

## GPS PROCESSING TOOLS FOR BETTER IMPACT ASSESSMENT OF EARTHQUAKES IN ROMANIA

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*Abstract.* Nowadays, advances in GNSS receivers technology and computational algorithms such as 1 Hz acquisition rate (and even more, up to 50 Hz), that are commonly available, make us search worldwide for systems & algorithms that would make possible a real-time estimation of waveforms and coseismic displacements. The present paper highlights the results obtained in recent years by looking at the Romanian GNSS data over 3 different study cases from another perspective, aims to elaborate on a number of issues and provide some directions for future work that involve nontraditional seismological sensors such as GPS and tiltmeters following the implementation of the new generation of tools into GNSS permanent reference network data processing, in help for a more accurate assessment of the Vrancea earthquakes impact.

*Key words:* GNSS, high-frequencies, GPS seismology, VADASE.

### 1. INTRODUCTION

The National Institute for Earth Physics (NIEP) developed a regional GNSS (Global Navigation Satellite System) network for monitoring the Carpathian-Danubian-Pontic space deformations and the impact of local earthquakes. The modern Romanian GNSS network started in 2001, when the first permanent station was installed on the Lacauti peak in the mountainous zone of the Carpathian Bending Zone, West of the Vrancea epicentral area. Nowadays the network has 30 real-time operational stations. Main objectives such as monitoring the surface expressions of the crustal changes occurring in and around the Romanian Carpathians and the neighboring tectonic units, as direct result of the tectonic processes viewed at a larger scale (for example on the Northeastern flank of the Africa-Europe interaction) and observation of the crustal motions in order to better understand the surface-to-depth interconnections of intermediate deep earthquakes with shallow expressions in the Vrancea zone, can be highlighted [1]. The GNSS network can also provide improved, reliable, high-accuracy environmental measurements for global weather forecasts,

climate monitoring, ionosphere and space weather analysis, earthquake precursors (ionospheric studies), coseismic studies, GNSS positioning and navigation, and other research for complementary purposes such as GPS seismology. Since GNSS technology was successfully used for the first time to estimate baseline components at the centimeter level of accuracy [2], capable to retrieve the amplitudes and frequencies of oscillations generated by an earthquake, it has been thereafter routinely used to precisely measure crustal deformation. In particular, significant advances in GPS hardware and data processing enabled GPS measurements at a very high frequency, those experiments can be considered the first examples of a new field of usage for the GPS sensors: the so-called GPS Seismology, defined by Larson as the application of conventional geodetic models in analyzing GPS data at high sampling rates ( $\geq 1$  Hz) and solving for the receiver position at every observation epoch [3].

GPS geodesy and seismology have traditionally been considered distinct tools focused on disparate frequency bands of the deformation spectrum. GPS Geodesy is focused on long-term secular tectonic deformation and static displacements from large earthquakes, while the latter measures dynamic displacements with periods ranging from fractions of seconds to several minutes. High-rate GPS positioning has been recognized as a powerful tool in estimating epoch-wise station displacement which is particularly useful in seismology. The major advantages of using GPS receivers as seismometers are represented by the fact that they can measure large dynamic displacements without saturation. However, GPS is a few orders of magnitudes less sensitive than seismometers, considering that GPS can only detect movements at the noise level of a few millimeters or accelerations at the noise level of sub-centimeter per second squared [4].

The goal of our analysis is to provide 1 Hz position horizontal, vertical and 3D reconstructed velocities in order to see if these can be compared to displacements derived from velocities/accelerations measured at nearby or collocated broadband seismic stations. The high-rate GPS data can capture the rapid co-seismic ground displacements over a range of frequencies and amplitudes that are comparable with those recorded by seismic sensors. High-rate, real-time GPS networks can enhance earthquake detection and seismic risk mitigation [5].

For the first time in Romania, the GNSS data and other collocated sensors measurements, such as tilt sensors, were analyzed at 1 Hz frequencies for three considered study cases: i) a crustal seismic swarm occurred in the eastern part of Romania, near Galati city; ii) a crustal earthquake of magnitude  $ML = 5.7$  that occurred near Focsani city, in Vrancea area and iii) an intermediate-depth earthquake of magnitude  $ML = 5.8$  in Vrancea area (Fig. 1).

Although these seismic phenomena were generated in different tectonic conditions and at different depths, all the studied earthquakes generated have a common feature that allowed us to pursue our goal, *i.e.* all the earthquakes studied generated large amplitudes of the ground motion that were well recorded by the seismic stations co-located or located close to GNSS stations (in a range between 10 and 15 m).

