# WP10-DDSS-018 - Products.EUREF.ReferenceFrame

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*02/02/2018*

The different EUREF products within EPOS are the WP10-DDSS-016 EUREF.Combined.Positions and WP10-DDSS-018 EUREF.ReferenceFrame. This document will present the Product EUREF.ReferenceFrame.

| DDSS Number | DDSS Name | Agency |
|---|---|---|
| WP10-DDSS-016 | Products.EUREF.Combined.Positions | WUT (PL)<br>Tomasz Liwosz |
| **WP10-DDSS-018** | **Products.EUREF.ReferenceFrame** | ROB (BE)<br>Juliette Legrand |

## Introduction

The primary purpose of the EUREF Permanent Network (EPN) is to provide access to the European Terrestrial Reference System 89 (ETRS89) which is the standard precise GNSS coordinate system throughout Europe. Supported by EuroGeographics and endorsed by the INSPIRE Directive 2007/2/EC, the ETRS89 forms the backbone for geolocation data on the European territory, both on a national as on an international level. To maintain the ETRS89, EUREF computes multi-year coordinates/velocities of the EPN stations in the latest ITRS/ETRS89 realization, also called the '**EPN multi-year solution'**. The coordinates/velocities of the EPN multi-year solution are regularly updated (each 15 weeks) and are used as the reference coordinates/velocities for densifying the ITRS/ETRS89 over Europe. It is the core product of EUREF, the IAG (International Association of Geodesy) Reference Frame sub-commission for Europe.

The DDSS called by EPOS "Products.EUREF.ReferenceFrame" corresponds to the EPN multi-year solution. It consists of the multi-year positions and velocities of the EPN stations which are published by EUREF each 15 weeks together with position time series, residual position time series, a list of discontinuities, a list of outliers and A/B station classes.

In this document, the EPN multi-year solution shown is C1950.

## Input files

The EUREF Reference Frame product, or EPN multi-year solution, is computed using the EPN daily combined SINEX files (Table 1): 1) from 001/1996 (GPS week 834) up to 363/2013 (GPS week 1772), the daily SINEX are resulting from the EPN-repro2, 2) after GPS week 1772, the routine daily EPN combined SINEX files are used.

In January 2017 (GPS week 1934), the IGS (International GNSS Service) released the IGS14 together with the isg_14.atx. The epn_14.atx calibration file, used within the EPN since GPS week 1934, consists of the individual antenna calibrations of the EPN stations plus the igs_14.atx. The EPN positions estimated prior to 028/2017 (GPS week 1934) were computed using epn_08.atx (indiv. calib. + igs_08.atx). In order to insure the consistency of the daily EPN solutions before GPS Week 1934 with the IGS14/epn_14.atx, their positions were corrected for the position changes caused by the switch from epn_08.atx to epn_14.atx. To maximize the consistency with IGS, when available, the position offsets computed by the IGS for IGS station/antenna pairs were used. If not available, the latitude-dependent models (IGSMAIL-7399) of the expected position offsets were applied.

| From | To | Type | Antenna Calibration | Position Offsets |
|---|---|---|---|---|
| **0834 – 1**<br>1996/001<br>1996-01-01 | **1772 – 6**<br>2013/362<br>2013-12-28 | EPN-repro2 | epn_08.atx<br>(igs08.atx) | Applied |
| **1773 – 0**<br>2013/363<br>2013-12-29 | **1933 – 6**<br>2017/028<br>2017-01-29 | EPN-routine | epn_08.atx<br>(igs08.atx) | Applied |
| 1934 – 0<br>2017/028<br>2017-01-29 | now | EPN-routine | epn_14.atx<br>(igs14.atx) | - |

**Table 1: EPN Solutions used to produce the EUREF Reference Frame**

## Methodology

The EPN multi-year position and velocity solution is computed with the CATREF software (Altamimi et al., 2007). The positions and velocities is aligned to the IGS14 reference solution under minimal constraints using 14 transformations parameters (translations, rotations, scale and their rates) on a selection of IGS14 reference stations.

During the stacking, discontinuities are introduced to account for jumps in the position time series. A new station position and velocity is estimated after each discontinuity and the velocities are usually constrained to be equal before and after a discontinuity. In addition, this solution incorporates the ITRF2014 post-seismic deformation models (ftp://itrf.ign.fr/pub/itrf/itrf2014/ITRF2014-psd-gnss.dat) for 5 stations: ANKR00TUR, BUCU00ROU, ISTA00TUR, REYK00ISL, TUBI00TUR. Also, except in cases of significant disagreements, the velocities of collocated sites are constrained to be the same.

