OTKA K-109464 project

European velocity model based on permanent GNSS networks

Final report

The primary purpose of this project was the integration of the dense, national permanent GNSS networks based on the long term, homogeneous processing results provided by the network operators. We are delivering a unified, high quality database of station positions and velocities, which will support later on the (semi-) kinematic geodetic reference frame realizations and will be highly exploited by geophysicists preparing large scale interpretations of the European tectonic processes.

The solution scheme is the following:

(1) Supporting the national level positioning needs countries are operating dense (60–90 km average inter-station distance) permanent GNSS networks. Beyond the maintenance of the positioning services the responsible institutions are routinely processing the data with scientific software (BERNESE, GAMIT, GIPSY …), following a uniform strategy elaborated and offered by EUREF. In the frame of EUREF and EUPOS (later on EPOS as well) the processing results were gradually made available for the project purposes, largely thanks to the cooperation network I established beforehand in other operational programs.

(2) We performed the network-wise testing of the processing results made available as of daily and/or weekly SINEX (Software INdependent Exchange format) solutions. The tests comprised the (1) checking of the meta-data (station identifiers and descriptors) availability and validity. This information should be available as station log files and/or processing support files (*.STA or station.info). Due to the independent establishment of the national GNSS networks, numerous naming overlaps were identified. (2) based on the multi-year combination of the observation sets the derived time series were used to identify and eliminate outliers, erroneous and noisy sections and (3) also we identified the dates, where mostly antenna changes or other unknown reasons caused position offsets, which should be taken into account in the consecutive combination steps. The standard input solution was the weekly COV (covariance) SINEX, if any solutions were submitted as NEQ (normal equation) SINEX it was converted to COV SINEX. These tests were performed either on daily or weekly SINEX files, but at the end the daily ones were converted into weekly resolution as the combination, due to the large amount of data were not feasible on the daily level.

(3) The network-wise homogenized, filtered weekly SINEX files then had been merged on the weekly level and we created a series of weekly SINEX solutions, where each of them included all SINEX information were available on that specific week. This step also encompassed a checking option, where we could cross-check stations available in more than one network solution. An important advantage of this kind of combination appeared here: at certain stations included in more solutions with not completely overlapping data content the combination should provide a more homogeneous and stable solution. Important investigation was here the testing the weighting of the different solutions in the combination and to find the optimal weight parameters. The EPN weekly solutions had been used as “skeleton” at each combinations.

(4) The last step of the integration is the multi-year combination of the combined weekly SINEX solutions and estimation of the cumulative position and velocity database as the primary product of the project.

By nature, all processing steps had been realized through several iterative steps in order to gradually eliminate all data inconsistencies starting with the large ones in one hand and for the upgrade and integration of the most recent, new solutions on the other hand.

Up to the end of the extended project lifetime we received new network solutions to be included (Scandinavian countries and Turkey at the end of 2017) and including them we could reach the best possible continental coverage, but we still expect solutions from the Balkan countries (Slovenia and Croatia). Those solutions will certainly be included in a later release of the combined product..

The network and the amount of data we handled were continuously growing with the consequence of demanding human and IT capacity needs. Now it is not anymore possible to perform the combination steps even on a high capacity PC, the server we procured at the beginning of the project became the essential tool.

The high level utilization is also valid for the combination software: we use CATREF software, developed by Z Altamimi, IGN, France, which is also the tool of the generation of the global ITRS reference frame realizations. Without its new version, where the software can exploit the multi-core server environment speeding up considerably the analysis, we could not complete our combination job.

Here some statistical parameters are provided about the data we collected and used:

- the data from 31 networks is available, 3 of them cover more countries (MON, CEGRN, IGN), and two are global (SGN, BIGF):

Network	country	GPS week from-to	comment
AGRS	The Netherlands	0782 → 1929	
AMO	Austria	1632 → 1933	
ARA	ARANZADI, Spain	1750 → 1933	
ASG	Poland	1632 → 1929	daily
BIGF	UK	0900 → 1831	global
BUL	Bulgaria	1417 → 1933	daily, GAMIT
CAT	Catalonia	1408 → 1933	
CEG	Central-Europe	1632 → 1933	
CZE	Czech Republik	1800 → 1933	
DEN	Denmark	1096 → 1933	
DSO	Greece	0834 → 1930	
EST	Estonia	1448 → 1933	
FGI	Finland	1000 → 1933	
GGI	Latvia	1751 → 1933	
GKU	Slovakia	1408 → 1933	
GRE	Greece	1721 → 1933	
GRF	Germany	1632 → 1933	
IBE	Spain/Portugal	1632 → 1933	
KAN	Turkey	1512 → 1877	GAMIT
LTU	Lithuania	1456 → 1933	
MAO	Ukraine	1100 → 1933	
MON	Middle-East	1632 → 1933	
NGI	Belgium	1656 → 1932	
NOR	Norway	1304 → 1877	
RGZ	Serbia	1632 → 1876	not public
ROB	Belgium	0938 → 1933	
SGN	France	1774 → 1933	global
SGO	Hungary	1200 → 1933	
SWE	Sweden	0887 → 1933	
TRK	Turkey	1513 → 1824	GAMIT
UPA	Italy	1632 → 1933	

- The complete database contains 4027 stations (point which appeared in ANY input SINEX solution), even if they are erroneous or having too short observation series;
- altogether we collected 12726 weekly SINEX files with ~28 GB storage requirement;
- the length of the data series varies between 0.5 and 16 years, the distribution statistics are shown on Figure 1 and 2.;

- the final solution includes 3192 stations, where 3053 are European, the rest are global;
- the solution being published however contains only 2350 stations, because due to some quality reasons, given in the next chapter, the results had to be filtered;