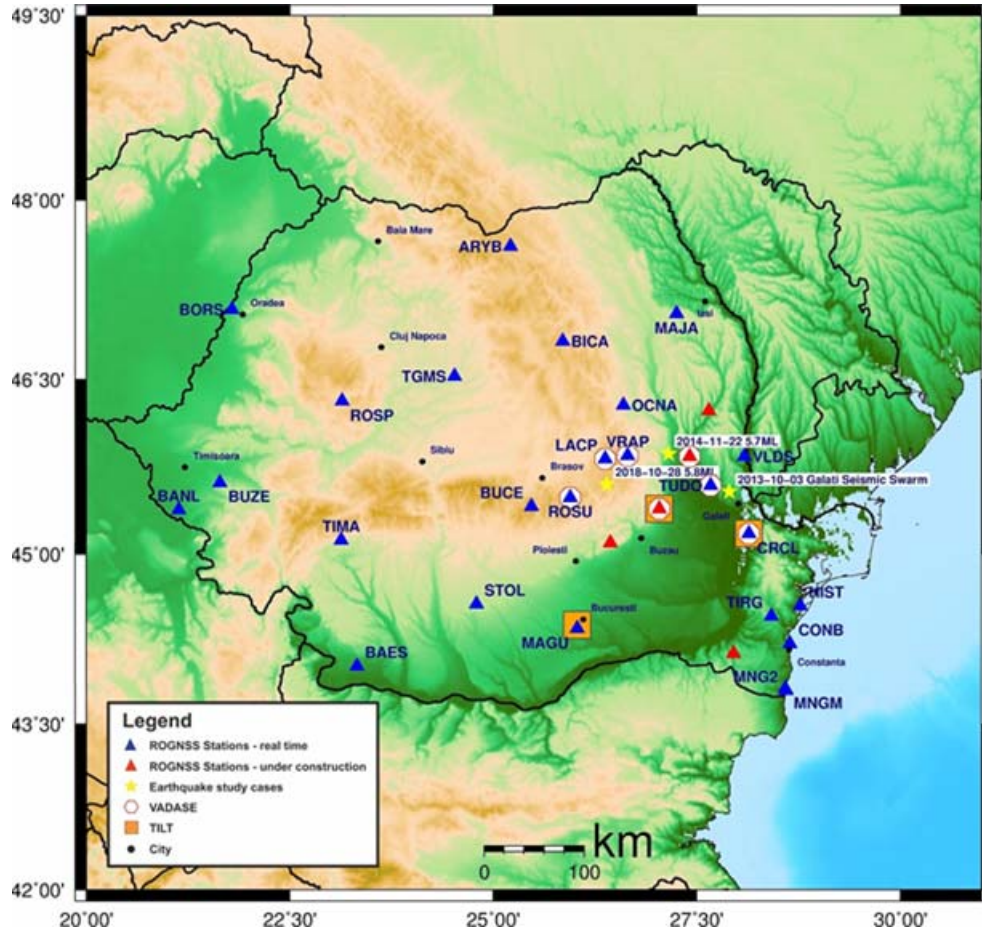


Fig. 1 – Romanian territory, with main cities (marked by black dots) and NIEP GNSS permanent stations network: real-time stations represented with blue triangle and the stations under development with red triangle. Overlapping some of the stations, are depicted co-located sensors and systems such as: tilt (orange square) and VADASE (red hexagone). The three study cases we chose are represented by yellow stars (Color online).

i) The seismic swarm in Galati area started on August 2013 and by the 5th of November were recorded 940 events with magnitudes (ML) varying between 0.1 and 4.0 [6]. During the swarm two seismic stations were temporary installed in the epicentral area and a GPS measurement campaign was carried out. The largest earthquakes within the swarm produced unusually high accelerations (around  $36 \text{ cm/s}^2$ ) that were well felt by the people in the epicentral area.

ii) The largest crustal earthquake ever recorded by the Romanian seismic stations occurred on 22nd of November 2014, had a magnitude  $ML = 5.7$  and was

generated at a depth of 39 km in the Vrancea seismic area at a distance of 19 km from Focsani. The earthquake was felt on most of Romania's territory and was well recorded by 82 Romanian strong motion seismic stations. High accelerations were recorded in the epicentral area (up to  $300 \text{ cm/s}^2$ ) as well as in the eastern part of the country (between  $60$  and  $200 \text{ cm/s}^2$ ).

