angles should at least be constant in time and identical for both reference frame solutions.

The rotation angles from Figure 5 are in the order of 5 to 10 μasec per year, what approximately corresponds to the blue curve in Figure 4. A significant event changing the offset in Figure 5 is visible. Whether it is related to the Earthquake in Chile (February 27th, 2010 with magnitude 8.8) or not cannot be answered by this experiment.

Conclusions

Five reference frame solutions have been evaluated with the most recent reprocessing series from the CODE analysis center. The ITRF2014 (provided by IGN, France) and the DTRF2014 (published by DGFI-TUM, Germany) have a conservative parametrization of the coordinate series by a limited number of parameters whereas the JTRF2014 (generated by JPL, USA) follows a filter approach. In this way the coordinate time series can optimally be represented because all variations in time (e.g., due to loading effects) can be considered by tuning the filter. In order to consider loading effects as well, the other two solutions include periodic terms (that are estimated; ITRF2014P) or provide corrections from loading models (that were used as background model; DTRF2014L).

When considering the short-term variations in time series, the coordinates from the reprocessing can best be represented. This is an advantage if, e.g., a regional solution shall be incorporated into the global reference frame. On the other hand, the more conservative parametrization is more beneficial to ensure the long-term stability that is essential for instance to establish Earth rotation series.

Acknowledgment

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