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Kinematic effects of M5.5 Zagreb earthquake assessed by GNSS method supported by Galileo Satellite System

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Abstract

CROPOS (Croatian Positioning System) is a Croatian permanent GNSS (Global Navigation Satellite System) network featuring 33 stations distributed over the national territory at an average distance of 70 km between stations. The system was established in 2008, in the meantime enlarged and improved, and eventually, in summer 2019 it was upgraded to support observations of the European Galileo satellite system (in addition to previously supported GPS and GLONASS systems). Within the project of CROPOS's upgrade co-funded by the EU (European Union), all permanent GNSS stations were equipped with the newest Trimble Alloy receivers and Trimble Zephyr 3 Geodetic antennas, whereas the software of the control center (Trimble Pivot Platform) was upgraded to a newer version. One of the CROPOS's stations (ZAGR) is located (more precisely its antenna) on the roof of the building where three faculties of the University of Zagreb (Geodesy, Civil Engineering, Architecture) are headquartered. For the first time, the effects of the M5.5 Zagreb earthquake, combined surface and building motion, have been identified and assessed by the GNSS method supported by E5, E5a, E5b, and E5AltBOC signals of Galileo satellites. By analysis of 1 Hz processing results, the effects of the earthquake being far above the noise level, have been discerned leading to the assessment of kinematic behaviour of the station caused by M5.5 earthquake. ZAGR station at the approx. 9 km distance from the estimated epicentre, have shown movements in the range of approx. 13 cm in direction N-S and approx. 6 cm in direction E-W, whereas some movements in the vertical direction were identified to be slightly above the noise level. Although the kinematic behaviour was pronounced, there haven't been revealed permanent displacements as a consequence of M5.5 earthquake. One second (1 Hz) resolution results have enabled a thorough analysis of the kinematic behaviour of ZAGR station and potential of the GNSS method.

Key words: CROPOS, earthquake, Galileo, GNSS, kinematic motion, PPK

1 Introduction

On March 22nd 2020 the wider area of the City of Zagreb was struck by a strong earthquake M5.5 with the epicenter approx. 9 km away from the center of the city. The earthquake was felt at a distance of over 400 km, causing damages to the buildings in the epicentral area, but the most pronounced damages were recorded on the old buildings in Zagreb downtown. The last time that the area of Zagreb has been struck by such a strong earthquake was in 1880. The first instrumental seismological recordings in Croatia were introduced in 1906 by Andrija Mohorovičić. The earthquake which took place in 1909 in the epicentral area of Pokupsko was recorded by instruments installed in 1908 and 1909. The analysis of data led to the discovery of the discontinuity surface between the crust and upper mantle (Moho discontinuity). After the strong earthquake in 1880, the wider area of Zagreb was struck by seismological phenomena in 1901, 1905, 1906, and 1990. Since that time, all earthquakes were thoroughly analyzed and recorded and numerous studies have been carried out. Base on those studies, it was estimated that the faults in the epicentral area of Medvednica mountain can give rise to earthquakes with a magnitude up to M6.5 [1, 2, 3]. A permanent monitoring of seismological activity carried out by the Croatian Seismological Survey (CSS) has enabled the creation of the Seismic Hazard Map of the Republic of Croatia [4]. On that map, a wider area of Zagreb, the area between Rijeka and Senj as well as southern Croatia (area of Dubrovnik) are recognized to have the greatest seismological hazard in Croatia. The State Geodetic Administration (SGA) of the Republic of Croatia in 2008 established a network of permanent GNSS stations, featuring 30 stations uniformly spread across Croatian territory (CROPOS). Subsequently, the network was enlarged by three additional stations on Croatian territory, and altogether 18 stations from neighboring countries (Slovenia 7, Hungary 4, BiH 5, Montenegro 2) were included in the networked solution. Today, data from altogether 51 stations is included in the networked solution. Since its establishment in 2008, the control center of CROPOS has been updated in terms of software and hardware. In the summer of 2019 the system was upgraded: at each station was installed the newest GNSS receiver Trimble Alloy and accompanying GNSS antenna Zephyr 3 Geodetic [5]. All installed GNSS receivers and antennas are multifrequency and multi-constellation equipment capable of receiving signals of GPS, GLONASS, Galileo, and BeiDou satellites. CROPOS offers three services, two of them – VPPS (Networked Real-Time Kinematic) and GPPS (observations used for Post-processing applications) are widely used and accepted by the surveying community in Croatia. The impact of the modernization of CROPOS on the performance of services has been investigated in the diploma thesis [6]. Additionally, the Galileo system and its implementation through modernization of CROPOS have been assessed in the diploma thesis [7]. The first thesis has shown that modernization hasn't provided a substantial improvement in terms of accuracy, but the availability and reliability were significantly improved. The second thesis has shown that Galileo as a system, even it hasn't already reached its Full Operational Capability, is capable of providing reliable individual solutions. This the first time that an earthquake in Croatia has been assessed by the kinematic GNSS method leveraging the signals of the emerging European Galileo satellite navigation system. The very first results of that research are presented in this paper.