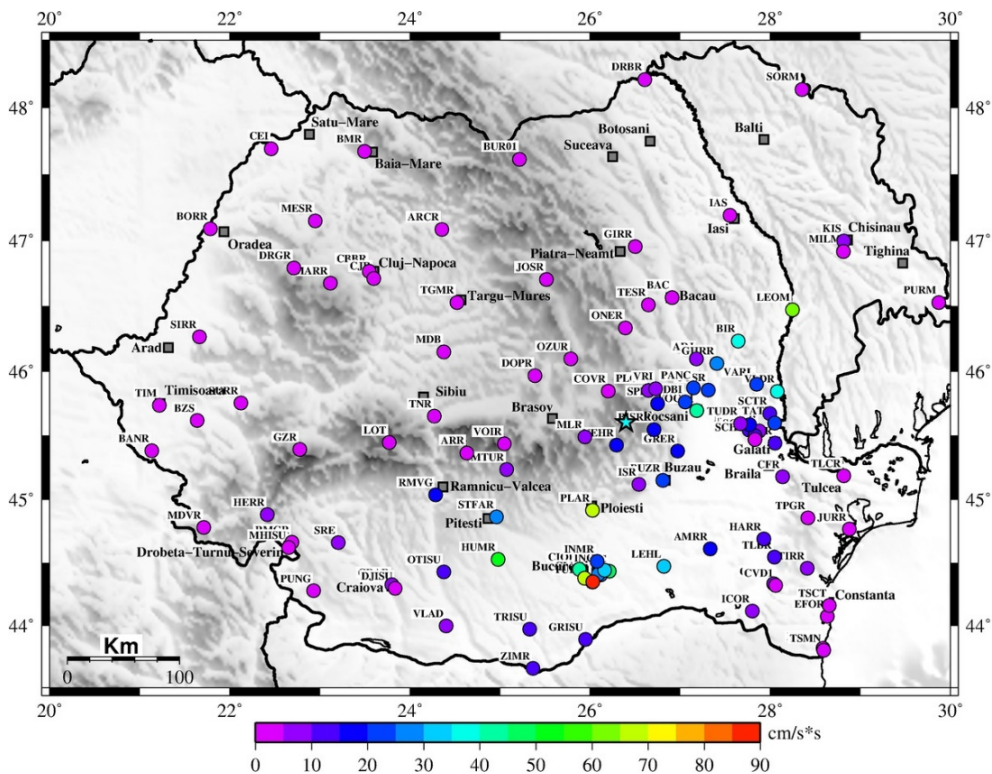


Fig. 2 – Distribution of the maximum accelerations recorded during the 22nd of October 2018 ML = 5.8 Vrancea intermediate-depth earthquake. Note the high accelerations values for stations located far from the epicenter on NE-SW direction. Blue star-earthquake epicenter.

iii) On October 28th 2018, the largest depth earthquake in the last fourteen years occurred in Vrancea area at a depth of 151 km with a magnitude ML = 5.8. The earthquake was felt in many cities from Romania as well as in Bulgaria, Republic of Moldova and Ukraine. The ground motion generated by the earthquake was well recorded by 108 strong motion stations deployed all over the country. The distribution of the recorded accelerations showed that the highest values (about  $60$ – $90 \text{ cm/s}^2$ ) were observed far from the epicenter on NE–SW direction (Fig. 2). This is a characteristic common to all moderate and strong Vrancea intermediate-depth earthquakes which also show higher intensities at larger distances than in epicentral area [7].

## 2. METHODS

At present, GNSS is commonly used for kinematic positioning and monitoring purposes in order to detect motions and displacements in (near) real time. Even if the network has the capability to record GNSS data, for all the three study cases we used only GPS data to be processed by two approaches mainly consisting of: Precise Point Positioning (PPP) and differential kinematic positioning (DP). To obtain the short-term dynamics motions we have used the sampling rate of 1 Hz.

Firstly, the PPP strategy was performed with the GIPSY-OASIS v.6.2 software, generating position solutions from each individual observation file [8]. The PPP strategy was used in a kinematic mode. We also used the Jet Propulsion Laboratory (JPL) orbits and clocks products, Earth rotation parameters (ERPs), as well as the wide lane ambiguity products, to invoke single-station ambiguity fixing. All position estimates are with respect to the International Terrestrial Reference Frame 2008. Solid Earth tides, ocean tide loading, and pole tide are applied, and antenna phase center variations are also corrected.

In this approach, we use dual frequency observations from a single Global Navigation Satellite Systems (GNSS) receiver to acquire high accurate displacements in a global reference frame. The results are based on the accuracy and availability of the ancillary required products, whose precision decreases with time latency. Moreover, the PPP method needs a “convergence” time that can range from several minutes to 1 hour, in order to reach centimeter accuracy. Every time the receiver loses the signal lock or experiences a tracking problem, we have to reapply the convergence time and wait for a highly accurate position to be available again.

