Categorization of permanent GNSS reference stations

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Abstract

The global reference frame realizations as ITRFyy[1] (International Terrestrial Reference Frame) and the corresponding IGSyy (International GNSS Service) and their regional densification solutions are published as SSC (Set of Station Coordinates and velocities) and SINEX files, where each of the included stations are treated in the same way and the coordinates refer to a single epoch. Although these realizations are considered the actually best solution, it does not mean that all involved stations have the same level of reliability. The only product quality indicators are the uncertainties rendered to the coordinates and velocities, therefore the users must pay special regard to avoid distortions in the actual applications.

In this paper the strict separation and categorization of the reference stations - which earlier were published in one single solution - is proposed. The categorization is based on the analysis of the series of consecutive cumulative solutions, where the convergence of the velocity estimates is considered as main categorization criteria. Class_A includes the reliable fiducial stations with long observation series (at least 2 years of recent data) and stable velocity parameters, and class B covers mostly young, sites, not yet fulfilling the criteria for being fiducial station, which may only be used for solution control. The categorization criteria and the related terms are described and discussed in the paper.

This approach is successfully implemented for the EPN (EUREF Permanent Network). We found that less than 80% of the EPN stations can be added to class_A, and more than 50 stations are not offered as fiducial for reference frame applications. The presented approach is straightforward and can easily be extended both to global and national long term GNSS solutions.

Keywords: reference frame, cumulative SINEX, velocity estimation, quality analysis

Motivation

The permanent GNSS networks from global to national scales are used for the realization, maintenance, and densification of reference frame solutions. The regional solutions are relying on global reference frame realizations (ITRFyy and IGSyy), while the national networks are connected to either the global or regional reference frame realizations (Europe: ETRFyy - EUREF TWG, 2008; North-America: NAREF - Craymer et al 2007; South-America: SIRG09P01 -Sánchez et al 2008). The quality and reliability of the actually used reference frame sites is therefore essential to get the best possible realization.

To measure the quality of a reference frame station could be a difficult and complex task, where numerous contributions ought to be considered. The most important factors are listed and briefly described in the "***Site quality agents***" section. The weakness of any of those 'parameters' may significantly decrease the site performance, and as a consequence they are manifested as different biases in the coordinate time series, like offsets, increased noise level, and non-linear coordinate variation. When a cumulative solution is computed, integrating all observations (in terms of daily/weekly SINEX solutions) available from each station, the site quality is indirectly expressed by the uncertainties of the estimated coordinates and velocities. The reference frame solutions, like the ITRS (International Terrestrial Reference System) realizations (as ITRF2005 - Altamimi et al 2007) and their regional densifications are such cumulative

1 yy denotes the IERS Annual Report for year yy, when the ITRS realization has been published.

solutions, where the results (coordinates, velocities and their formal uncertainties) are published as SINEX and SSC files, where the coordinates are referred to a single, pre-defined reference epoch (for ITRF2005 the epoch is 2000.0). If one needs the coordinate for a particular station at another epoch the appended velocities should be used to map the coordinates to the desired epoch.

In the practice the users should aware of the importance of the published velocity uncertainties, especially when one wishes to map coordinates far from the reference epoch. Mapping the coordinates of a reference station, attributed with higher velocity uncertainty - mostly due to a short (less than 2 years) observation history – definitely increases the coordinate uncertainties and additionally leads to biased coordinates (see Figure 1), which in extreme cases can reach up to 10 cm! Therefore the users of the reference frame solutions should devote a special care when selecting reference stations for their actual applications.

The approach of the single reference epoch is also critical when a cumulative solution is regularly updated, extending the existing solution with new data. In such cumulative solution series, newly appearing stations, having short length of observation series, may show significant coordinate and velocity variations between successive solutions. These variations will depend on the site performance and will converge only after 2-4 years of observations. As already proved by Blewitt et al, 2002, when a harmonic (sinusoidal) seasonal variation is present in a coordinate time series, the real velocities can only be estimated if the observation series is longer than 4.5 years. The situation could be seriously worse if the series is noisy and contaminated with other non-linear effects. In order to provide a clear view those effects they are listed and shortly described in the following section.