2 Galileo and other satellite systems

Today the term GNSS includes four globally available navigation satellite systems, namely, the American GPS, the Russian GLONASS, the Chinese BeiDou, and the Europen Galileo. Currently, (February 2021) the Galileo constellation encompasses 26 satellites, two of them being unavailable and the remaining 24 satellites are set to be usable [8]. The Galileo system, once fully operational, will offer five high-performance services worldwide: Open Service (OS), Public Regulated Service (PRS), High Accuracy Service (HAS), Commercial Authentication Service (CAS) and Search and Rescue Service (SAR) [9]. With the declaration of *Galileo Initial Services* in 2016, Galileo officially moved from a testing phase to the provision of live services. Galileo navigation signals are transmitted in four frequency bands (E5a, E5b, E6, and E1) providing a wide bandwidth for the transmission of the Galileo signals [10]. Galileo signals recorded by the GNSS receivers Trimble Alloy installed at each CROPOS station, were in frequency bands E1, E5a, E5b, and E5 AltBOC (Open Service). Future development plans of the Galileo system including the production of 12 additional Batch 3 Galileo first-generation satellites which will be ready for launch from middle 2021 onward are outlined in [11].

3 CROPOS ZAGR and ZABO stations

The ZAGR CROPOS network station is located atop of the Faculty of Geodesy, the Faculty Civil Engineering, and the Faculty of Architecture building. The average distance between CROPOS stations across the national territory is 70 km, but the closest station to ZAGR station is located in Zabok (ZABO), at a distance of approx. 25 km. Although the coordinates of all CROPOS stations were precisely determined in ETRF2000 R05, epoch = 2008.83, in order to check the accuracy of ZAGR station coordinates, data collected with 15 seconds logging interval were downloaded for both stations for 24 hours time window (March 22nd 2020, start at 00:00:00 GPST, stop at 23:59:59). Since the main earthquake shock occurred at 05:24 UTC, on 22nd March 2020, observation data at both stations with 1-second logging interval for the time window 5-6 GPST were downloaded from CROPOS GPPS as well. Data collected with 1-second logging interval was used for computation of kinematic solution and assessment of earthquake effect on ZAGR station. To ensure the environment for a reliable solution determination the, time window for the whole day 22nd March 2020 was checked for ionospheric conditions using GNSS online Planning Tool [12]: Ionospheric index, TEC (Total Electron Content), and Scintillation were minimum, consequently contributing to a reliable solution determination.

4 Static and kinematic processing

The coordinates of the ZAGR station were determined from 24h static baseline processing where ZABO station coordinates were held fixed. That solution was regarded as a reference for the subsequent kinematic results analysis. All the coordinates presented in this paper were computed in the official geodetic reference system HTRS96/TM (Easting, Northing) and the official vertical referent system HVRS71 (height H). Static and kinematic baseline processing was carried out in Trimble Business Center (ver. 5.3) using observation of all available GNSS signals (GPS, GLONASS, Galileo, and BeiDou), elevation mask 10°, and broadcast ephemerides.

In baseline processing, the coordinates of the ZABO station were held fixed enabling computation of ZAGR station coordinates and estimation of baseline components precision. The estimation of baseline components precision can be regarded as an estimation of ZAGR coordinates precision, given with confidence level 95 %: ± 0.002 m (*E*), ± 0.002 m (*N*), ± 0.010 m (*H*). The comparison of the ZAGR coordinates obtained by static single baseline ZABO-ZAGR solution (24h) and the official coordinates, has given the following differences: ΔE = -0.005 m; ΔN = -0.008 m; ΔH = 0.013 m proofing that a calculated solution may be regarded as reliable. Taking into consideration a declared accuracy of the CROPOS GPPS (< 1 cm), the accuracy of the static method itself and the fact that the official coordinates were determined with different software, reference stations, ephemeris data, and different time epoch, the coordinates obtained by a single-baseline solution can be regarded as highly reliable providing a robust base for the analysis of kinematic solutions.