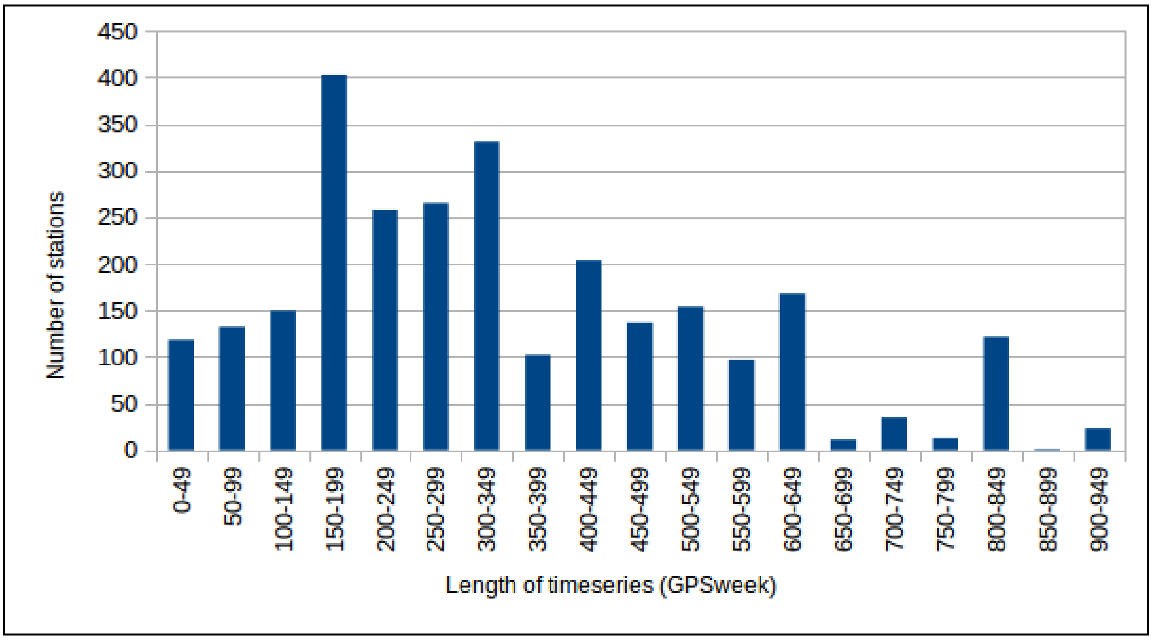


Figure 1. The histogram of the length of the data series measured in GPS weeks.

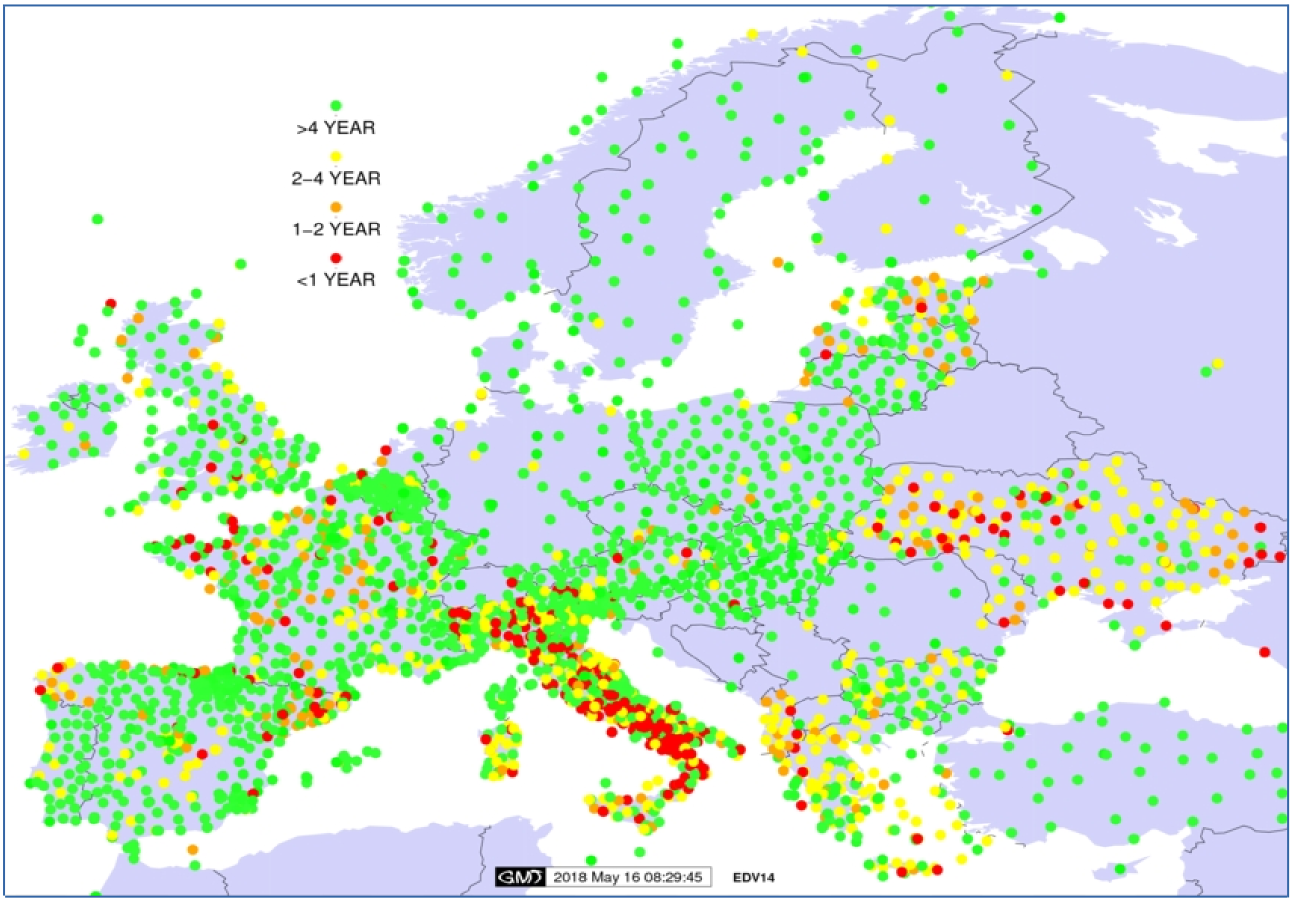


Figure 2. Distribution of the points with color-coded length of the data series.