To demonstrate the coordinate variability of the young stations in a cumulative solution series an example is shown in Figure 1., where the coordinate 'evolution' of CNIV (Chernihiv, Ukraine – included in the EPN since GPS week 1400) is plotted. Each dot on the plot refers to a cumulative solution, which accumulates EPN weekly combined solutions starting at GPS week 860 up to the corresponding GPS week marked on the x-axis. At each case the computed coordinates were mapped to epoch 2005.0 using the estimated actual velocities. In Figure 1. the deviations from the mean coordinate value for the North, East and Up components are plotted. The coordinates start to converge after 1 year for the horizontal components, while the convergence for the vertical component is much slower – an attenuated annual variation is present - due to the presence of a 5 mm-amplitude seasonal signal in the original coordinate time series (see Figure 2.)

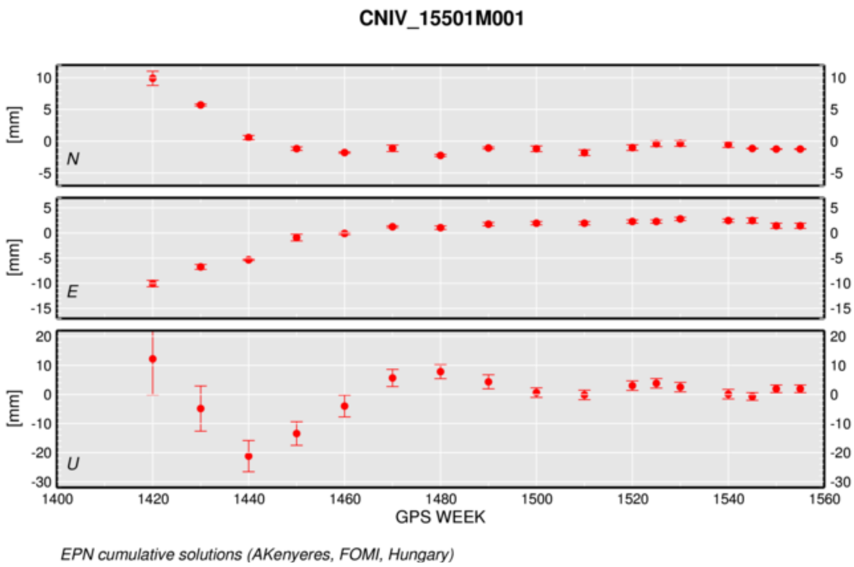

Figure 1. Series of the coordinate estimates of CNIV (included in EPN since GPSweek 1400) extracted from the consecutive EPN cumulative solutions. Each dot on the plot refers to a cumulative solution, which accumulates the EPN weekly combined solutions from GPS week 860 up to the corresponding GPS week marked on the x-axis. At each case the computed coordinates were mapped to epoch 2005.0 using the estimated actual velocities. The deviations from the mean coordinate values for the North(N), East(E), Up(U) components are plotted.

The reference frame is ETRF2000, so the effect of the plate motion is negligible. The observed cm-level coordinate variation between successive solutions and the increased uncertainties (especially in the up component) are caused by the mapping of the reference epoch from the mean epochs to 2005.0. The coordinate variation would be much bigger, when the coordinates were mapped to earlier epochs (e.g. 2000.0 as in ITRF2005). Although a permanent station should have high quality coordinates after few weeks, in the presented form, due to the mapping it must not used as fiducial station for reference frame realization/densification.