Secondly, the entire projects were computed using GAMIT/GLOBK/TRACK software [9]. The differential method can reach sub-centimeter accuracy level [10, 11], but only provides positions relative to a reference station. This represents an important inconvenience when strong earthquakes occur that may affect the entire area covered by the permanent stations network, as the reference station will likely be affected by the displacement. Theoretically, we can recover only relative co-seismic displacements (not in a global reference frame) in real time across the entire network area.

The processing was done in two stages. First, the data was processed with GAMIT for static processing until the moment of the earthquake using the IGS final products. To estimate parameters, we used the double-differenced ionosphere-free combination (LC) to eliminate ionospheric effects. The resulting coordinates were then fed into the kinematic data processing software called TRACK. Also, the atmospheric delay was computed with GAMIT atmospheric zenith delay and atmospheric gradients were estimated every 5 minutes and then the results were used by TRACK. We have used the Global Mapping Function (GMF) and the *a priori* tropospheric delay was obtained from the global pressure and temperature (GPT2) model [12]. TRACK pre-reads all data before processing which has its upsides and downsides. To resolve L1-L2 cycles, TRACK uses the Melbourne-Wubbena wide lane (MW-WL) to

estimate the number of cycles in the slip and resolve to an integer value of the phase data. The MW-WL is a very useful combination of data where GNSS receiver coordinates are changing. Also, floating point estimate was determined with LC which eliminates the ionospheric effects, MW-WL, and ionospheric delay constraints to determine the integer biases and the reliability of them. Absolute antenna phase calibration models were used to correct antenna offsets of receivers. The elevation cut-off set both on GAMIT and TRACK was 100 and we have applied an elevation-dependent weighting of data according to an assessment of the post fit phase residuals. The earthquakes have taken place on more than 95 km depth and at the processing strategy in TRACK, we have allowed random process noise on both site positions to allow it to move but also on atmospheric delay estimation. We then encountered a problem: if a too large noise was added, then the height estimates and atmospheric delays estimates presented very high correlations, but if the noise was too small, the atmospheric delays variations map into the height variations. The interval at which the processing was done is 1 Hz.

Also, in TRACK, we have used two stages. In the first stage, we have kept all the fixed stations so TRACK will be able to resolve more easily the ambiguities and then those ambiguities were used in the second stage of the processing. In this second stage, we have added the random noise walk to allow the stations to move and to estimate the displacement waveforms.

Additionally, we have the opportunity to test for a couple of months in 2018 the Leica Velocity And Displacement Autonomous Solution Engine – VADASE, available onboard the GR10 & GR30 reference station receivers that provide fully autonomous precision high-rate velocity information of a GNSS station antenna [13]. This innovative method has been initially described by the University of Rome “La Sapienza” [14]. It uses high-rate (1 Hz up to 20 Hz) GNSS data to obtain real-time estimated velocities and displacements on the order of cm/s and cm, respectively [15], without the need of any kind of additional correction stream or service.

The approach is based on time single-differences of carrier phase observations collected at a high-rate (1 Hz or more) using a stand-alone receiver and on standard GPS broadcast products (orbits and clocks), which are ancillary information routinely available in real time. In this approach, we primarily estimated the time series of epoch-by-epoch displacements. The computation of the velocity of a site location, or GNSS antenna position respectively, is enabled through the use of a highly accurate time-differenced phase observation. The time-differenced phase observation allows a very precise estimate of the position change on an epoch-to-epoch basis that is then transformed into a precise velocity estimate. We used time-differenced phase observations to estimate the velocity knowing that higher rate processing only required to also capture higher dynamic movements of a site location. Time-differencing the phase observations allows to remove the unknown ambiguity parameter, provided continuous observations are collected. This allows the processing of the observations without the need to do any phase ambiguity resolution and allows VADASE to produce a velocity estimate from any two epochs of phase observations.



### 3. RESULTS

In order to implement a study on GPS seismology analysis, we looked carefully to all the particular events in the past 10 years and we selected 3 different events that were analyzed either by PPP or DP approaches:

i) The seismic swarm in Galati area. This event was analyzed in detail in the Ph.D. thesis “Integrated GNSS and seismotectonic study of the NW Galati seismogenic area”, a study that is still in progress. In this particular case, was analyzed a series of 10 days with a lot of small crustal events. The most significant events occurred on the day of October 3rd 2013, when on GPS campaign station IZVO, installed in the proximity of the seismic swarm epicenters, approximately 3 km away, some amplitude displacements a little bit larger than the average noise level on 24 hours were recorded. We can assume that they have been caused by those events (see Fig. 3).

