New Products of the EPN Time Series Special Project: Status Report

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Abstract

The main task of the Time Series Analysis Special Project is the monitoring of the EPN weekly combined SINEX solutions in order to further improve the quality of the EPN products. The routine monitoring involves cleaning of the individual station coordinate time series and the maintenance and publication of the detected coordinate offsets and outliers. This information has also been used for the computation of the ITRF2005 and its regional densification. Using the CATREF software (Altamimi et al 2004) cleaned cumulative solutions are also computed and analyzed. The estimated coordinates and velocities, together with the outlier and offset database are regularly updated and published on the EPN CB website.

Beyond the routine monitoring the noise and harmonic analysis of the EPN coordinate series has been started. The analysis is being done with the CATS software (Williams SD, Proudman Oceanographic Laboratory), which uses the MLE (Maximum Likelihood Estimator) approach to determine the noise characteristic and seasonal variation of the coordinate time series.

The noise analysis proved the presence of the coloured noise in the EPN time series. The use of the right noise characteristics allowed the computation of more realistic station velocity uncertainties.

The harmonic analysis covered the estimation of the amplitudes and phase lags of the seasonal signal may present in the time series. The analysis has shown moderate seasonal amplitudes, 1-2 mm for the horizontal and 2-4 mm for the vertical component. The phase lag distribution for the horizontal components are not random, well determined phase lag values were found. The up component phase lag distribution is totally different, it is more uniform without peaks. The physical reality of the phase lag values is not yet studied. The results and products are published and regularly updated at the TimeSeries section of the EPNCB website.

1 Computation of the EPN cumulative solution

The primary product of the EPN analysis is the series of the combined weekly SINEX files created at the BKG Combination Centre. The combination is based on the subnetwork solutions of the 16 EPN Local Analysis Centres. The combined solutions are tied to the actual ITRF realization by tightly constraining a subset of EPN-ITRF sites. Since GPS week 1330, the new ADDNEQ2 program (Beutler et al 2006) and the more favourable minimum constraint (MC) approach is used. During the 10 years of operation both the network of reference sites and the reference frame realizations were changed resulting in inhomogeneous coordinate series. To eliminate part of the inconsistencies (reference frame changes and misalignment) the EPN Time Series Special Project computes monthly a cumulative solution using CATREF. This software applies the minimum constraint approach to align the EPN to the latest ITRF realization (by the end of 2006 we used ITRF2000 and the following reference sites: BOR1, JOZE, GRAS, MATE, NYA1, MAS1, METS, ONSA, VILL, POTS, WTZR). The main advantage of the minimal constraint approach is that the influences of the site specific, non-stationary coordinate variations of the reference sites on the results are minimized.