## Metadata checks

In order to correctly apply the position offsets to mitigate the position changes caused by the switch from epn_08.atx to epn_14.atx, the SINEX metadata (antenna/radome type, serial number, antenna offset) have been compared to the station metadata and the antenna calibrations. Days with hardware of firmware changes are rejected from the multi-year solution. When the antenna/radome and receiver information is not available in the site log of the station, the day is excluded.

### Internal checks

Several indicators are useful to assess the validity and the quality of a multi-year solution computed with the CATREF software: time series of the weighted root mean square, time series of the Helmert transformation parameters, behavior of the station position time series and station quality checks…

#### *Weighted Root Mean Square (RMS)*

Figure 1 shows the time series of the RMS of the residuals for the EPN multi-year solution. As only a linear motion was assumed when estimating the station velocities, the time series of the RMS of the residuals reflects the noise, but also the seasonal signals which affect the GNSS stations.

The time series of the WRMS of the residuals has been compared with the results from the previous EPN multi-year solutions and shows the same noise level or a very slight increase. As with the EPN-repro2 and this new multi-year solution, the EPN switched from weekly time series to daily time series, the increase was expected. The fact that the noise level did not increase significantly encourages the use of daily positions instead of weekly positions.

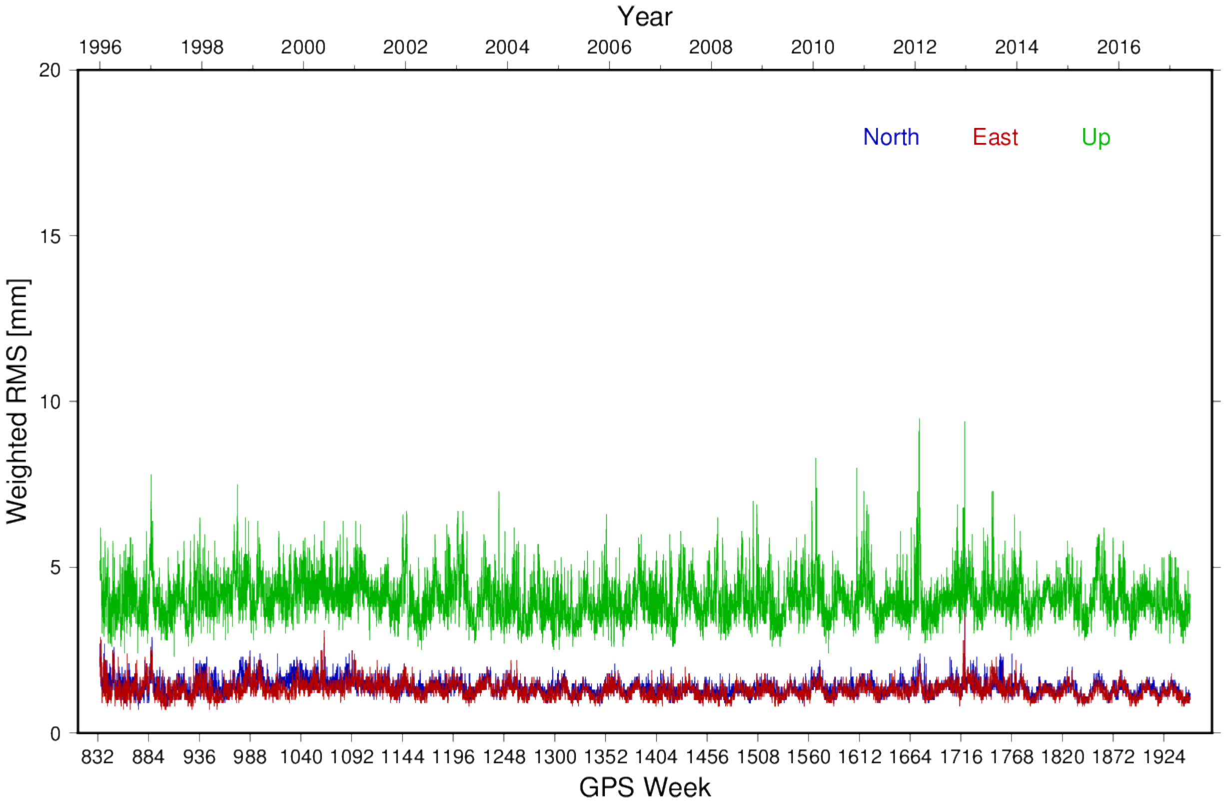



**Figure 1: Time series of the weighted RMS (North, East and Up values) of the cleaned daily combined EPN SINEXs with respect to the multi-year combination.**

#### *Helmert Transformation Parameters*

The transformation parameters shown in Figure 2 have no physical meaning and they should be taken with caution. Indeed, the daily combined EPN SINEXs have been aligned to the IGb08 (before 029/2017) and to the IGS14 (after 029/2017) with 3 translations using a set of reference stations, while the seven transformation parameters are estimated between the daily combined EPN SINEXs and the multi-year SINEX using all the stations in the network. Nevertheless, these transformation parameters are useful to check the consistency of the alignment of the daily EPN solutions with respect to the combined solution, it allows to compare the reference frame alignment of the daily solutions with respect to the multi-year position and velocity solution.