In order to satisfy the homogeneity criteria, in the final combination we exclusively included network solutions computed using the IGS08/IGb08 antenna model (IGb08.atx), while in the earlier tests all available solutions, also computed with the IGS05 model were involved. This is why we see at several solutions GPSweek 1632 as starting date (04.17.2011), the date of the introduction of IGS08. Earlier starting dates reflect reprocessed solutions. The closing date (GPS week 1933 – 01.28.2017) is also related to reference frame change as after this date the solutions are already available in IGS14.

The biggest part of the work was the data preparation and the multi-level, iterative processing. We could successfully collect enormous amount of data, well beyond our expectations, which could have been built up gradually entering new network solutions with the consequence that the checking and combination had to be performed several times. However, a unique amount and homogeneous database had been built up, which can be exploited at several interdisciplinary research and application fields.

There was a further quality step ahead in the final solution compared to the test ones: the final solution, as the initial milestone of a later series of integrated solutions had been prepared and published in the ***ITRF2014*** reference frame. This solution has numerous advantages:

- the ITRF2014 solution is the latest global reference frame solution (2016) with more input data, more reliable frame parameters,
- IGb08 has already shown the signs of degradation because of the old reference epoch (2005) and the largely decreasing usable reference stations – in ITRF2014 we could use twice more stations as shown in Fig.3.,
- ITRF2014 is based on the IGS reprocessing, which IGb08 parameters, therefore we are in complete agreement,
- ITRF2014 allows the use of post-seismic deformation (PSD) models, describing the non-linear position variation followed by relevant earthquakes and also the modeling of the seasonal (annual and semi-annual sinusoidal) position variations.

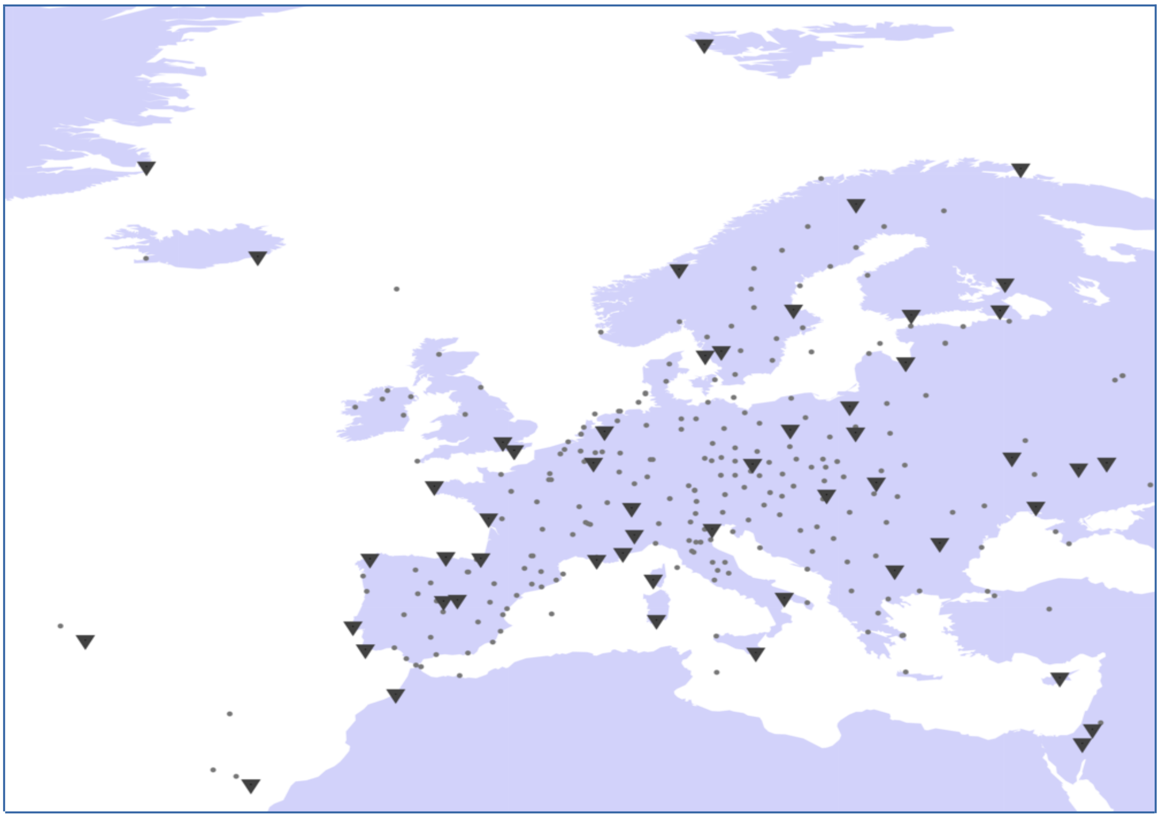


Figure 3. The distribution of the ITRF2014 reference stations (triangles) used for the realization of the combined solution. The gray dots indicate the ITRF2014 stations.