A kinematic solution for the ZAGR station providing 1-Hz coordinates was computed in post-processing using a PPK (Post-Processed Kinematic) method. Before the baseline processing, it was estimated that having a baseline length of 25 km, a reliable solution would be feasible. Indeed, this is the first time that such a method has been used for PPK processing using GNSS (GPS, GLONASS, Galileo, and BeiDou) enabling the kinematic assessment of earthquake effect on a permanent GNSS station being part of the CROPOS network. For the PPK method, which was intended to be used for coordinates determination, the phase ambiguities have to be resolved before starting the survey. Dual-frequency receivers require up to 1–2 minutes of observations for baselines up to 20 km to resolve the ambiguities kinematically. It can be estimated for a 10 km long baseline and dual-frequency observations at dozen epochs, this will result in a position accuracy of 2 cm [13]. Several previous papers e.g. [14, 15], although at much lower baselines lengths, have shown the potential of the PPK method to provide results with 1-2 cm accuracy level. Of course, as will be shown and discussed later, that level of accuracy has been chiefly reached for considerably longer baselines (25 km).

5 PPK results of ZAGR station

Considering the location of ZAGR station being distant approx. 9 km from the 5.5 earthquake epicenter and bearing in mind the damages suffered by the buildings in the Zagreb downtown, it was supposed that the effect of the earthquake could be registered, assessed, and subsequently analyzed by a kinematic solution. As stated above, for a PPK being a relative method, observations from additional GNSS station are necessary to provide a solution. The closest to ZAGR station, having the potential of providing a reliable solution, was the station ZABO which is approx. 18 km away from the M5.5 epicenter. Recent scientific research activities (a dedicated scientific paper on that topic is being prepared) have shown that the ZABO station was slightly influenced by the M5.5 earthquake, thus not jeopardizing the achievement of a reliable solution. First data about that earthquake (referred to as the mainshock) was taken from European-Mediterranean Seismological Centre (EMSC) web site [16]. Additionally, data about earthquake event was received from of the Croatian Seismological Survey (CSS). Data about the coordinates of the epicenter, depth of the hypocenter, along with the magnitude and time of origin of the mainshock are reported in Table 1.

Table 1. Data about the earthquake registered by CSS and EMSC.

Source	CSS	EMSC
Latidude	45.884°	45.87°
Longitude	16.013°	16.02°
Depth	8.3 km	10 km
Magnitude	M_L = 5.5	M_W = 5.4
Time of origin	05:24:03.1 UTC	05:24:02.8 UTC

Distance between two epicenters derived by CSS and EMSC is 1.6 km which is within the 95 % Confidence ellipse (semimajor axis 2.9 km reported by EMSC). The time difference between origins is 0.3 sec which is below the RMS travel time of 0.93 seconds reported by EMSC. In further analysis of the earthquake effects, parameters determined by the CSS will be deemed as reference. The distance between the epicenter (CSS) and stations ZAGR and ZABO is 9.3 km and 18.1 km, respectively.

Observation files spanning 1 hour (5-6 GPST) collected at stations ZABO and ZAGR were kinematically processed and the coordinates of the ZAGR station were computed for each second. It was chosen to display the timestamps in UTC since the seismological data is given in that system. GPS observations are referenced to the GPS Time, the difference being at the time of observations GPST – UTC = 18 seconds. Out of possible 3600 epochs, 3599 PPK solutions of ZAGR station with fixed ambiguities were computed enabling further analysis.

After the PPK computations, the statistics of Easting (*E*), Northing (*N*), and Height (*H*) values were analyzed. The first analysis of the 1-hour time window, paying special attention to the range values (Range = Max – Min), has shown large values, being far beyond the expected noise level, especially in Easting and Northing components: ΔE = 0.059 m, ΔN = 0.132 m and ΔH = 0.047 m. Since the largest range was found in Easting and Northing components, distanced between each 1-second PPK solution and static (24h) solution were plotted against time and shown in Figure 1. Distances between each PPK (i) solution and a fixed static (24h) solution were calculated according to Eq. (1):

$$dist\left(PPK\left(i\right)-STATIC\right)=+\sqrt{\left(E\left(PPK\left(i\right)-E\left(STATIC\right)\right)^{2}+\left(N\left(PPK\left(i\right)-N\left(STATIC\right)\right)^{2}} \qquad (1)$$

From Figure . 1 can be seen a spike occurred approximately at 05:24 UTC which corresponds to the time of the earthquake (Table 2). Other results before and after the time of earthquake are mostly below 2 cm (max 25 mm), thus that value can be regarded as a level of bias and noise normally present in the PPK solutions.