Any systematic effects (bias or tilt) are an indicator of the stability and the reliability of the reference frame definition. This is a difficult point in the frame of a regional network as position and velocities in such network are very sensitive to the reference frame alignment.

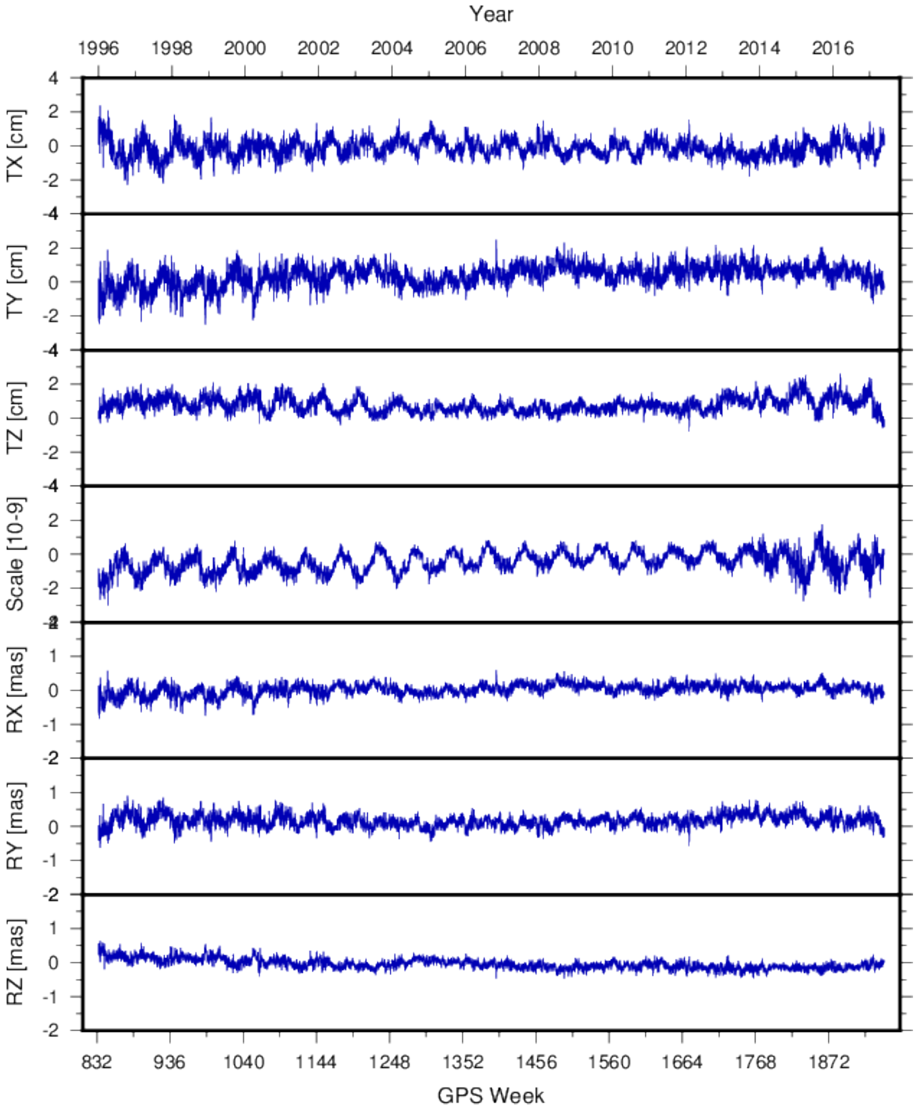



**Figure 2: Transformation parameters between the input daily combined EPN SINEXs and the EPN multi-year SINEX output of the combination. These 7 parameters shows the reference frame alignment of the daily combined EPN SINEXs with respect to the EPN multi-year solution**

Both the WRMS and the Helmert transformation parameter time series can be a good indicator of any inhomogeneity in the daily solutions. The switch from the EPN-repro2 solutions to the routine solutions can be seen at GPS Week 1773 but the impact remains small and doesn't degrade the estimated velocity field. The EPN multi-year positions and velocities would benefit of a complete reprocessing, which is foreseen in the coming years.