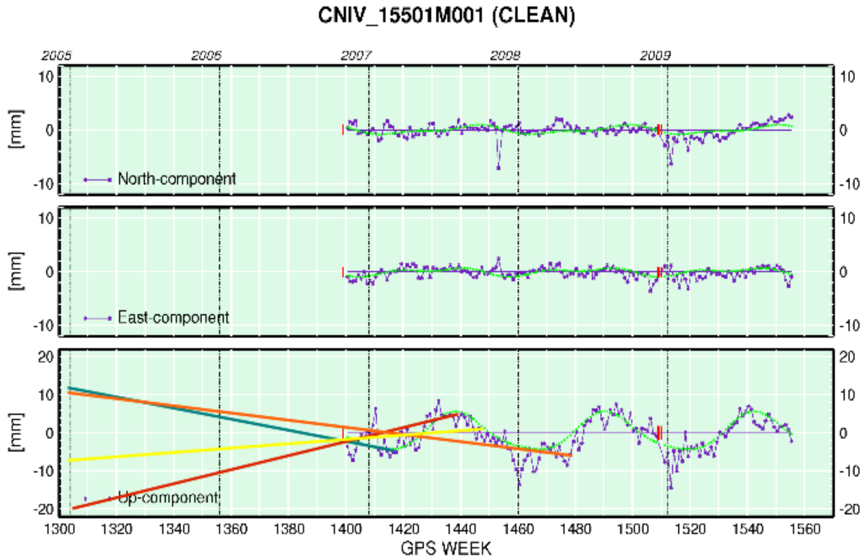

Figure 2. Coordinate time series of CNIV, Ukraine. The Up component velocity estimates, based on different observation lengths are also plotted and showing (in accordance with Figure 1) high coordinate variability.

Site quality agents

The reliability and temporal behavior of a permanent GPS station depends on various factors, which, in order to facilitate the easier interpretation and exploitation of the time series analysis results are grouped as follows:

A) ***local effects***: they give the '*personality*' of each site, but mostly these features represent deviations from the ideal/optimal settings. A far not complete list of the effects is given below with some examples and references, where the interested reader can find more details.

- Monumentation and marker: the permanent GPS stations are often installed on buildings or the selected technical solution for the monument is not in accordance with the environmental challenges (soil type, ground water, freeze, wind, temperature variation, etc.), which may lead to marker instability and systematic coordinate variations on different timescales, usually at daily and annual scales. At the Up component the separation of the real physical effects and monumentation problems on the seasonal scale is difficult, but considering the horizontal components, an annual signal above 1 mm amplitude (perfect EPN examples are HFLK and CHIZ) should come from the weakness of the monument (thermal effects) as the environmental models do not predict significant seasonal effect for the horizontal components (van Dam et al 2007).
- Geometry of the environment: any nearby objects may cause code/phase/near field multipath, which can significantly bias the observations, may decrease the success of the ambiguity resolution and may also introduce seasonal pattern into the time series. More details about multipath can be found in Hannah 2001. The near field multipath is considered relevant, as high percentage of the antennae are mounted on pillars, where the pillar-top is a nearby reflector surface (Wübbena et al 2006). Nearby objects may also block the satellite signal reception causing significant, azimuth-dependent satellite cutoff, which also bias the observations.
- Stability of the environment: if the long term temporal stability of the site environment cannot be

maintained, the time-variable contributions, as trees growing/cutting/trimming, surface reflectivity changes (snow coverage during wintertime) bias the coordinate and velocity estimation.

- Electromagnetic disturbances, interferences: any sources broadcasting near to any GNSS frequencies (or their overtones) could significantly degrade the GNSS data quality.
- Antenna quality and PCV (Phase Centre Variation) modeling: the different hardware/software technologies applied by the manufacturers to suppress local effects (multipath, interferences) should be carefully considered. Today an acceptable quality can only be reached by antennae having absolute PCV model (Böder et al 2001). Unfortunately the local effects may overwrite even the individually calibrated PCV solutions, we still observe coordinate offsets after antenna replacements,
- Conscience of the site operator: the site operator plays important role in the site maintenance (e.g. cleaning the radom) and also providing site log with authoritative records.

The handling and possible correction of the local effects are representing the hardest 'nut' in the GNSS analysis as each site is unique and no general modeling solution is available yet.

B) analysis artifacts

Inside the error budget they represent a less critical group with decreased site dependence, and having the opportunity of the gradual removal by re-processing of the actual dataset.