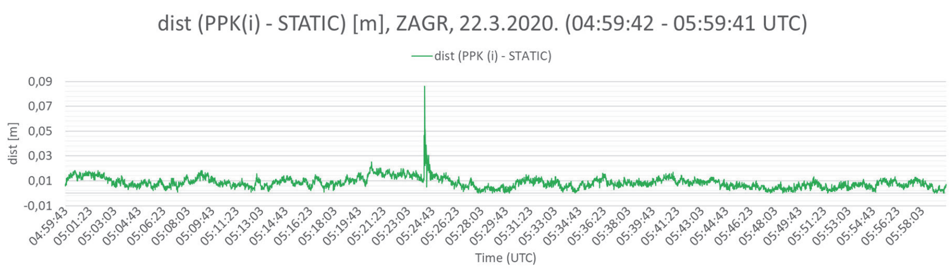

Figure 1. Distance between each PPK(i) solution and the reference static (24h) solution for the time window 5-6 GPST (22nd March 2020)

The height of the ZAGR station computed for each epoch is displayed in Figure . 2. Although the vertical accuracy is normally 1.5 – 2 times worse than the horizontal one, the height H generally shows a bias and noise within ± 24 mm that corresponds to the half value of the H range. A rough analysis of H values in Figure . 2 indicated the absence of spikes, even around the event of the earthquake at 05:24 UTC. Moreover, from both Figure 1 and Figure 2, it turns out that no significant and noticeable permanent displacement has been registered. Indeed, distances between the individual PPK (i) solution before and after the mainshock (05:24 UTC) remained unchanged (Figure 1), similar can be said for the height (Figure 2) leading to the conclusion that the mainshock hasn't caused any significant permanent displacement.

In the time window 5-6 UTC, the CSS reported the occurrence of four earthquakes in the same epicentral area with M ≥ 2.5. The mainshock is well visible in Figure . 1 as a spike, the presence of other earthquakes (05:26:23.3 UTC M2.7, 05:28:34.9 UTC M2.9, and 05:29:35.4 UTC M3.3) are not visible in Figure 1 nor Figure 2.

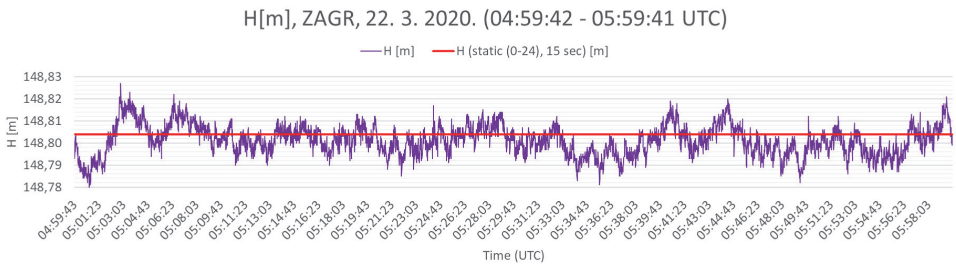

Figure 2. Height of ZAGR station computed by PPK method for each epoch for the time window 5-6 GPST (22nd March 2020)

The presence of earthquake effects in the PPK results (especially in Easting and Northing) deserves a more detailed analysis.

6 Kinematic assessment of the mainshock effects

A subset of PPK results around 05:24 UTC was subject to detailed analysis. Considering the time of origin of the earthquake (Table 2), estimating the duration of its effect and taking 30 seconds before the advent of the earthquake and 30 seconds after it, the subsequent analysis was carried out. By numerical analysis of the PPK results and visual analysis of results shown in Figure 3, it was Figure d out that the effect of the earthquake at the station ZAGR started at 05:24:09 UTC and lasted for 29 seconds until 05:24:38 UTC. The largest departure from the static solution amounting to 8.6 cm was registered at 05:24:11 UTC. After that, the oscillations started to attenuate, and finally, at 05:24:38 UTC reached the level of noise.