### *Station Position Time Series*

The residual station position time series have been visually checked in order to identify the position discontinuities affecting the position time series and to remove the outliers. Several kinds of time series have been considered:

- Position time series (with trend and position jumps)
- Detrended position time series (usefull to assess the discontinuities and velocity changes)
- Residual position time series
    - trends and jumps are removed
    - trends, jumps and annual and semi-annual seasonal signals are removed

The outliers have been removed iteratively. Except for about 10 stations which are noisier, all the residuals are below 10 mm for the horizontal components and 20 mm for the vertical components.

### *Long-term tracking performance of the stations*

In addition to the position time series, the long-term tracking performance of the stations has been inspected. Several indicators computed with the G-nut/Anubis software (Vaclavovic and Dousa, 2016) have been considered:

- the ratio of the number of observations with at least two frequencies in the daily RINEX file with respect to the number of expected observations. The elevation cut off angle as set in the station log file as well as the lowest elevation cut off actually observed in the RINEX data are also considered.
- the number of identified phase cycle slips for each constellation.
- the code multipath for each constellation on each frequency.

All those indicators and especially their variations in time give information about the health of the stations and their reliability. It helps to distinguish real station motions from motion due to changes in the satellite geometry or to signal interferences.

For example, between 2003 and 2005, several position jumps have been observed at AXPV00FRA station (see Figure 3). These jumps are not related to hardware changes documented in the site log.

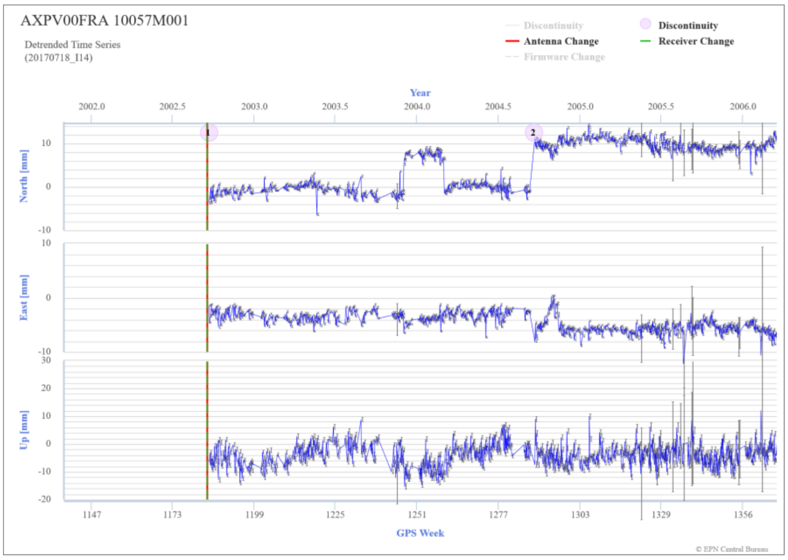



**Figure 3: Station AXPV00FRA: raw detrended position time series between 2002 and 2006.**

The ratio of the number of observations with at least two frequencies (black curve in Figure 4 ) in the daily RINEX file with respect to the number of expected observations between 2003 and 2006 shows sudden changes (December 2003, March 2004, September 2004) that can be correlated with the position changes in Figure 3.

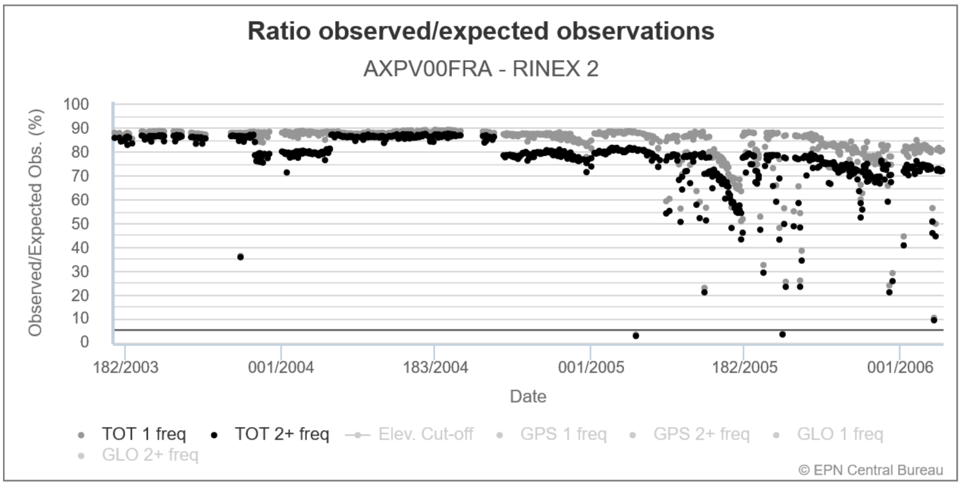



**Figure 4: Time series of the ratio observed versus expected RINEX observations between summer 2003 and 2006 at AXPV00FRA.**