The European-scale database had been set up in the frame of the project comprises (1) the processing results for all included stations, (2) the corrected metadata (station identifiers, equipment …), (3) bad, filtered single data and data periods, (4) cumulative position and velocity values. Beyond the aggregated data the experience, expertise and analysis environment set up during the last years represents high value for several fields of later use.

Velocity results

Based on the multi-year observation series we can estimate the position changes of the given stations as of a linear velocity and seasonal variation. In our process the velocities were estimated by CATREF as the output of the multi-year combination process.

Our primary interest is the linear velocity estimate, where we explicitly suppose that this is due to the large scale tectonic processes. However for the reliable linear velocity estimation – proven by simple mathematical derivation - we need at least 2.5 year length of clean observations just to eliminate the seasonal effects. In the presence of noise the required time span should be considerably longer.

In Fig.4. we show the horizontal velocity field, expressed in ETRF2000, relative to the Eurasian continental plate. Stations with shorter than 3 years of observation lengths are indicated with green dots only. Without such default filtering a chaotic velocity distribution could be seen, making hardly observable the main tectonic regimes as of Fennoscandian post-glacial rebound (radial velocity distribution due to the dome-like uplift) and the complex tectonic patterns of the Mediterranean region.

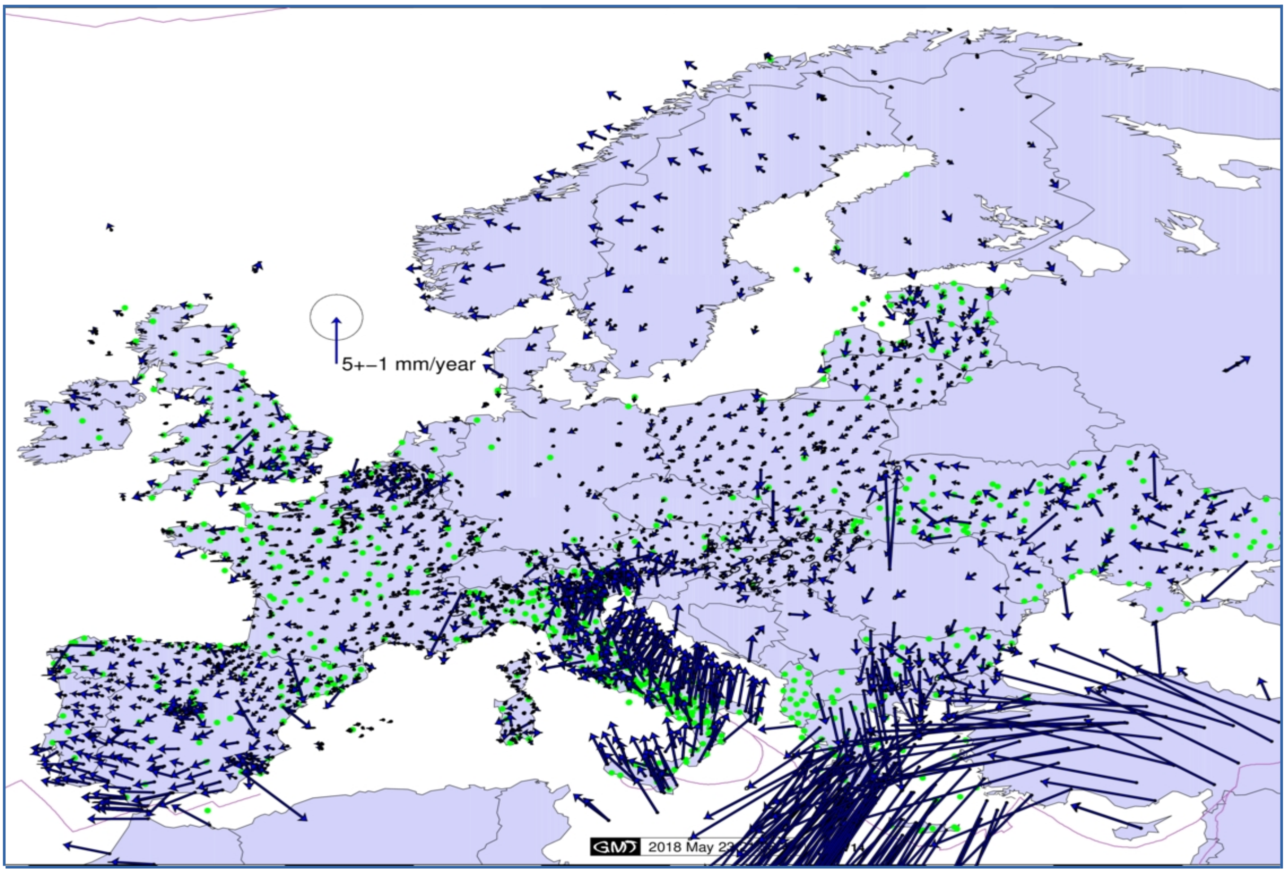


Figure 4. The horizontal velocity field of the combined solution expressed in the ETRF2000 reference frame, relative to the Eurasian continental plate. The green dots are indicating stations where we have shorter than 3 years of observation series.

The height variations are shown in Fig.5., where we can also observe the main patterns: (1) the general subsidence primarily due to the sediment compaction, (2) Fennoscandian and Scottish PGR uplift, (3) the rise of the Alps and the Southern Apennines.

This uniform velocity field from Svalbard to Crete will be an essential reference tool for later large scale studies.