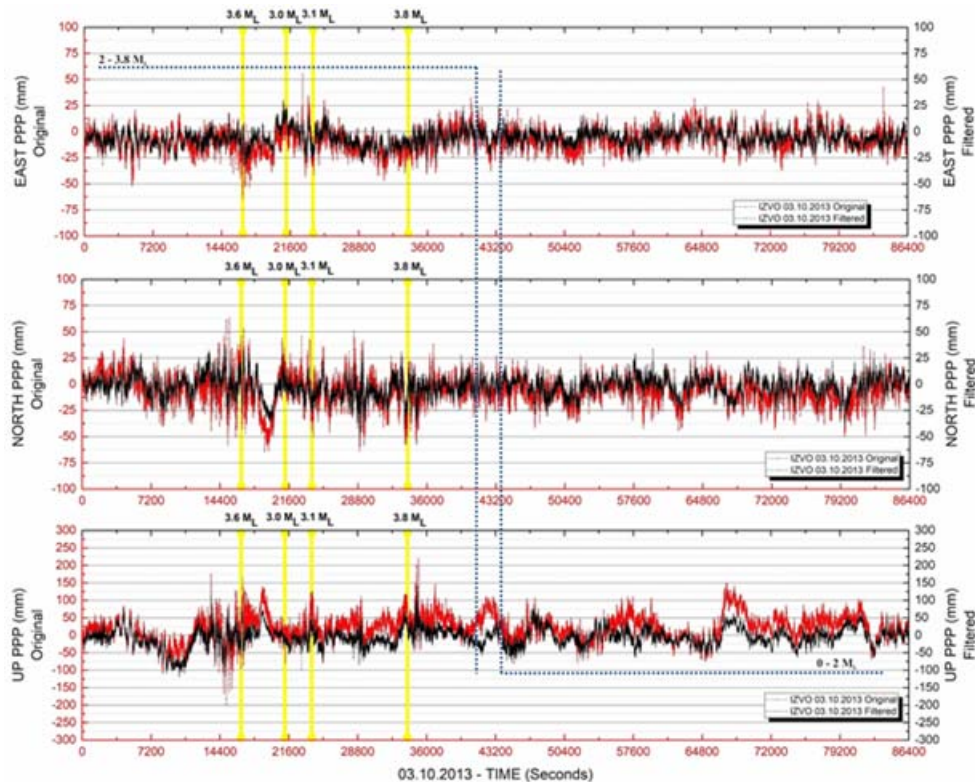


Fig. 3 – PPP 1 Hz original solutions for 24 hours (red line) and overlapped filtered solution (black line). Yellow vertical line represents the strongest earthquakes that occurred during the time interval. The blue dot line divides the daily time interval in 2 periods: the first one with earthquakes ranging between 2 and 3.8 magnitude and the second one with earthquakes smaller than 2 ML (Color online).

Furthermore, we applied a filtering method (a common mode filter) based on the median values recorded on stations not affected by the swarm (far from epicenters, around 30 to 150 km, LACP station as seen in Fig. 1) and median values were subtracted from the original measured ones.

ii) The largest crustal earthquake ever recorded by the Romanian seismic stations occurred on 22nd of November 2014 and had a magnitude  $ML = 5.7$ . For this case, we chose to present the signal recorded on the closest GPS permanent station to the epicenter, in a 24 hours interval. After that, we zoomed in on the one-hour interval including the event and also overlapped the 30 s processing in order to emphasize the increasing of the ambiguities along with frequency (see Fig. 4). The last representations that include all the component recordings show an additional noise, induced immediately after the earthquake occurred, but the level of displacements does not exceed 2 sigma error.