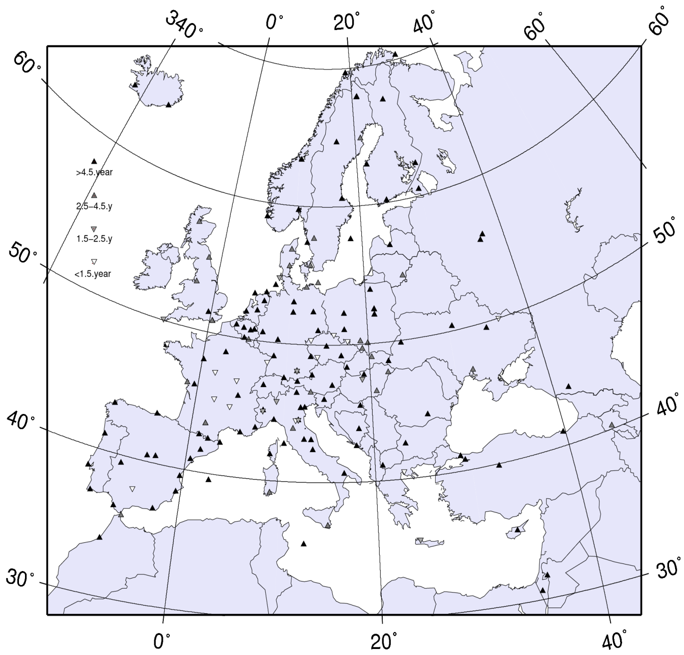


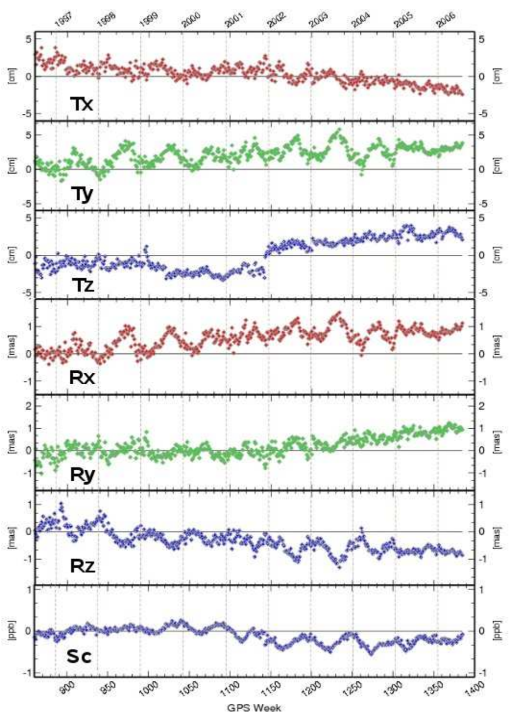
Fig. 1. Distribution and 'age' of the EPN sites (status 30.11.2006). The orientation and grey shades of the triangles indicate the length of the available data series.

The final step of the combination is a series of 7-parameter Helmert transformations, performed between the cumulative and each of the individual weekly solutions. The transformation residuals represent the time series that will be analysed. As a by-product, the values of the weekly transformation parameters are saved and plotted in Fig. 2. All parameters show a drift and an annual periodicity. The periodicity of the rotation parameters appears only for the X and Z components, while the translation parameters only have a periodicity for the Y component!

Fig. 2. The Helmert translation, rotation and scale parameters between the multiyear and the weekly

The positive offset in the Z translation at GPS week 1303 corresponds exactly to the epoch, when the ITRF2000 was introduced. The offset is caused by the reference frame difference between ITRF96 and ITRF2000 implicitly present in the EPN solutions through the IGS orbits, which are kept fixed in the EPN analysis. Similarly the new ITRF2005 also has, but a negative (-5.8 mm) Z offset with respect to ITRF2000 (Altamimi, 2006) – not yet seen on the plot. The temporal appearance of the seasonal variation of the scale between GPS weeks 1020 and 1280 caused by the tidal bug of the Bernese software.

Before starting any further interpretation of the discussed transformation parameter series it must be emphasized that the evolution of the series reflects the time variable recovery of the global reference frame by the regional network and is not necessary related to real physical phenomenon.



solutions.

During the routine analysis the coordinate offsets related to equipment change and the outliers caused by short or long term inconsistencies (e.g. snow coverage, antenna problems) are manually identified and removed from the time series. The database of the outliers and offsets are published at the EPNCB website both in a simple text file and in the internationally recognised SINEX format. An extract of the outlier datafile is presented below in Table 1.

Status: 2006:200

Station_ID	GPSweek from	to	Estimated outlier value(*) North	East	Up	explanation
ANKR_20805M002	1023	1040	[-3,3]	[0,8]	[-15,0]	Izmit EQ
ANKR_20805M002	1054	1054	-8	x	66	single_outlier
ANKR_20805M002	1266	1281	x	x	[15,55]	antenna_malfunction?
BOGO_12207M002	0860	0898	x	x	[-5,-15]	station_start
BOGO_12207M002	1123	1125	[8,21]	x	x	single_outlier
BOR1_12205M002	0943	0944	x	x	[-14,-22]	single_outlier
BOR1_12205M002	1307	1307	x	x	13	single_outlier
BORK_14268M001	1212	1221	3	x	[-8,-23]	antenna_malfunction
BORK_14268M001	1222	1224	x	x	5	temporary_antenna
BRST_10004M004	1083	1083	6	-16	-13	single_outlier
BRST_10004M004	1237	1237	x	x	14	single_outlier
BRST_10004M004	1317	1324	[5,13]	-6	x	antenna_malfunction
BRUS_13101M004	1059	1059	-3	-2	13	single_outlier
BUCU_11401M001	1002	1021	4	-3	x	station_start
BZRG_12751M001	1123	1167	[0,-30]	[0,9]	[10,-13]	antenna_malfunction
...						
...						
ZECK_12351M001	0935	0935	x	x	-34	equipment_change
ZIMM_14001M004	0886	0886	x	x	-17	single_outlier
ZOUF_12763M001	1301	1301	-4	x	-38	equipment_change
ZWEN_12330M001	1057	1066	[-34,-55]	[20,44]	[-20]	antenna_malfunction
ZWEN_12330M001	1078	1080	10	[15]	[-40]	temporary_equipment
ZWEN_12330M001	1115	1123	[-9]	[-6,-20]	[1,18]	antenna_malfunction
ZWEN_12330M001	1210	1210	x	x	27	single_outlier
ZWEN_12330M001	1274	1288	[36,0]	[10]	[10]	fragment
ZWEN_12330M001	1289	1296	x	x	[-10]	fragment