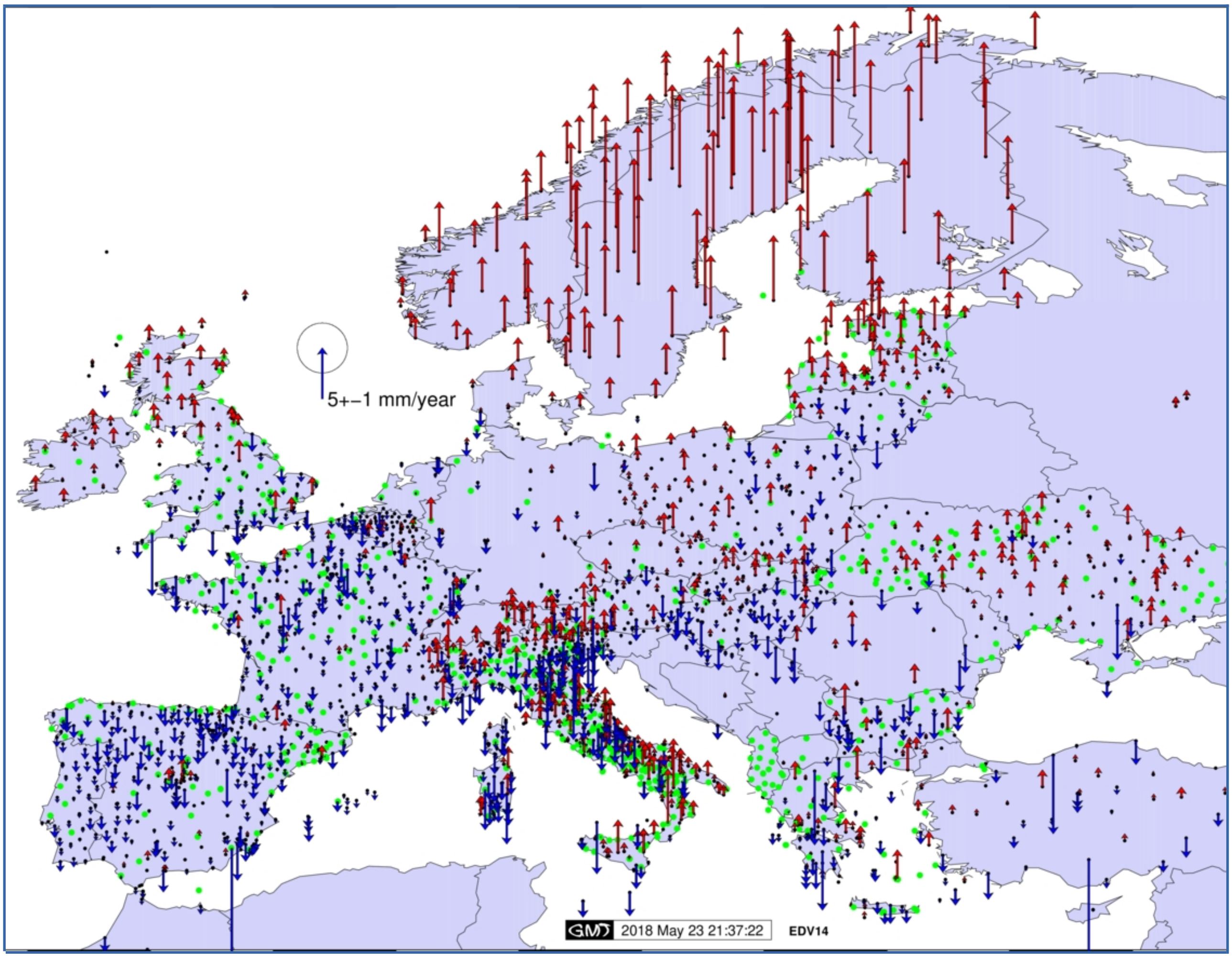


Figure 5. The vertical velocity field of the combined solution. The green dots are indicating stations where we have shorter than 3 years of observation series.

Despite of the default elimination of the velocities based on data shorter than 3 years in both plots we can observe stations with velocities seemingly not well representing their tectonic environment, local effects may overwrite that.

The station specific effects may grouped as follows: (1) monumentation issues (as everyone knows the general purpose permanent GNSS stations are built on rooftop of buildings and in numerous cases the instability of the building or the monument itself (foundation, roof structure, thermal expansion …) distorts the time series), (2) lower data quality (equipment or multipath), (3) disregarded position offsets, (4) real small to medium scale effects (water extraction, mining).

Beyond the extreme large outliers, easily observable on the overview maps in Fig. 4-5., there exist certain questionable cases on the 1 mm/year velocity level (or below), which can be identified and marked only with mathematical testing. To facilitate the refined velocity filtering investigations based on the the available publications we set up the list of main tectonic units in Europe (see Figure 6.). Let us assume that on a given tectonic unit the velocity pattern can be described as a spherical rotation and the velocities within a small threshold should be considered as equal.

We performed such velocity testing on all identified tectonic units using 3 different algorithms. The work related to the filtering including program development (Python libraries) and visualization of the results had been done by a young researcher Bálint Magyar works in the SGO.