In order to understand this reduction of dual frequency observations, the epoch-based multi-GNSS data quality checks have been verified. The Azimuths and Elevations of the signals tracked at AXPV in February 2004 (Figure 4) show a loss of dual frequency observations (red) at low elevations. In May, the problem was solved and the station was again able to track dual frequencies at low elevations. Such behaviour had an impact on the station positions and some discontinuities have been introduced.

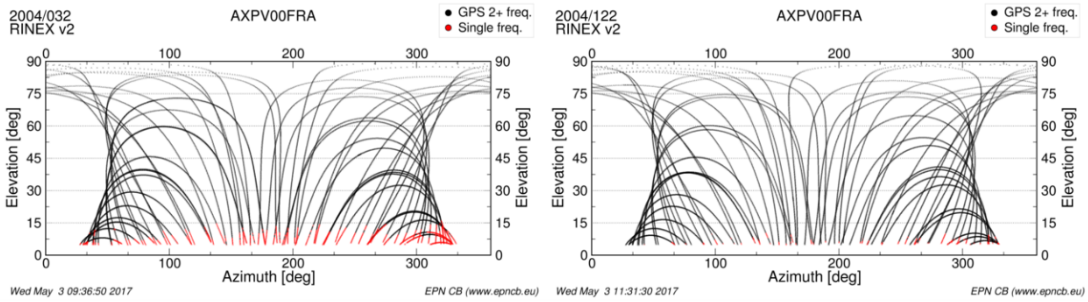



**Figure 5: Azimuth and Elevation plots for AXPV in February (left) and in May (right) 2004.**

No threshold was applied to exclude some observations, but the plots showing the long-term tracking performance of the stations and the monthly snapshots of the epoch-based station tracking have been checked for all the stations and with a special attention for the stations having unexplained behavior, position jumps or velocity changes for unknown reasons.

Both position changes and tracking performances are monitored at each release of the EPN multi-year solution, station owners are contacted when a degradation of the tracking is observed.

***List of discontinuities and velocity changes***

In cases of position jumps for unknown reason or velocity changes, the relevance of the applied discontinuity has been checked. The impact on the estimated velocities has been verified and its significance has been checked.

The list of applied discontinuities has been compared to several existing lists (former EPN discontinuity list, IGS discontinuity list,…). In case of disagreements, the causes have been investigated, whenever it was possible the discontinuities have been harmonised with IGS especially for reference stations.

***Choice of the reference stations***

The EPN multi-year solution has been expressed in IGS14 under minimal constraints using 14 transformations parameters (translations, rotations, scale and their rates) using a selection of IGS14 reference stations. A maximum number of IGS14 stations showing a good agreement with IGS14 and having at least 3 years of data in the solution and in IGS14 were retained as reference stations. In practice, only IGS14 stations whose IGS14 reference pos/vel agree better than 3 mm on the horizontal and 5 mm on the vertical positions and 0.2mm/yr on the horizontal and 0.4 mm/yr on the vertical velocities wrt their estimated pos/vel, are selected as reference stations. IGS14 reference stations computed in the EPN with individual antenna calibrations are removed first in case of disagreements.

## Comparison with external solutions

The EPN multi-year solution has been compared to several external solutions. First, the solution has been compared with the IGS14 as it is the solution used as reference solution. It has been also compared to the ITRF2014 and the previous EPN solution C1934. For this 2 last cases, the focus has been set on the velocities as the positions are affected by the underlying station antenna calibrations (igs08.atx for ITRF2014, epn_08.atx for C1934 and epn_14.atx for C1950). The solution has also been compared with the IGS multi-year solution going up to the same GPS week (IGS17P21).

For each solution, the discontinuity list, the residual position time series, the period of observations and the estimated positions and velocities have been compared and the differences have been analysed in order to understand them and to make the EPN solution as consistent as possible with the IGS solution.

As for EPOS, the most interesting comparison is the one with respect to IGS17P21, it is the only comparison shown here.

***Comparison with the IGS solution IGS17P21***

The positions and velocities of the EPN multi-year solution C1950 (GPS weeks up to 1950) agree well with the IGS solution for the same GPS week (IGS17P21). The plots below show the histogram of the position (left) and velocity (right) differences in North, East and Up components.