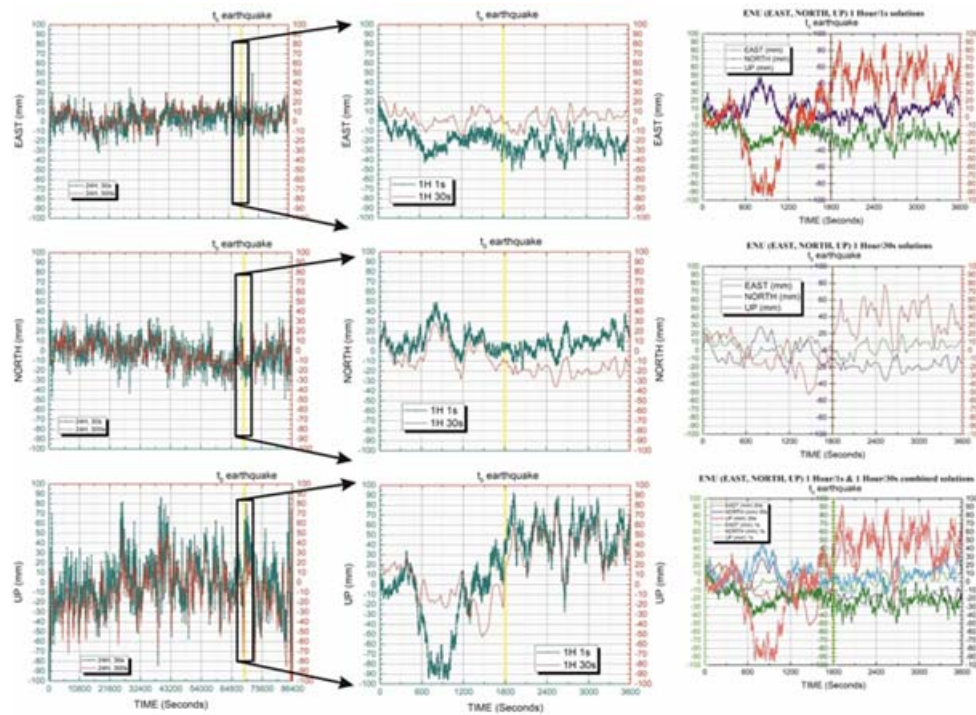


Fig. 4 – First column on the left: PPP 1 Hz original solutions for 24 hours (green line) and overlapped PPP 30 seconds solution (red line). Middle column: one hour zoom with yellow vertical line depicts the strongest earthquakes that occurred during the time interval (5.4 magnitude). On the right column, there are 3 figures: starting with the one on top we represent on the same hour zoom all 3 components at 1 second interval, the figure below shows all 3 components at 30 seconds interval and the bottom one is the overlap of the first two (Color online).

iii) On 28nd of October 2018, the largest intermediate-depth earthquake in the last fourteen years occurred in Vrancea area at a depth of 151 km with a magnitude



ML = 5.8. Now we observe that on the DP solutions and especially on the filtered solutions (using the same common mode filter as in i) case) a perturbation on the displacement recorded a couple of minutes before the earthquake, during and after the event (see Fig. 5). On account of those perturbations not being related to the shaking caused by the events, we can take into account Ionospheric anomalies, knowing from previous publications that anomalies were highlighted for Vrancea earthquakes from TEC (Total Electron Content) analyses [16, 17, 18].

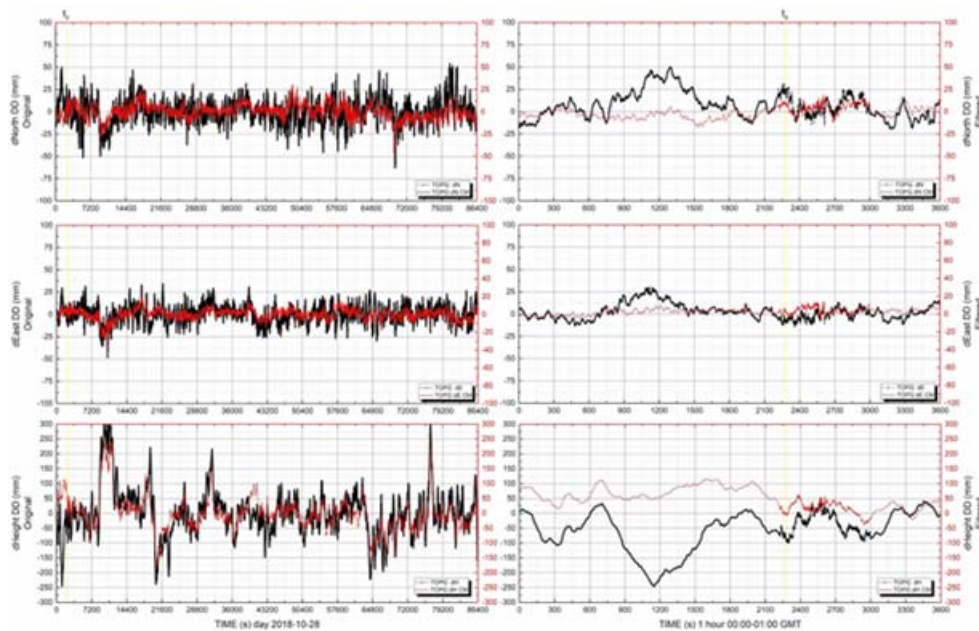


Fig. 5 – Left column illustrates the DD 1 Hz original solutions (black line) for 24 hours and overlapped filtered solutions (red line) and on the right column one hour zoom with the yellow line represents the origin time of the 5.8 magnitude earthquake (Color online).

Additionally, to the GPS analysis, we take into consideration the tilt and the strong motion sensors recordings and test the VADASE system.

Strong-motion instruments which are used in earthquakes measurements are sensitive not only to the translational motion but also to tilt [19]. This sensitivity can be neglected in studies of far-field measurements, but it must be taken into account in near-field strong motion studies (for example, Vrancea earthquakes) as it can introduce long-period errors, especially for the calculation of residual displacements.