- software bugs,
- modeling deficiencies can appear at any stage of the GNSS processing, decreasing (or better to say: not yet fully exploiting) the technique capabilities and site performance. Best example is the introduction of the absolute PCV models in 2006, which brought a huge improvement in the coordinate time series with respect to the previously used relative models (Rothacher, 2001). At the other hand inadequate models simply introduce spurious harmonic signal (e.g. tidal modeling Penna et al, 2007) in the height component.
- analysis deficiencies: when a long term, densification cumulative solution is computed, due to the network effect the coordinate and velocity solution could be biased (Legrand et al 2009; Kenyeres et al 2009).

C) real (geo)physical contributions

In geodesy, a high quality reference station is characterized by stable, linear coordinate variation, where any non-linear (harmonic, exponential) effect decreases its usefulness and value. What is a nuisance factor in geodesy, the same is considered as signal in geophysics and can be well studied and interpreted using the GNSS observations:

- nearby tectonic activity (earthquakes) may introduces coordinate jump and the follow-on tectonic relaxation process results in non-linear coordinate variation,
- the presence of harmonic annual or semi-annual signals in the GPS *height* time series is a natural phenomenon and in theory it should be well correlated with the variable load of the Earth crust by the atmosphere, terrestrial and oceanic water masses. As most of the instrumental and modeling problems appearing in the height component time series former studies reported weak agreement between GPS estimates and loading/GRACE models over Europe (van Dam et al. 2007). Using the re-processed IGS series better agreement was found, but the agreement with the EPN estimates is still weak (Kenyeres et al. 2009). As negligible loading effect is predicted by the models in the horizontal components a seasonal signal in the GNSS estimates over 1 mm amplitude should be related to monumentation or analysis/modeling problems.

All factors listed here have different kind and level of impact on site quality. Their ***objective*** 'measurement' or estimation is hardly possible and would require detailed, in-depth information about the site and its performance. We can conclude however, that all of the treated site quality agents are directly or indirectly reflected in the coordinate time series in terms of offsets, noise, harmonic and other non-linear coordinate variations. The in-depth study of the original station coordinate time series and the derived cumulative coordinate series can provide reliable quality information for an affordable effort.

Station categorization

The idea of permanent station categorization came from the experience that occasionally some users of the reference frame solutions did not take the importance of the velocity uncertainties into account and did not consider the danger of using less accurate data for network alignment. A solution was sought, which provides the up-to-date information and in which the reliable, and the still not 'consolidated' stations are well distinguished and firmly separated. Partially we have to give up the tradition of publishing all sites and all information in single SSC and SINEX files with a single reference epoch. The traditional SSC and SINEX files should only be published for the fiducial stations, while for the others only reduced information should be provided. As concluded, the main source of the problems is that user applications require coordinate epoch mapping of the reference solution which results in degraded reference coordinates for sites having unreliable velocities. Therefore velocities should not be made available for stations not conforming pre-defined criteria, and instead of the uniform reference epoch, their coordinates should refer to the station-dependent epoch of minimum variance[2].

A permanent GNSS station can be considered as geodetic reference station, when its coordinates are known within a certain accuracy limit at any epoch of its lifetime. This simplified definition implicitly involves, that the site velocity must be known precisely, at least at a level, which corresponds to the coordinate accuracy and lifetime requirements. Considering e.g. the geodetic reference networks the usual ***coordinate accuracy*** expectation is 1 cm, and if this should be modeled and maintained over 20 years the station velocities should be known better than 0.5 mm/year accuracy. This term should not be mixed up with the ***coordinate stability***, which supposes negligible site velocity (remaining at the 1 cm stability over 20 years this means maximum 0.5 mm/year intraplate velocity). In geodynamics the accuracy requirement is even higher, usually velocities should be known better than the 0.1 mm/year level.

Although the primary definition is related to the coordinates, the practical realization of the station categorization would have difficulties if exclusively a criterion based on the coordinates would be considered. The main reason is that the coordinate time series of almost all stations are contaminated with jumps from equipment changes, where the book-keeping of the offsets and the tracking of the offset-free coordinate variation impose complications and loss of consistency.