The positions differences are computed for each solution number at the epoch 2010.0. In Figure 6 (left), the histograms including all the estimates are shown in black. When using only stations with the same applied discontinuities and more than 2 years of observation, the RMS is 1.3 mm for the North, 1.7 mm for the East and 5.6 mm for the Up component. The histograms of the position differences for this selection are shown in red.

One velocity estimate per station has been selected, the histogram of all the velocity differences are shown in black. After rejecting EPN stations with less than 3 years of observations or less than 50% of observation completeness, the rms of the velocity differences of the C1950 wrt the IGS17P21 is 0.19 mm/yr, 0.15 mm/yr, 0.51 mm/yr for resp. the North, East and Up components. The histograms of the velocity differences for this selection are shown in red in Figure 6 (right).

Most of the large position and velocity differences can be explained by different discontinuity handling or different periods of observations (a large data gap or sparse time series affecting the IGS solution). This effect is clearly seen in Figure 7: 33 of the 212 common stations have less than 50% of observations in IGS while the same stations have more than 80% of availability in the EPN.

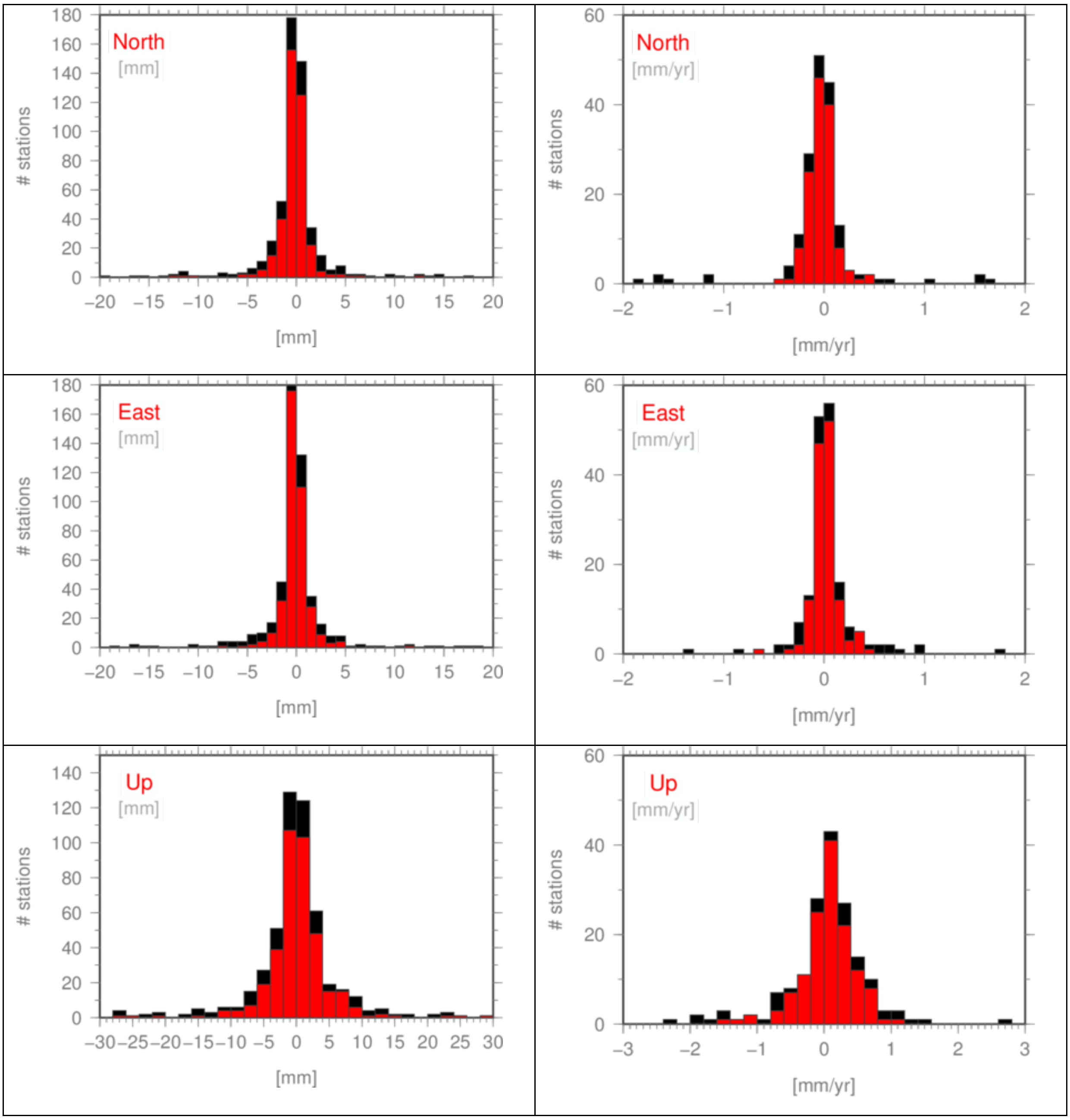



**Figure 6: Histogram of the position (left) and velocity (right) differences between the EPN solution C1950 and the IGS solution IGS17P21**