As vertical sensors are less sensitive to tilt, they are potentially more useful for long-period and residual displacements calculations [20]. Knowing those facts, we decided to install, record and analyze the responses of collocated biaxial horizontal tiltmeter sensors with the purpose of achieving a more accurate assessment of the

impact of Vrancea earthquakes. The tilt record shows us that the recordings of seismic sensors, in our particular cases, of strong motion ones, are proportionally affected by the movement implied by both P and S wave arrivals (Fig. 6). Although the inclination data is measured at 1 Hz in respect of the 100 Hz measurement of the accelerometers, their information is reliable as it can be seen in Fig. 6 and could be added into advanced seismic records error analyses.

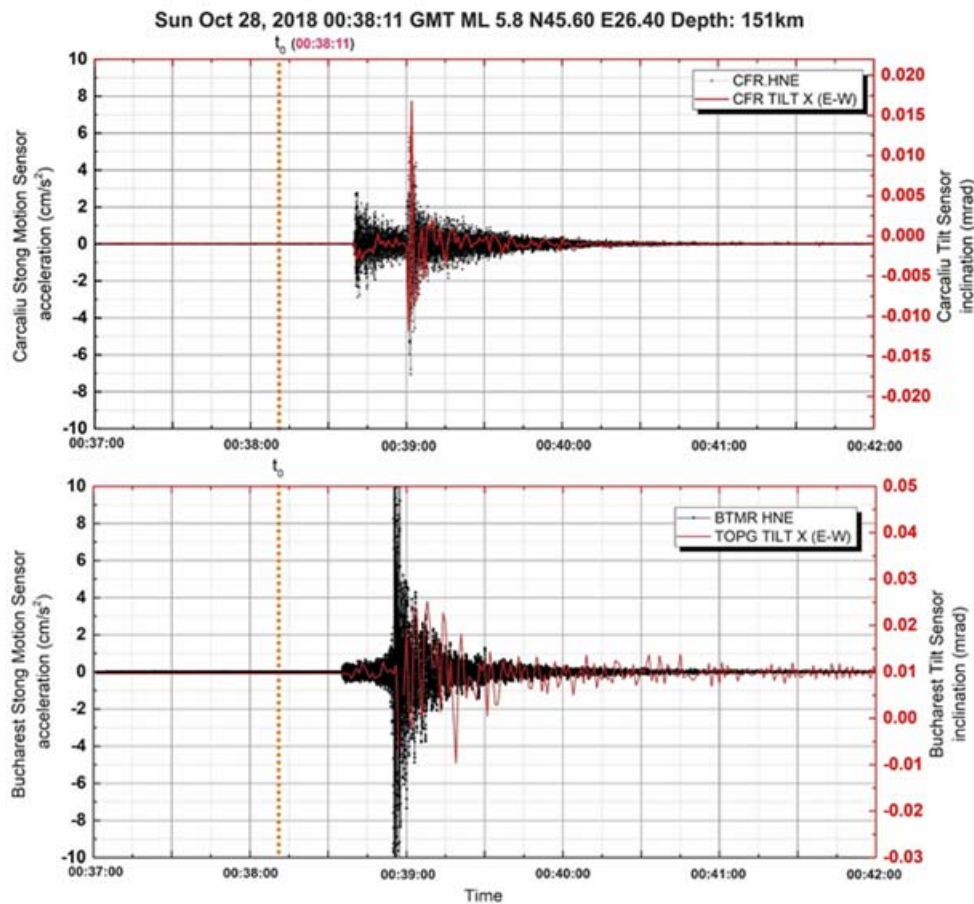


Fig. 6 – Black lines and dots show the Carcaliu (top figure) and Bucharest (bottom figure) strong motion sensor acceleration on a 5 minute interval. On top, the red line represents the collocated tilt sensor inclination recorded. The yellow dot line indicates the  $t_0$  of the earthquake (Color online).

As Fig. 7 illustrates, during Spring 2018, when the VADASE system was tested, for one of the earthquakes that occurred in that time interval (Wed. Apr. 25, 2018, 17:15:49 GMT ML = 4.6 N45.60 E26.42 Depth: 147.3 km), it partially recorded the S wave arrival on the ROSU GPS permanent station.