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(*) Explanation of outlier value designations:
       x         : no significant outliers for the component
  single value   : well determined single value for the week(s)
 [single value]  : typical, well determined average value for the interval
 [from, to]      : the outliers vary between the given range
```

Table 1. An extract of the EPN_outliers.www file available at the EPNCB website.

The quality of a single weekly solution is characterized by the weighted RMS (root mean square) values (see Fig. 3a,b) obtained from the multiyear combination. The quality improvement after the removal of the offsets and outliers, especially for the height component is quite remarkable. However, still some seasonal variation of the WRMS (weighted RMS) remains, with peaks around winter time; these are clearly correlated with the snow coverage of some GPS antennae. The reason of the temporary drops in the horizontal WRMS values is not yet understood, but we suspect that it caused by the improperly removed constraints from the combined solution.

The WRMS plots, given in Fig. 3a-b, stress the importance of the offset and outlier elimination from the time series. After the cleaning we obtained an RMS of 1.4, which is an improvement of 40% compared to the results obtained without any offset and outlier elimination.

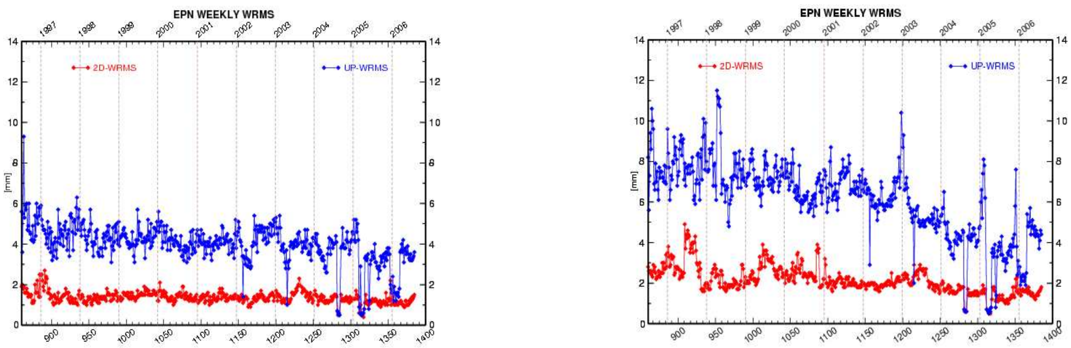

Fig. 3a-b. Weighted RMS of the weekly EPN solutions before and after the elimination of the coordinate offsets and outliers. The improvement is more than 40 %!

2 Noise analysis of the EPN series

The power spectra of the noise present in the coordinate time series is characterized by a power-law dependence on frequency *f*:

$$P(f) = P_0 f^K$$

where $\boldsymbol{K}$ is the spectral index and P_0 is a normalizing constant. The spectral index can get any floating number, but as the natural processes mostly have more power at low frequencies they are characterized by negative indices. Some integer values are assigned to special processes, $\boldsymbol{K}$=-2 is called random walk, $\boldsymbol{K}$=-1 is flicker noise and $\boldsymbol{K}$=0 is white noise. The right modelling of the real noise spectra of the GPS time series is critical, especially when station velocities are estimated. According to previous studies (Mao et al, 1999, Williams, 2003) it is incorrect to assume, like in most of the GPS processing and combination softwares, that the time series containes white noise only. A direct consequence of this mismodeling is the over-optimistic estimation of the coordinate and velocity uncertainties.

In our study we used the MLE (Maximum Likelihood Estimation) approach of the CATS software.

After the removal of the linear and annual terms we estimated the spectral indices of each EPN station (Fig. 4). The obtained spectral indices ranged between [0;–2]; the average index for all coordinate components was near –1 (flicker noise), clearly indicating the presence of coloured noise in the EPN coordinate solutions.