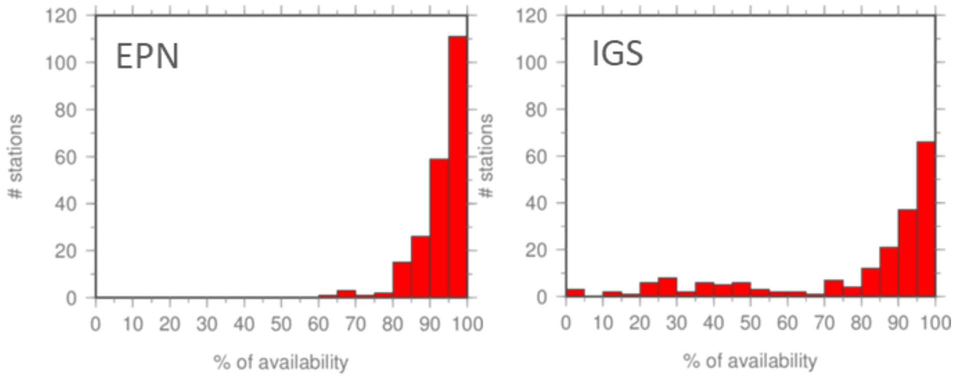



**Figure 7: Data availability in the time series (%) in the EPN solution C1950**

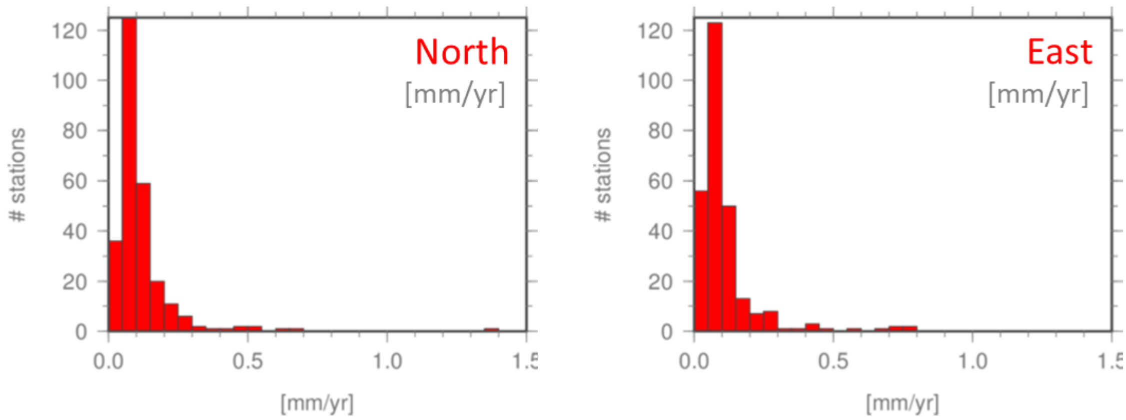
**(left) and the IGS solution IGS17P21 (right) for the 212 common stations with more than 10 weeks of observations in both solutions.**

### Comparison with Hector estimation

CATREF is a combination software based on a least squares adjustment, therefore the estimated velocity errors neglect temporally correlated noise affecting the position time series and are too optimistic. In order to assess the quality of the stations and to derive realistic error estimates, the Hector software (Bos et al., 2013) has been used to estimate a linear trend, an annual and a semi-annual signal assuming a power-law stochastic model and white noise.

For this purpose, positions, velocities and residuals estimated with CATREF were used to reconstruct cleaned and well-referenced position time series. In a second step, those position time series served as input for the Hector runs.

The Figure 8 shows the histogram of the velocity errors derived with the Hector software.