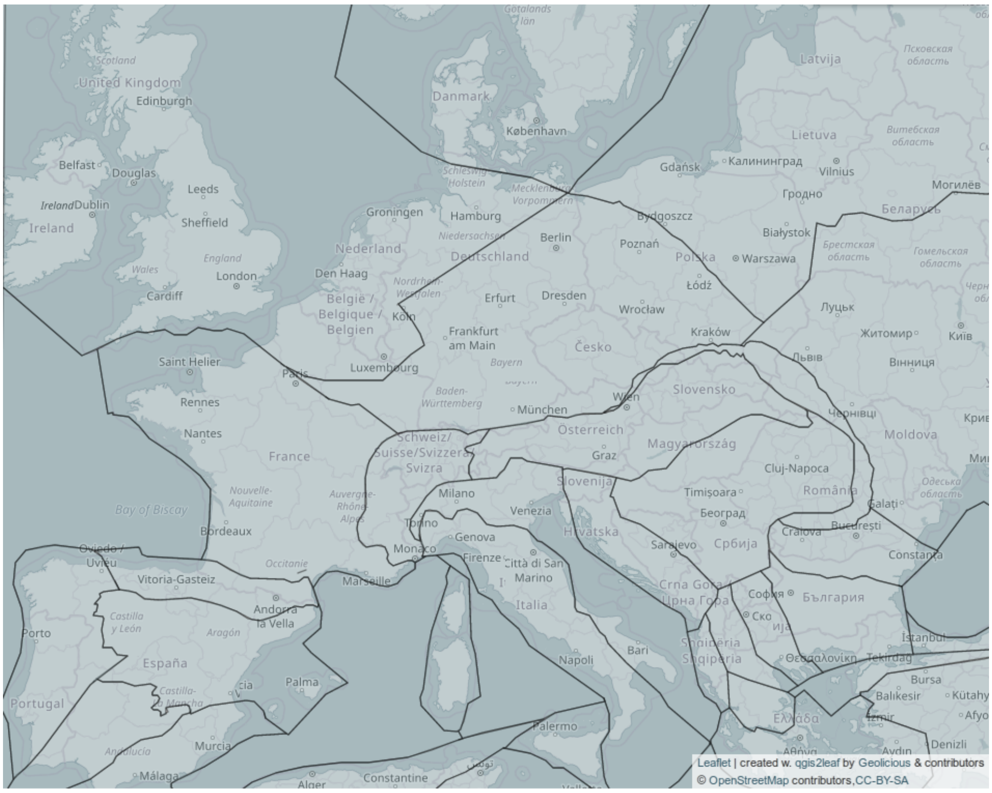


Figure 6. The identified tectonic units.

In Figure 7. the velocity field of the Tisza-Dacia tectonic unit is shown, where we tested three filtering algorithms:

- robust covariance
- empiric covariance
- OCSVM (One-Class Support Vector Machine) algorithm

According to our general experiences the OCSVM algorithm provided the most realiable results, but we considered important to open an additional option for a manual testing and correction, where the analyst can interact manually and able to consider additional information for example the time series of any selected station. In Figure 8. we also show a screenshot of the Tisza-Dacia Unit analysis being done by the velociRaptor software. This is an extremely useful tool, opening the option for the analyst to check selected stations and identify not yet detected time series issues may responsible for the biased velocity.

Performing the above analysis for all tectonic units we set up a refined velocity field, which only contains the filtered values. We also prepared a web-based publication solution, where the OpenStreetMap provides the map background for the velocities (see in Figure 9.). The combination of the map and the velocity display was not a straightforward, easy solution, this required programming and developing expertise.

At this phase the map for the horizontal velocities – which is the primary interest for the user groups – is prepared, but later the height velocity map will also be published.

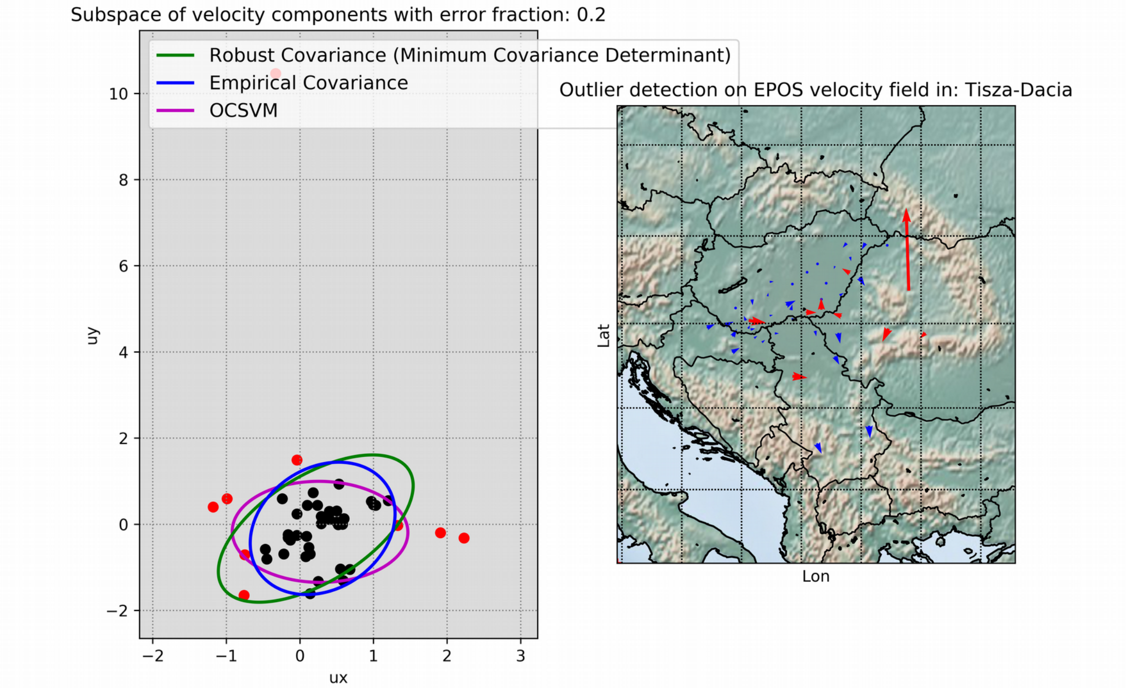
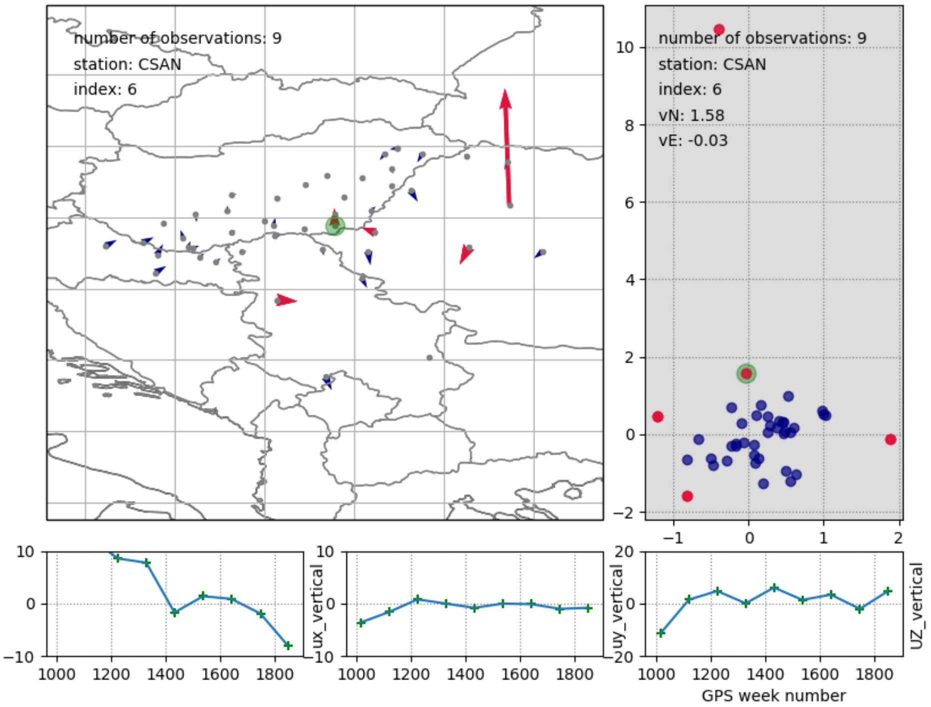