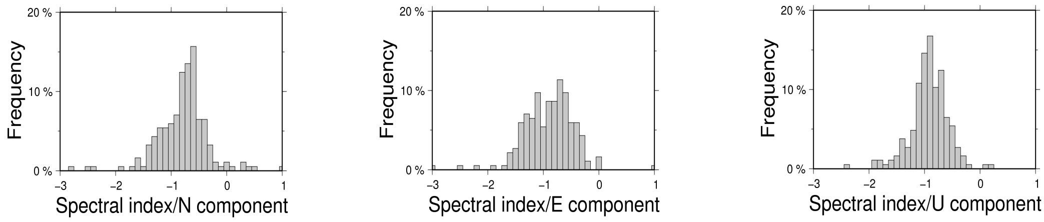

Fig. 4a-b-c. Histograms of the distribution of the estimated spectral indices for the North (a), East (b) and Up (c) coordinate components. The 'extreme' values (-2> k > 0) are from short series (> 1 year).

This result is in full agreement with the ones derived for other regional networks (e.g. Williams et al, 2004). In addition, the spectral indices do not show random walk type noise, which indicates the long-term monument stability of the sites.
The histograms of the spectral indices for each of the components are characterized by slightly different distributions. Remarkable is the diagram of the East component, which shows a less significant peak around k=-1. When the linear and seasonal terms are not removed the flicker noise is much more dominating.
Using the above discussed white+coloured noise model, we estimated the velocity uncertainties of each EPN station. The computed uncertainties were 4-6 times larger than the values coming from the white noise-only model. Since they are based on a well-determined statistical model, our values are considered more realistic. All results are available from the EPN CB website (www.epncb.oma.be) for anyone interested in geophysical interpretation.

3 Harmonic analysis

The stacking of the weekly SINEX files eliminates the inconsistencies caused by the reference frame changes and also removes a regional signal related to the time variable alignment of the regional network to the global frame. This latter can be studied through the series of the parameters of the 7-parameter Helmert-transformation (see Fig. 2). All transformation parameters show seasonal variation caused by the common movement of the EPN with respect to the global frame. However these parameters are not helpful to extract real, station-specific information. The residual coordinate time series, which are obtained after the stacking, reflect better the local behaviour of the individual stations and will be studied in the following.

Using the CATS_MLE software, the phase lags and amplitudes of the annual periodic terms were estimated. Considering the results of the previously described noise analysis the estimation was done assuming the white+flicker noise model. We found average amplitudes of 1 mm both for the North and East components and 2 mm for the Up component.
The estimated harmonic parameters were used to create new time series plots. The existing cleaned plots, showing the coordinate development of the stations in the ETRS89 frame (with respect to the Eurasian plate) has been retained, but the de-trended plots were replaced with two additional plot sets. One is the extension of the existing de-trended plots with the estimated annual sinusoidal coordinate variation and the other is the same plot, but the annual term is removed from the original one (see the examples in Fig. 5). This latter residual time series may more clearly show the

variations in the series.

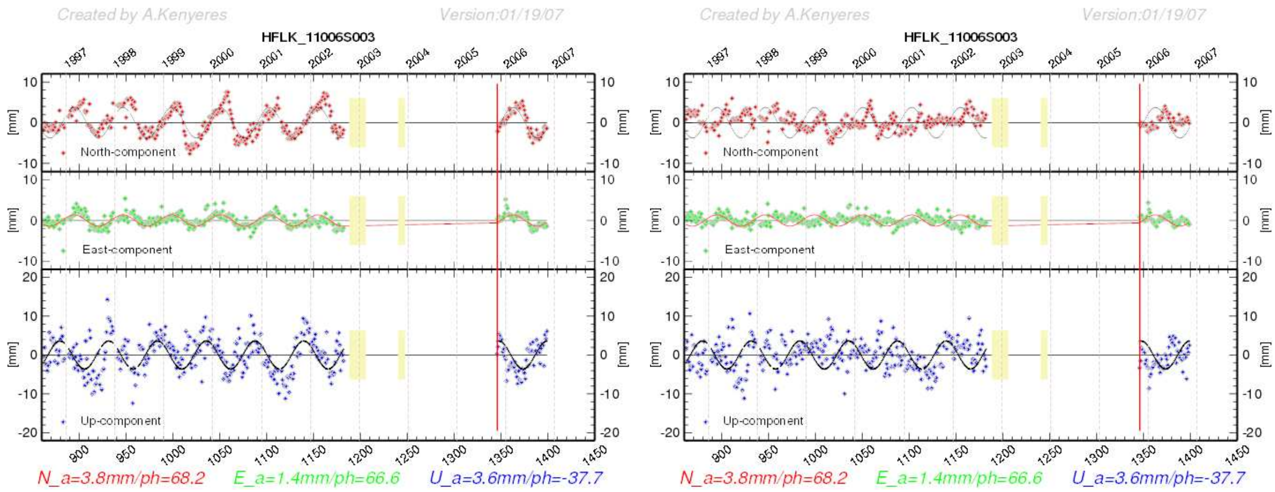