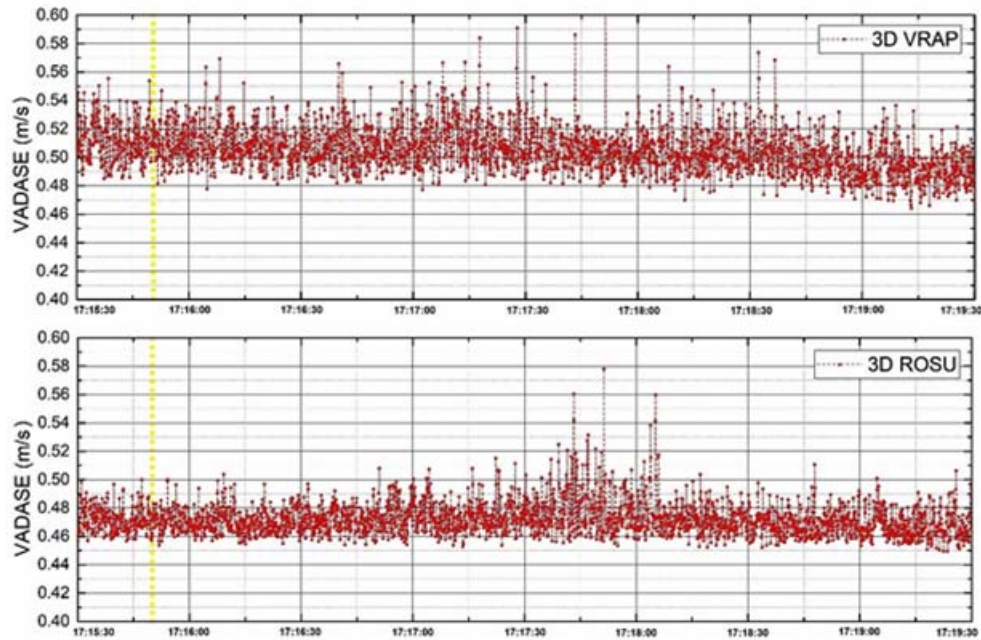


Fig. 7 – VADASE Velocity on 3D (10 Hz) during the Wed. Apr. 25, 2018 17:15:49 GMT ML = 4.6 N45.60 E26.42 Depth: 147.3 km earthquake on epicenter GNSS VRAP and ROSU GNSS station. The yellow dot line indicates the  $t_0$  of the earthquake.

#### 4. DISCUSSION

We have described the estimation of displacement waveforms using an optimal combination of collocated high-rate GPS and very high-rate accelerometer data with tilt sensors.

This paper aims to elaborate on a number of issues and provide some directions for future work that involve nontraditional seismological sensors such as GPS and tiltmeters. By comparing all three components of the estimated displacement waveforms from GPS alone with those estimated using the smoothed filter, for various collocated stations, we have concluded that the noise level significantly decreases in the latter.

The optimal combination of GPS displacements with accelerometer data provides distinct advantages. The P-wave arrivals could be detected in the combined solution for many strong earthquakes around the globe, thanks to the greater precision of the accelerometers.

Contrary to the combined method, the GPS-only approach did not detect the P-wave arrivals because of the reduced sensitivity of GPS to the vertical motions. The detection of the P-wave arrival is critical for earthquake early warning, as it

allows for prediction of the arrival of the destructive S wave. We noted that there are certain limitations in the real-time estimation of displacements from the GPS data, but we proved that our GNSS network is capable and prepared for such analysis and additional contributions to our National Seismic Network in the unfortunate case of a major Vrancea earthquake impacting Romania.

We took one step further by applying a filter to obtain an optimal combination of data from collocated high-rate GPS and very high-rate accelerometer stations, which takes advantage of the strengths and minimizes the weaknesses of both data types. This resulted in a new methodology for providing displacement time series with millimeter/centimeter precision that can be used to have a better assessment of the seismic source [21].

Under normal to favourable conditions, VADASE will output velocity noise in the horizontal and vertical components with a  $\sigma$  in the order of  $1 \sigma = 1$  mm/s, East  $3 \sigma$ , North  $5 \sigma$ , Height  $8 \sigma$ . As a general case, the minimum sensitivity for VADASE algorithm, minimum velocity detected should be East 3.6 mm/s, North 3.6 mm/s, Height 8 mm/s and recommended minimum velocity to be used for accurate displacement computation should be East 8 mm/s, North 12 mm/s, Height 20 mm/s. According to all the acceleration values recorded in all our three study cases, those values do not exceed the recommended and in some cases the minimum velocities for detection.

For our multi-sensors and multidisciplinary studies, we had collocated velocity & accelerometers seismic sensors, in particular cases, we have some additional: atmospheric, magnetic, infrasound, tilt and/or seismic array sensors. Starting from January 2019, due to the slow recurrences of strong seismic events in the Vrancea area, we propose to extend the test VADASE DEMO licenses for more stations – 7 GR receivers and for a longer period of time, up to 12 months.

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