Figure 7. The velocity field and the filtering approaches for the Tisza-Dacia tectonic unit. Blue arrows indicate the velocities kept in the solution and the red ones are marked as outlier. In the left hand side graph we see the velocity component distribution, where the red dots are indicated the filtered points. The ellipsis corresponds to the different filtering algorithms, they delimit the filtered points. The largest outlier is CLUJ situating on the building of the Astronomic Observatory, which most probably moves downward on a slope.


number of observations: 9
station: CSAN
index: 6

number of observations: 9
station: CSAN
index: 6
vN: 1.58
vE: -0.03

Figure 8. A screenshot of the interactive velocity filtering tool. The interpretation is supported by the time series of the selected station – in this example CSAN (with biannual campaigns) - where the analyst may have the opportunity to update and modify the the automatic filtering.

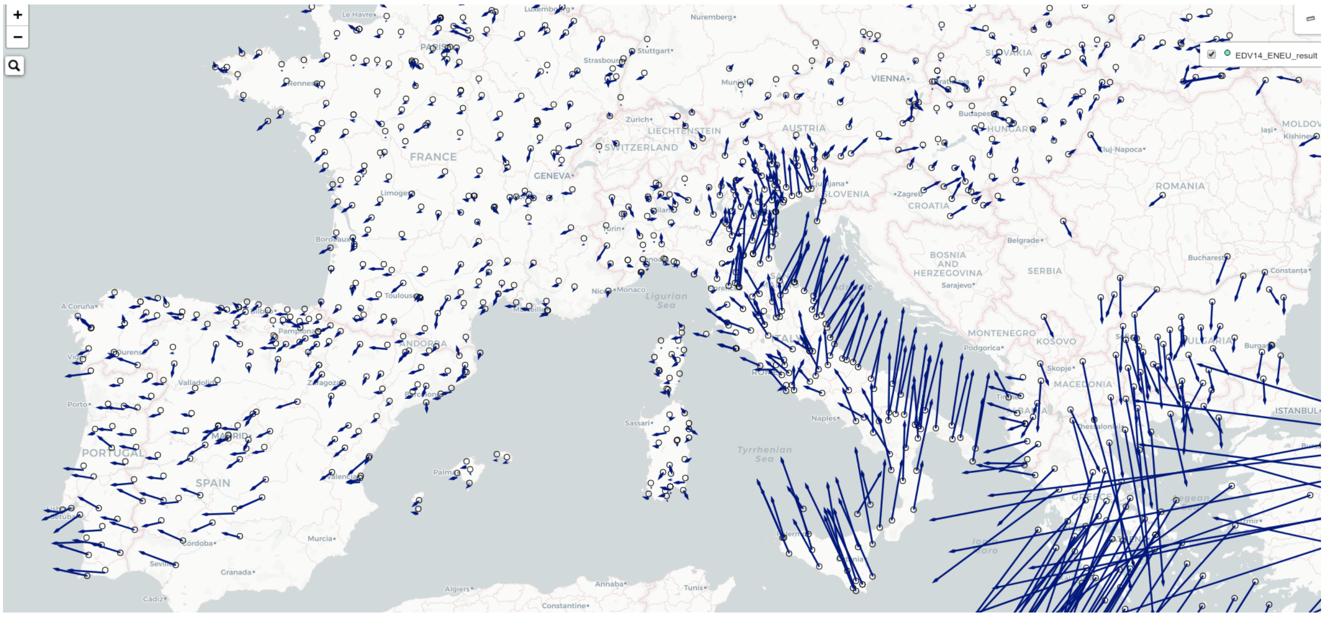


Figure 9. The filtered velocity field visualized in a geoinformation framework (QGIS). Clicking on single stations basic information as name, coordinate, velocity components) are appearing.