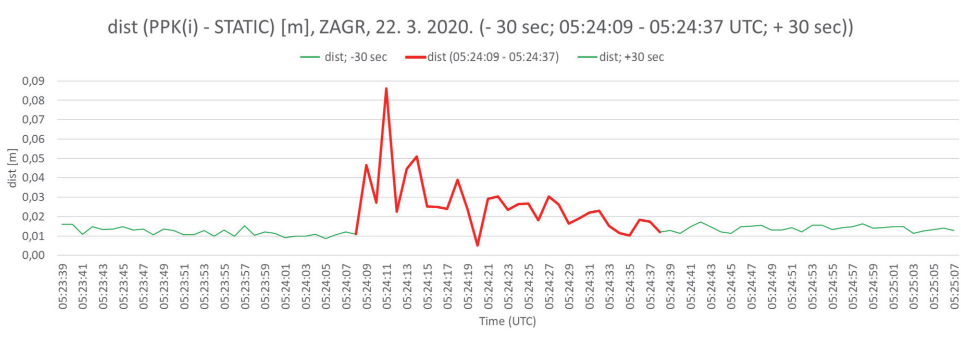

Figure 3. Distance between PPK (i) solutions and reference static (24h) solution for the time window encompassing 30 seconds before the earthquake, the earthquake itself (red line), and 30 seconds after the earthquake has been attenuated/vanished

A similar analysis can be done for the height, although the signal of the mainshock is considerably less pronounced. Maximum departure from the reference static solution was registered at 05:24:15 UTC amounting to 13 mm that normally should be below the level of noise. Therefore, it can be concluded that the heights determined by the

PPK method are not significantly affected by the earthquake, although there is present a larger amount of noise. That noise could be a consequence of the GNSS antenna swinging (shaking) during the mainshock. The swinging directly affected the Easting and Northing coordinates and indirectly the determination of height *H* which is not an independent component causing thus a higher level of noise. Both Figure 3 and Figure 4 present a time window lasting for 88 seconds.

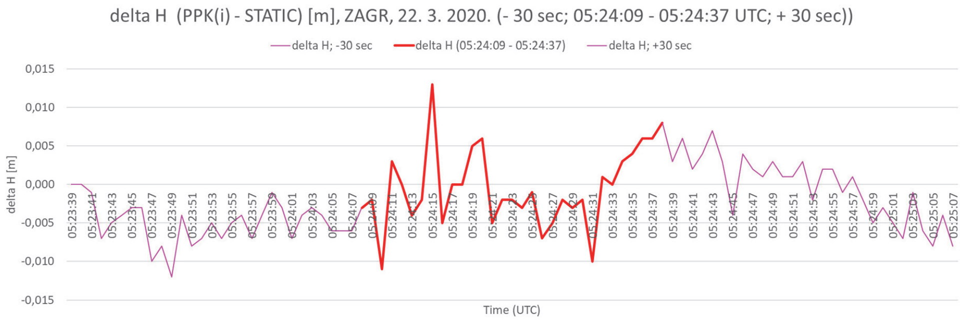

Figure 4. Height difference between each PPK (i) solution and the static (24h) solution for the time window featuring the earthquake episode with additional 30 seconds before and after it

To have a better picture of the behavior of the earthquake and the effect it has caused on the building of the Faculty, more specifically and directly to the GNSS antenna which ultimately sensed the earthquake, the time window spanning 88 seconds will be displayed jointly for Easting and Northing.

The solution calculated for the time 05:24:08 UTC was assigned a number 0, the next one at 05:24:09 UTC holds the number 1, etc., the solution for the epoch 05:24:38 UTC hold a number 30. In that way, 30 points (solutions) belonging to the 29-second time window are chronologically displayed in Figure 5.

The dots belonging to the time window 30 seconds before the earthquake are displayed in blue color. Those points being tightly grouped show a small noise. The effect of the earthquake is visible starting with point 1, then the movement goes in direction North, then it goes to the South, the movement turns to the West, then to North-East, then to South-East, South-West and so on. After point number 13 it can be Figure d out that the points are getting closer to the group of points marked with grey dots which belong to a time window 30 seconds after the mainshock. Most likely, this is the reason why the citizens of the City of Zagreb often report that the earthquake lasted for 13 seconds. The maximum ΔN occurred between points 1 and 3 (ΔN = 13.2 cm), the maximum ΔE took place between points 5 and 7 (ΔE = 5.9 cm). The longest distance between two consecutive PPK solutions was between points 1 and 2 amounting to 7.2 cm. The average departure of blue and grey dots (point estimated to be free of earthquake effects) from the static (24h) solution is estimated to 1.3 cm, which can be regarded as the bias of the PPK solution.