Fig. 5. De-trended time series plots of HFLK (Hafelekar, Austria). The estimated amplitude and the phase lag values of the annual signal are given at the bottom of the plots. The annual sinusoidal terms are indicated on both plots, but at the right plot the annual term is removed from the series. Similar plots are available for all EPN stations at the EPN CB website.

In Fig. 6a-b-c the normalized polar histograms of the North, East and Up components of the estimated annual periodic terms are shown. The histograms give a clear insight into the distribution of the estimated phases and amplitudes. The horizontal and vertical annual signals have a completely different phase lag distribution. While the horizontal components show two representative phase lag values of about +30 and -150 degrees (corresponding to +1 and -5 months) the vertical component exhibits a more uniform phase distribution. The geophysical models describing the temporal variation of the solid Earth do not indicate a significant annual periodicity in the horizontal components and therefore the observed distribution is most probably due to an artificial signal caused by e.g. processing and modelling shortcomings. It is expected, that when the whole EPN observation dataset will be re-processed with better and uniform models for the antennae phase centres and the atmosphere, the horizontal seasonal signal will be highly reduced.

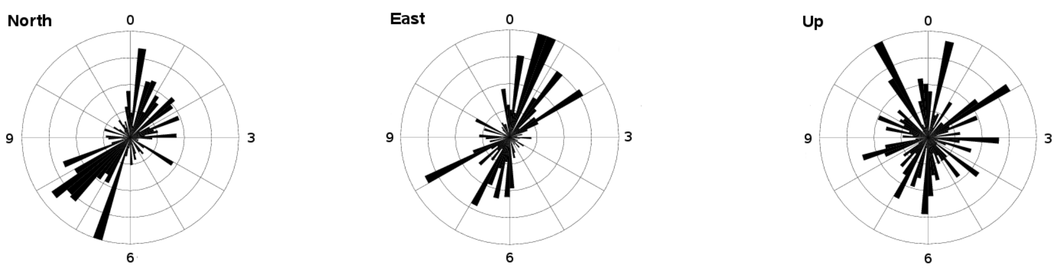

Fig. 6a-b-c. Normalized polar histograms of the estimated phase lag distribution for the North, East and Up coordinate components. The phase lags are expressed in months.

Considering the vertical component on the regional scale statistically we may not expect one representative phase lag group, because the loading variation depends on the latitude, longitude and time. However according to independent investigations (King et al, 2005) the phase lags estimated from the GPS data do not agree with the geophysical model predictions. Therefore the estimated EPN vertical phase lags also suggest modelling shortcomings.

4 VELOCITY ESTIMATION

Beyond the station performance, the quality of the estimated coordinates and velocities is also dependent on the length of the observation series. A significant portion of the EPN sites has less than 3 years (see Fig. 1) observation history. Due to the apparent noise and annual periodicity in the series those sites should be treated with caution when coordinates and velocities are estimated (Blewitt and Lavallee, 2002*)*. Fig. 7 shows an example of the dependence of the estimated velocity on the length of the observation series.

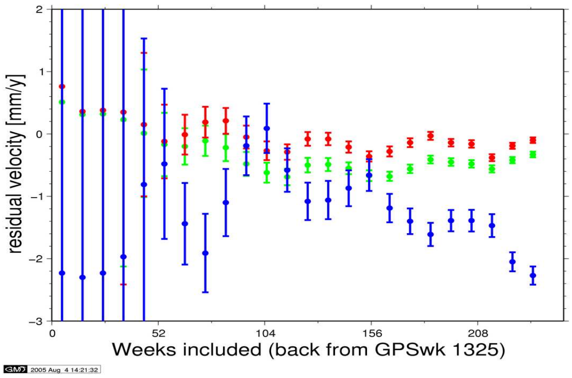

Fig. 7. Dependence of the estimated velocity on the available observations, when annual periodicity is present. This example is derived from the time series of CHIZ (Chize France), which has an annual periodic signal with 2 cm amplitude at each component.