Instead of the coordinates, the velocities should take over the basic role in site categorization. In the normal combination procedure the estimated velocities are the tool to map the coordinates from the epoch of minimum variance to the predefined epoch, and then the users can map them to any further epochs. Additionally in the combination procedure the velocities are constrained to be the same before and after a coordinate jump, indirectly meaning that the velocity estimate getting independent of the offsets (exceptions are rare and well established). Consequently the station categorization procedure can easily be simplified to the study of the convergence and stability of the velocity estimates.

In 'static' cases (official ITRS realizations, IGS network and regional frames), when a single coordinate/velocity estimate is published in each few years, the only measure of the site accuracy/quality is the given ***single*** uncertainty estimate, which is not always sufficient to serve as categorization criterion. In contrary, when a cumulative solution is regularly updated ('dynamic' case) a series of coordinate and velocity estimate will be available for all sites, which allows the tracking of the convergence and stability of the cumulative coordinate/velocity estimates (see Figure 3). Using the series of velocity estimates and setting up certain quality measures the permanent GNSS sites can be easily categorized and the set of reliable reference stations can be separated.

2 The epoch of minimum variance is a mathematical term, which obviously refers to the epoch with the smallest variance of the solution. In the ideal case, it is equivalent with the mean epoch, but depending on the distribution of possible data gaps and variable noise level it may significantly deviate from the mean. For a mathematical description of the epoch of minimal variance, we refer to Altamimi et al., 2002.

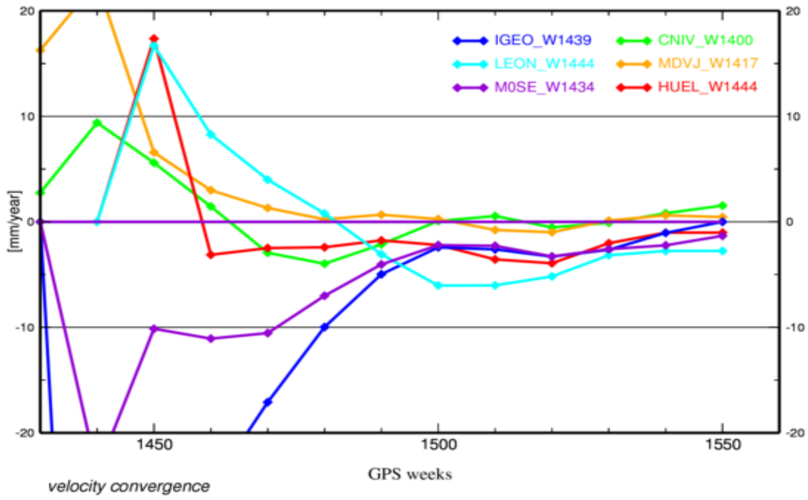

Figure 3. Convergence of the vertical velocity component estimates of selected, recently installed EPN stations. Each 10 weeks, - including all EPN weekly SINEX files from GPS week 860 to the actual week, marked on the x-axis - an updated EPN cumulative solution was computed and the estimated velocities were plotted. The installation date (in GPS weeks) of the stations are shown on the plot legend.

The convergence of the vertical velocity component, extracted from the successive EPN cumulative solutions is shown on Figure 3. for a selected set of recently installed EPN stations. As seen on the plot the newly installed permanent station shows significant velocity variation during the first year, then the velocity starts to converge to the real value. The convergence depends on the magnitude of the noise level and the amplitude of the annual signal present in the original coordinate time series. The velocity repeatability (the RMS scatter with respect to the mean value) of the last few velocity estimates can be the measure of the convergence and the approximation of the nominal value.

Following the classical EUREF categorization rules for the campaign stations (Gurtner et al 1997) similar categories can be established for the permanent GNSS stations:

- class_A: 1 cm-accuracy coordinates for any epoch of the station's lifetime and better than 0.5 mm/year velocity repeatability,
- class_B: 1 cm-accuracy coordinates for the epoch of minimum variance, that way the reference epoch mapping of the coordinates is avoided. The reference epoch is different for each site, and changes in the consecutive cumulative solutions. The velocity repeatability is worse than 0.5 mm/year, the values themselves are not published!