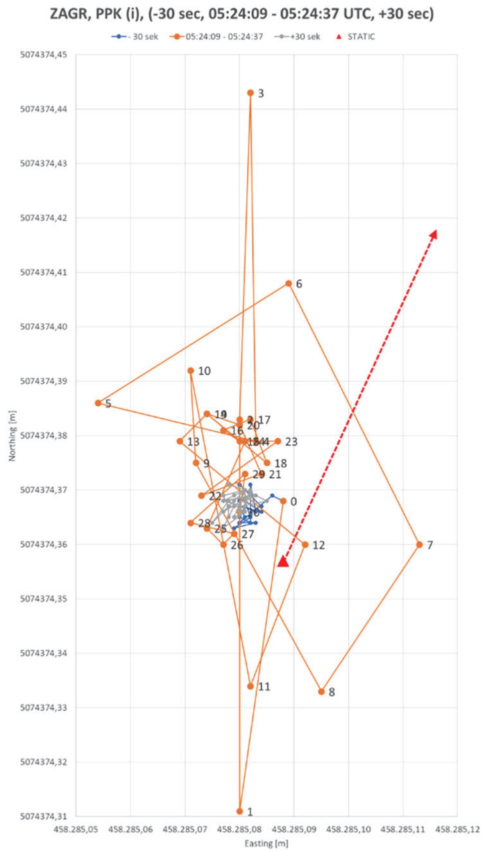

Figure 5. Kinematic effects of the M5.5 earthquake on CROPOS ZAGR station derived from PPK results on 22nd March 2020, 05:24 UTC

The dashed red arrow in Figure 5 indicates the direction to the epicenter (azimuth 25°). Considering the time between the origin of the earthquake (Table 2) and the time it was felt by the ZAGR station (05:24:09 UTC) and taking into consideration the distance between ZAGR and epicenter 9.3 km, and depth of the hypocenter 8.3 km (spatial distance between the hypocenter and ZAGR station is estimated to 12.5 km), an average speed of the seismic waves can be estimated to approx. 2.1 km/s.

This is the first time the PPK method was used for the assessment of the earthquake effect using Galileo satellite signals. Therefore, independent and individual processing using Galileo-only signals was conducted leading to a fixed ambiguity solution. Solutions obtained from all available signals (GPS, GLONASS, Galileo, and Beidou) were compared to Galileo-only solutions for each epoch belonging to the time window 5-6 GPST. The maximum horizontal distance between simultaneous solutions was up to 27 mm, height differences were in the range (-27 mm up to +24 mm). Considering the 88-second time window, horizontal differences are up to 14 mm and height differences are in the range -13 mm up to + 15 mm. All PPK Galileo solutions were calculated from simultaneously observed 6-7 satellites, whereas the GGGB solution was obtained from observed 21-26 satellites. Although the solution with more satellites is better and more accurate, this computation has shown that an individual solution using Galileo-only observations was feasible providing reliable results.

6 Conclusions

The first results of the M5.5 Zagreb earthquake effects sensed by the CROPOS ZAGR station and determined by the PPK method were presented in this paper. This is the first time that an earthquake occurred at Croatian territory was kinematically assessed and analyzed by GNSS observations collected at stations of the CROPOS network. Since the earthquake is an unpredictable natural phenomenon causing oscillations with different frequencies and amplitudes, permanent GNSS observations are needed to enable a kinematic assessment of its effects. Although four earthquakes with M ≥ 2.5 occurred in the same epicentral area in the period 5-6 UTC on March 22nd 2020 were reported by the Croatian Seismologic Survey, only the mainshock (05:24 UTC) was detected in the PPK results of the ZAGR station. The mainshock with the epicenter approx.. 9.3 km from the ZAGR station, has caused its movements in the range ΔN = 13.2 cm, and range ΔE = 5.9 cm, whereas the range ΔH = 2.5 cm is estimated to be slightly above the level of noise. Although significant horizontal movements have been detected, no permanent displacements were registered. The results obtained by the PPK method have shown its potential in detecting the effects of the earthquake as well as assessing its kinematic behavior even at larger distances (e.g. 25 km). The upgrade of CROPOS now supporting Galileo and BeiDou systems has additionally improved the possibility to assess the effect of the earthquake on the GNSS antenna directly, but indirectly on the building or the structure it is mounted on. PPK solutions obtained by Galileo-only observations compared to solutions computed jointly by all GNSS systems have shown small differences. A further and detailed interdisciplinary and collaborative approach with seismologists and civil engineering experts will be needed to leverage the potential of the method in the assessment of the earthquake effect on natural and man-made structures.

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