As a compromise between targeting the highest accuracy and responding to user needs, we decided not to publish any velocities for sites having data for less than 18 months. Using the procedures explained in this paper, we compute and publish reference coordinates and velocities of the EPN stations at the EPN CB website. This information is regularly updated.

Finally the map with the estimated horizontal residual velocities is presented in Fig. 8. All velocities are relative to the Eurasian plate, where the NUVEL1A-NNR model velocities - modified by Altamimi to better fit to ITRF2000 - are used to derive the intraplate velocities. The velocity uncertainty ellipses are derived from the values we computed by CATS_MLE taking the coloured+white noise model into account.

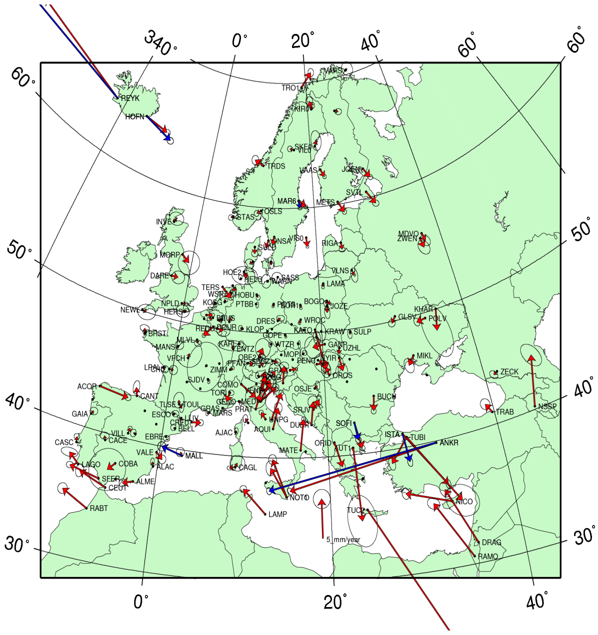

Fig. 8. The estimated EPN residual velocities wrt the Eurasian tectonic plate. Some sites has double velocity estimations, where following an event (equipment change, earthquake) the station had apparently different behaviour.

5 SUMMARY

The EPN Time Series Special Project monitors the weekly SINEX files, eliminates the observed offsets and outliers and maintains a database including the detected inconsistencies. This database is harmonized with the IGS discontinuity table used for the computation of ITRF2005. The discontinuities of the non-IGS EPN stations are used to generate an EPN solution delivered for the regional densification of ITRF2005. Using the cleaned weekly SINEX files monthly updated ITRS coordinate and velocity solutions are published on the EPNCB website. Until the regional densification of ITRF2005 will be published, these solutions are considered as the most accurate and up-to-date source of the ETRF coordinates and velocities for the EPN stations.

In this paper we presented new results of the detailed studies concerning the analysis and improvement of the EPN's long-term products as coordinates and velocities. We have shown how the performance of all stations are monitored and how the station problems are kept track and the combined weekly SINEX files are cleaned. The handling of the offsets and outliers makes 40 % overall improvement of the cumulative solution. We proved the presence of the coloured noise and we computed reliable velocity uncertainties. A general harmonic analysis was done, which just called our attention for the existing modelling problems.

In the future we plan to validate our estimation of the vertical annual periodicities with information from independent processing approaches (PPP by Bernese or GIPSY) and by comparing them with real environmental and satellite based models. We should note here that the unavoidable global and regional GPS reprocessing will provide more realistic coordinate time series for the further studies.

Acknowledgements

The stacking of the EPN weekly SINEX files has been done by the CATREF software developed by *Z. Altamimi* (IGN, France). The velocity uncertainties and spectral indexes were computed with the CATS software kindly provided by *SD. Williams* (Proudman Oceanographic Laboratory, UK). The maps and histograms were created by the GMT 3.4 software.

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