The categorization practically means, that a newly installed station starts its life in class_B until both its velocity formal error, coming from the cumulative solution, and the velocity repeatability, computed from the series of velocity estimates as RMS deviation from the mean value decrease below 0.5 mm/year. This parameter corresponds to the 1 cm coordinate reliability over 20 years and also validated by tests, focusing on the right epoch selection of the category upgrade. Within EUREF the main target and main consequence of the categorization was that a EUREF densification campaign can only be accepted as class_A if only class_A EPN stations are used as fiducials (Bruyninx et al 2009).

The monitoring of the velocity estimates has been elaborated to track the station performance, and promote stations with better performance to be declared fiducial station as early as possible. If we would follow the strict theoretical rule derived by Blewitt and Lavallée 2002 we should wait at least 4 years to get the best velocity estimate, and to declare a station as reliable fiducial station.

In the EPN, each 5 weeks an updated cumulative solution is computed using the CATREF software (Altamimi et al, 2004). Based on the series of gradually extending cumulative solutions a procedure has been elaborated to manage the station categorization:

0./ the station's 'lifetime' starts when it is activated in EPN,

1./ during the first 2 years the station is kept in class_B, without checking,

2./ after having two years of observations it is moved to class_A, if:

a.) the velocity repeatability of each components (N,E,U) computed from the last 10 estimates (approximately one year back from the actual epoch) is below 0.5 mm/year, **and**

b.) the square root of the squared mean of the 3 velocity ***uncertainty*** components for the last cumulative solution is also below 0.5 mm/year,

c.) when a station is inactive for more than two years - although fulfilling the class_A velocity criterion – it is moved to class_B.

When a young, class_B station fulfills the above requirements it is moved to class_A, explicitly meaning the publication of its velocity estimates and changing the reference epoch from the epoch of minimum variance to the predefined epoch. To minimize coordinate jumps when a station is upgraded from class_A to class_B the class_A epoch should be between the reference epoch of the used reference frame (ITRF2005, epoch 2000.0) and present. In the current realization the class_A epoch was set to 2005.0.

In Figures 4-6 examples are shown to demonstrate the effectiveness of this approach. The plots are created analogously as Figure 1., see the description there. Such plots for all EPN stations are available, and accessible on the EPNCB website (http://www.epncb.oma.be/_trackingnetwork/coordinates/plot.php?station=site_domes_number, replacing in this link the actual site name and domes number).

Figure 4 shows the cumulative coordinate estimate series of CNIV, after the implementation of the above categorization rules. Comparing this plot with Figure 1, the advantage of the approach is clear, in early stage stable coordinates can be derived and served. Although CNIV coordinate time series (Figure 2) has significant Up component seasonal variation, the station can reach the class_A status (green dots) after 3 years.

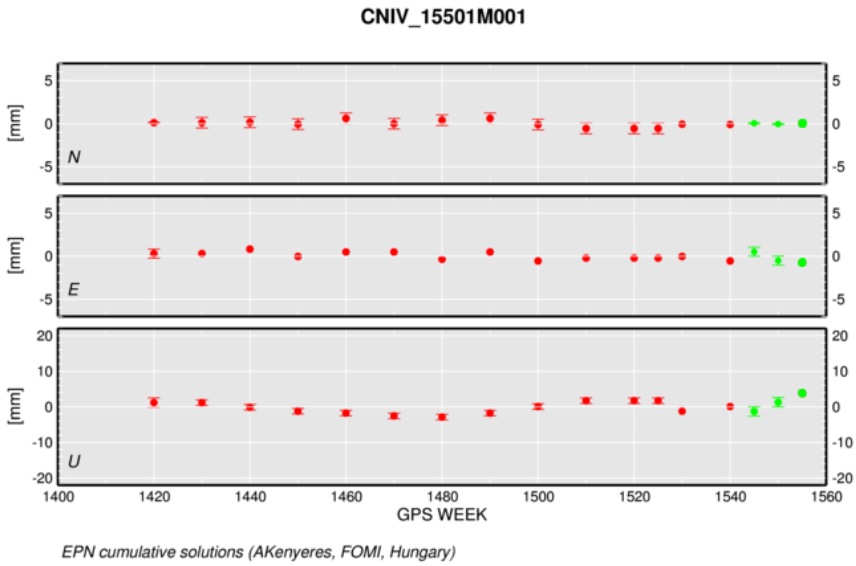

Figure 4. The categorized cumulative coordinate estimate series of CNIV (Chernihiv, Ukraine) station in local (N,E,U) coordinate system. The red dots correspond to class_B with variable reference epoch (from early to late 2007), and the green dots are for class_A and refer to epoch 2005.0. The coordinate variation is only few mm and only a negligible offset is seen at the category change.