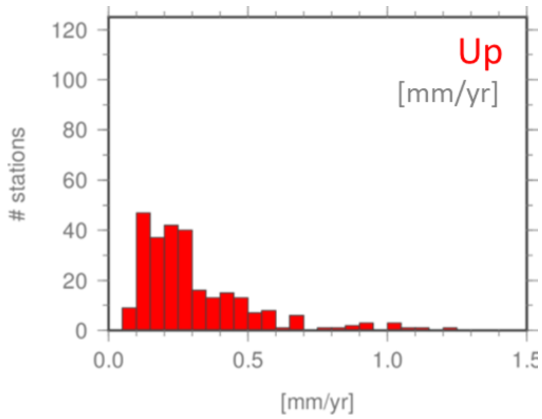




**Figure 8: Realistic velocity error estimates derived with Hector software**

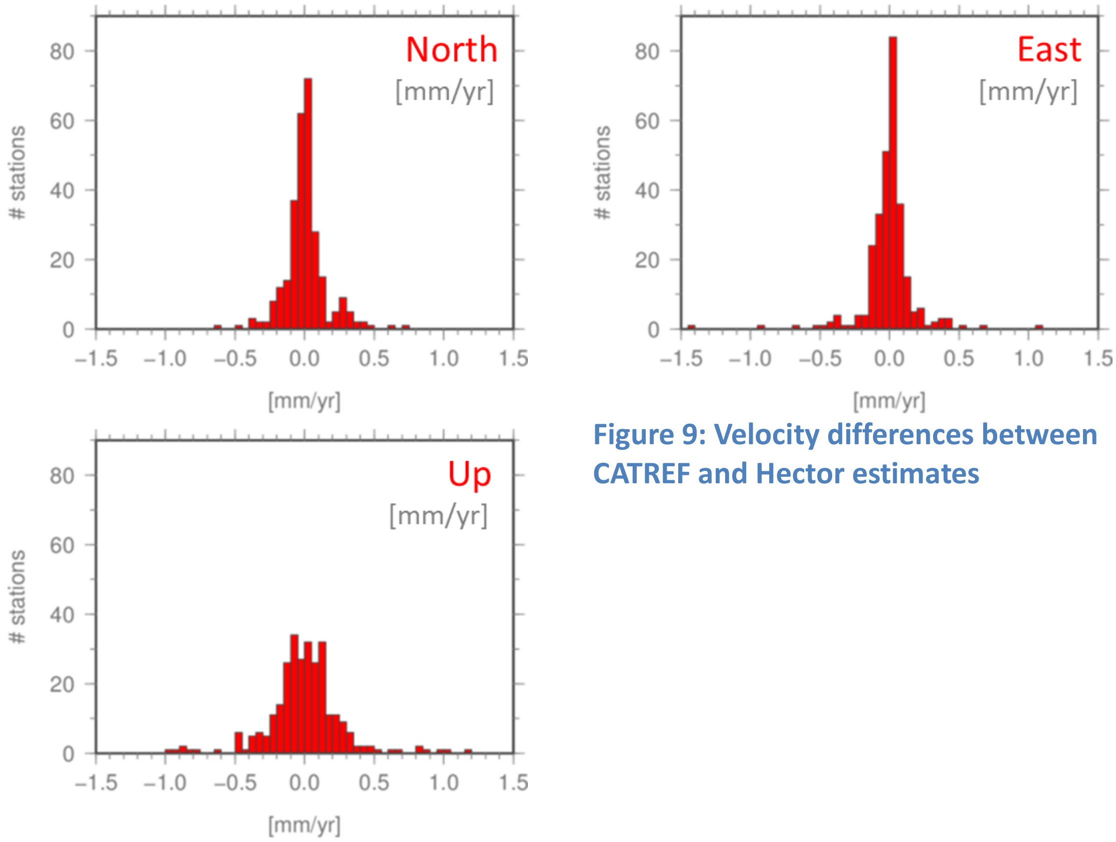



**Figure 9: Velocity differences between CATREF and Hector estimates**

The Figure 9 shows the velocity differences between the CATREF and Hector estimates. One velocity estimate has been selected per station. The agreement between both is very good and the largest differences give information on the weakness of the velocity estimation for those stations. For stations with more than 5 years of observations, most of the large differences can be explained by velocity changes within the period of observation or collocated sites (which are constrained to be equal in CATREF and not in Hector).

## EPN Classes

As not all EPN stations are suitable as reference stations, EUREF categorized the EPN stations taking the station quality and the length of available observation span into account (Kenyeres, 2009):

- Class A stations with positions at the 1 cm precision and velocities at the 1mm/yr precision at all epochs
- Class B stations with positions at the 1 cm precision at the epoch of minimal position variance of each station

Currently, the class definition is under revision. The new definition will be based on the comparison of Hector and CATREF results and the velocity errors estimated with Hector taking into account the correlated noises.

## References

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Bos, M.S., Fernandes, R.M.S., Williams, S.D.P., Bastos, L., 2013. Fast error analysis of continuous GNSS observations with missing data. J. Geod. 87, 351-360–.

Kenyeres, A., 2009. Maintenance of the EPN ETRS89 coordinates. Present. EUREF TWG 2009 Spring Meet. Feb 26-27 2009 Bp.

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