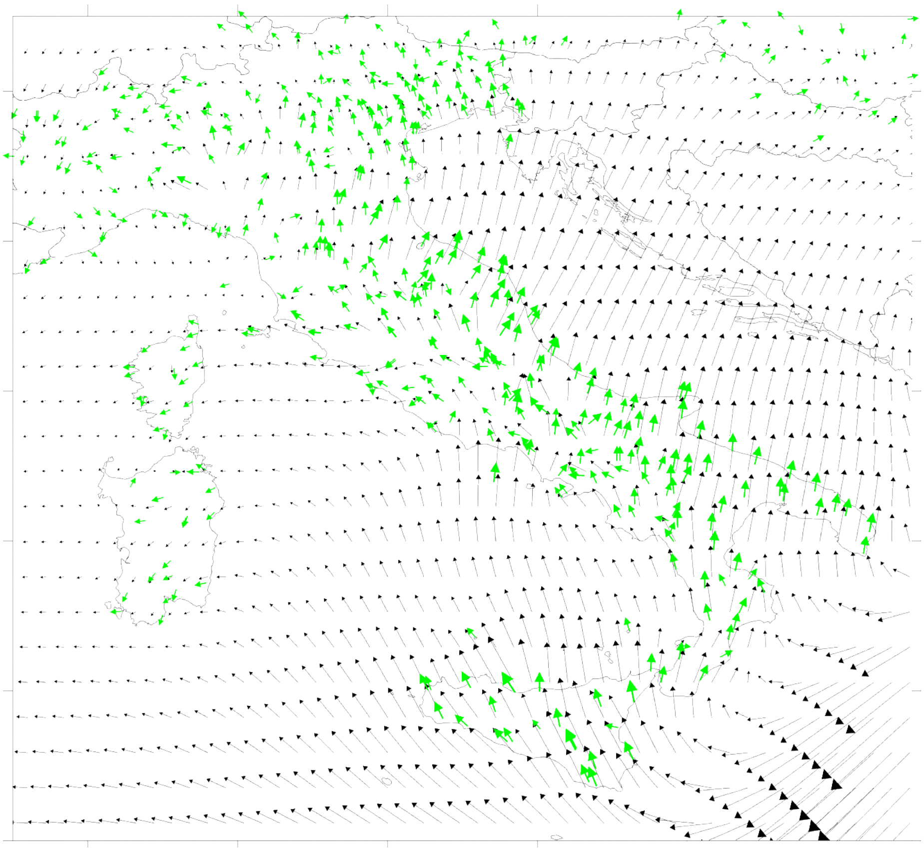


Figure 10. Interpolated horizontal velocity solution for the Italian territory, based on the combined velocity solution available at randomly distributed stations (green arrows.).
We tested several interpolation approaches and finally selected interpolation technique was the krieging.

Publicity

The product level network integration is known in the international community as EPN (EUREF Permanent Network) Densification. The results are published on the EPNCB website (http://www.epncb.oma.be/_densification/). We built up an information system, which includes the lists and descriptions of the stations (log files, meta-data, station equipment) and the results in graphical and numeric forms made available for everyone.

During the project lifetime we regularly gave status reports in the form of oral and poster presentations at relevant international conferences as the EUREF annual symposium, EGU and AGU General Assemblies.

Beyond the presentations in the frame of the established cooperation I contributed to the publication of two refereed paper published in renowned journals.

Based on the results achieved in the project a dedicated paper is prepared and being submitted to GPS Solutions. In this paper we put in the international context of this unique integration process and we publish the official results offered for the user community. The high level interest on the results establish our expectation that later we can be part of several highly ranked international cooperation.

Continuity and future activities

The closure of the current project does not mean at all the closure of the work. Within new frameworks we continue on long term our activity related to the network integration!

The most important agent will be the EPOS (European Plate Observing System) ERIC, starting its operational work in 2019. ***EPOS ERIC*** will be a European level research infrastructure related to Earth physics, where the networks and products of seismology, volcanology, Near-Fault Observatories and GNSS networks will be distributed in the frame of Thematic and Integrated Core Services.

Partially thanks to our results achieved in the present project we had been invited to be part of EPOS ERIC and to continue our activities on long term and deliver integrated velocity solutions to be published in the EPOS services. We are going to combine the daily processing results of the two pan-European Processing Centres (INGV, Italy and UGA-CNRS, France) and deliver combined times series and station velocities. We also deliver the results of EPN Densification.

EPOS ERIC will be one of the relevant European research infrastructures, where the Hungarian participation is our elementary interest. The project, which aimed the preparation of EPOS ERIC provides some support, but afterwards we would certainly need national (governmental or institutional) resources to maintain the long term work.

Further relevant future application field should be the ***European Ground Motion Service*** (EU-GMS), initiated in 2017 and probably starts acting also in 2019.

EU-GMS targets the realization and maintenance of the European level map of surface motions derived from long term satellite radar interferometric (PS-InSAR) data analysis.

As PS-InSAR is a relative technology, a homogeneous continental scale height velocity database is needed as reference and ground truth to connect the independently derived patches of relative motions derived from series of satellite radar images. EPN Densification should be the ideal tool for this purpose.

In April 2018 I attended the EU-GMS Task Force meeting in Copenhagen, where there was a general agreement on the use of GNSS height velocities for the mosaicing of the PS-InSAR solutions.