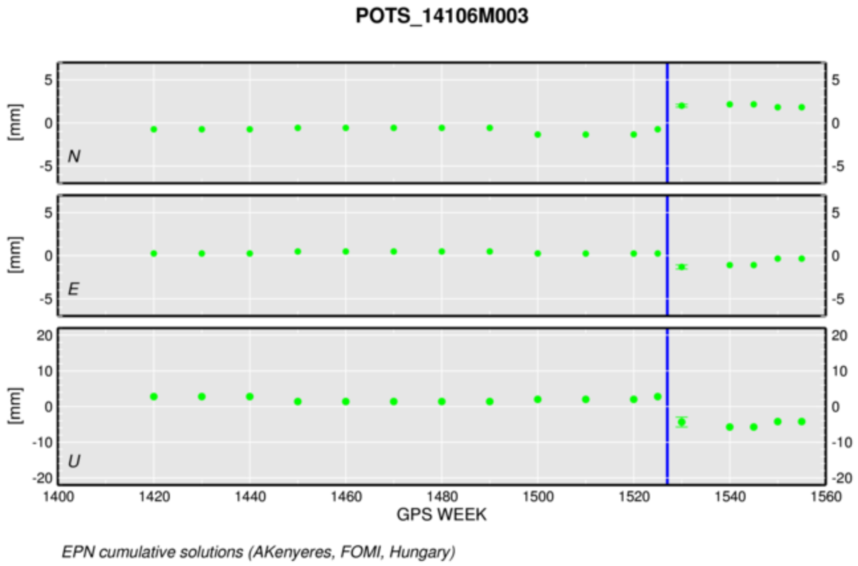

Figure 5. The categorized cumulative coordinate estimate series of a high quality fiducial station, POTS (Potsdam, Germany) in local (N,E,U) coordinate system. The blue line indicates an offset, due to an equipment change. The first solution after the offset has slightly higher uncertainty, as when it was computed still less data was available to estimate the coordinate for a new partial solution. The coordinates refer to epoch 2005.0, within all partial solutions they are stable on the 1-2 mm level.

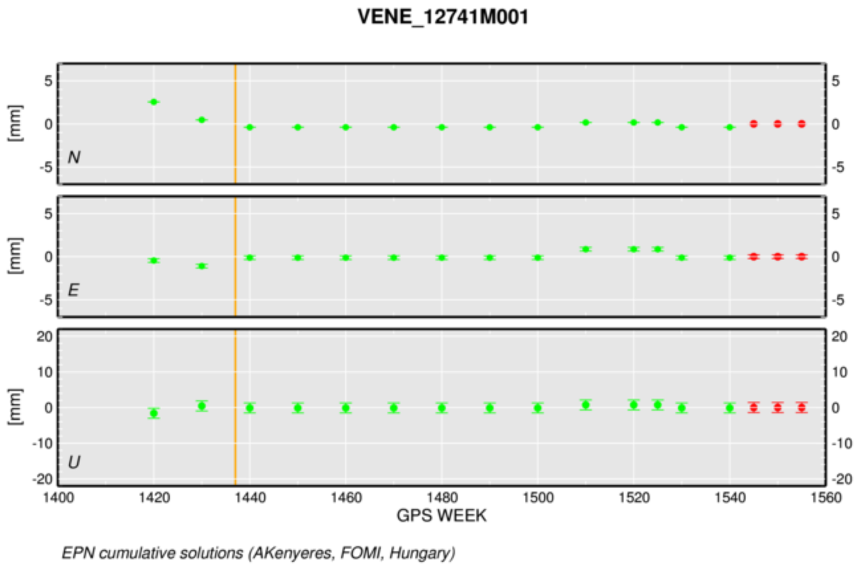

Figure 6. The categorized cumulative coordinate estimate series of VENE (Venezia, Italy) in local (N,E,U) coordinate system. The orange line corresponds to the date when the station was withdrawn from the EPN. After 2 years of inactivity the station was moved to class_B.

Within the EPN this categorization scheme has been fully implemented in 2009. The EPN cumulative solution in the form of SSC and SINEX files is maintained and published on the EPN Central Bureau website (http://www.epncb.oma.be/_trackingnetwork/coordinates/index.php). Although intermediate cumulative solutions are computed each five weeks, the EPN database is only updated each 15 weeks.
As described in the EPN densification guidelines (Bruyninx et al, 2009) only the class_A EPN stations are promoted to use as fiducial station. Class_B stations may also be included in such campaigns, but they may serve verification purposes only and cannot be included in the set of datum definition stations. Although EPN operates and accepts only high quality permanent sites, about 50 stations (as of late 2009) were moved to class_B (see Fig.7), but half of them are inactive or withdrawn for more than 2 years and the rest is younger than 2 years!

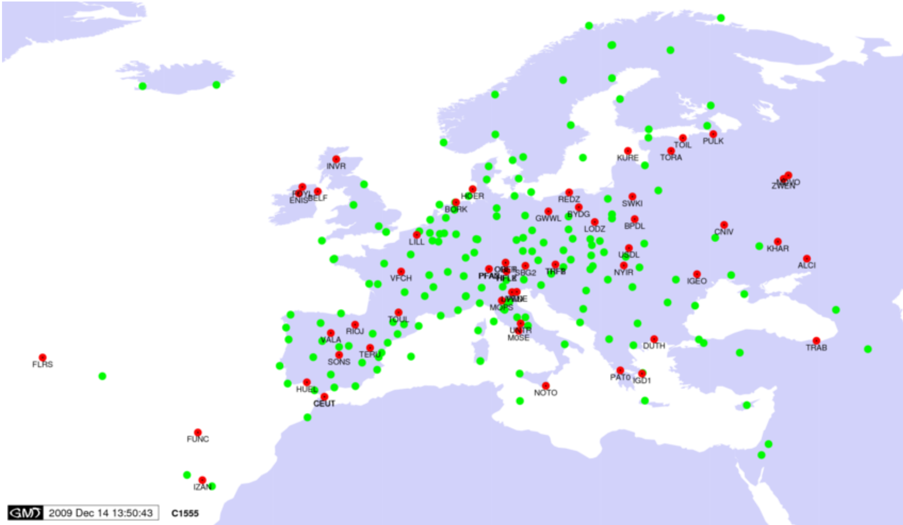

Figure 7. The map of the EPN indicating the site categories as of December 2009.
(classy_A – green dots; class_B with name – red dots)

Summary

The geodetic reference frame solutions are based on space geodetic observations, where the permanent GNSS tracking stations are playing crucial role. These reference frame solutions are intended to be used by a wide community for both scientific and practical purposes. This paper proposes an approach to evaluate the long-term performance and coordinate/velocity reliability of the permanent GNSS stations. The main emphasis is on the firm separation of the high quality fiducial stations (class_A) and the stations, which are still not feasible to be used for reference frame definition on regional to local scales (class_B). The presented approach is based on monitoring of the consecutive long term cumulative solution series, where the convergence and stability of the station velocity estimates are investigated. Based on empirical criteria the categorization of the treated reference network stations can easily be done. The class_A (fiducial) stations are treated on the 'classical' manner, where both coordinates and velocities are published in the SSC and SINEX solutions and the coordinates are refer to a single epoch. For class_B stations only the coordinates are published and they refer to the epoch of minimal variance, which is different for each station. The presented approach has been successfully implemented for the EPN, and can easily be extended or adapted for any permanent GNSS networks from global (IGS) to local scales. Beyond EPN, a categorization case study has already been successfully performed for the Hungarian National GNSS Network (GNSSnet.hu) as well.

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