Single Base RTK Solutions Obtained Individually With Galileo And Beidou As Well As In Combination With Other Fully Operational GNSS

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Key words: GNSS/GPS, single base RTK, Galileo, BeiDou, Fixed solution

SUMMARY

GNSS RTK (Global Navigation Satellite System Real Time Kinematic) positioning method is the most widely used and the fastest surveying method for coordinates determination on the surface of the Earth. Due to its speed and reliability, it has found a wide application within surveying and geodesy. Similar to other satellite positioning methods, the efficiency of the RTK method is highly dependent on the number of simultaneously visible satellites in certain epoch. Currently, GPS and GLONASS are the only two fully operational systems which are commonly used for single base (conventional) or networked RTK positioning. Two additional GNSSes – European Galileo and Chinese BeiDou – are planned to achieve their Full Operational Capability (FOC) by 2020. Although Galileo and BeiDou are still under development, the idea of assessing the possibility and feasibility of positioning by single base RTK method using these two satellite systems has arisen. The investigations about the feasibility of the single base RTK positioning using individually Galileo and BeiDou satellites has been carried out and presented in this paper. Therefore, two GNSS receivers (base and rover) of the Topcon's newest model HiPer HR with the capability of observing all available GNSS constellations have been used. In addition to the receivers, the field controller FC-5000 with the Topcon Receiver Utility (TRU) software was used enabling the selection of the GNSS constellation combination for positioning. Prior to surveying, the mission planning was carried out pointing out those time windows with optimum visibility of Galileo and BeiDou satellites. Altogether 13 combinations of GNSS constellations were observed during two consecutive days of measurements, enabling the subsequent accuracy and precision analysis. Static GNSS occupations carried out on the base and rover receiver stations prior to RTK observations (using GPPS CROPOS – national permanent GNSS network) enabled the underlying accuracy evaluation. The analysis of the results obtained with different 13 combinations of GNSS constellations has pointed out that the RTK fixed solutions were obtained in all combinations, including Galileo and BeiDou individually. Due to the small number of available satellites and constellations under construction, Galileo and BeiDou as systems are still not ready for reliable individual RTK coordinates determination. The availability of numerous multi-constellation observations in the future will enable faster and more reliable ambiguity resolution as well as the subsequent GNSS positioning.

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INTRODUCTION

Satellite positioning methods have been used within geodesy and surveying in Croatia and all over the world for more than 20 years. The RTK (Real Time Kinematic) positioning method has become the most widely used and the fastest surveying method for coordinates determination on surface of the Earth. As other satellite relative positioning method, the RTK method requires at least two GNSS (Global Navigation Satellite System) receivers: base and rover. At the early stages of the RTK method, there was a base receiver set up at the station with known coordinates observing the same GPS (Global Positioning Satellites), calculating the differential corrections of the phase observations which were via the radio link transferred to the rover GPS receiver enabling it so solve the phase ambiguities and subsequently the coordinates in real-time. This positioning method was referred to as conventional RTK providing cm-level accuracy up to 20 km distance from the base receiver. In the meantime, the concept of Networked RTK (NRTK) was developed modelling the distance dependent errors of the GNSS observations (ionospheric and tropospheric refraction, orbital errors) and thus extending the distance between permanent GNSS stations up to 70-100 km (Janssen 2009). Until recently, two fully operational GNSSes were used for RTK positioning: the American GPS and the Russian GLONASS. They are about military satellite systems which usage for civilian purposes has revolutionized the navigation and positioning methods. Today, GPS and GLONASS are not the only two GNSSes, there is the European Galileo and the Chinese BeiDou systems which are under development and are envisaged to reach their Full Operational Capability (FOC) by 2020. Additional and new satellite system will improve the accuracy, availability and reliability of precise positioning having he positive consequences on geodesy and surveying as well as to the design and production of more sophisticated GNSS receivers.

As early as in 2006, some leading manufacturers (Topcon, Trimble, Leica) started the production of the GNSS receivers with capability of tracking Galileo (GIOVE – Galileo In-Orbit Validation Element) satellites (URL1, URL2, URL3) satellites. Today, almost all recently developed and produced GNSS receivers support the tracking of Galileo and BeiDou satellites but the usage of those systems for positioning is not yet fully deployed. Although Galileo and BeiDou systems are still under construction, the testing of their possibility and feasibility for RTK positioning has been carried out and presented within this paper. The aim of the research activities was the answer to the questions whether Galileo and BeiDou satellite systems could be already used individually for RTK positioning or not and if the answer was positive give the comparison of the results obtained in combination with GPS and GLONASS satellites system. Altogether 13 different data combinations have carried out through two days of field observations leading to the analysis of the obtained results in terms of accuracy and precision as well.

1. GLOBAL NAVIGATION SATELLITE SYSTEMS

1.1 Global Positioning System (GPS)

GPS is the first GNSS. The system development was initiated in the early 1970s, the first satellite was launched in 1978. Since then, a few generation (blocks) of satellites were launched. The system has reached its Full Operational Capability (FOC) in 1995. The current GPS constellation consists of 31 satellites (12 Block IIR, 7 Block IIR-M, 12 Block F) (URL 4, URL 5, URL 6). The satellites are deployed in 6 orbital planes with inclination 55° to the equator at the altitude of about 20200 km above the surface of the Earth. Commonly, one GPS satellite takes 11h 58min to complete its orbital motion. GPS satellites broadcast signals based on Code Division Multiple Access (CDMA) at the frequencies L1, L2 and L5. The next generation of satellites – Block III – will broadcast the fourth civilian GPS signal, L1C, which will be backward compatible with L1 and will provide greater civilian interoperability with the European Galileo (URL 7).

1.2 GLONASS

GLONASS was developed by the Soviet Union as an experimental military communications system during the 1970s. The first GLONASS satellite was launched in 1982 and the system was declared fully operational in 1996. After a period where GLONASS performance declined, Russia committed to bringing the system up to be fully operational again in 2010 (URL 8; Torge and Müller 2012). Currently, the GLONASS constellation features 23 operational satellites being of GLONASS-M or GLONASS-K type (URL 9). GLONASS satellites signals are based on the Frequency Division Multiple Access (FDMA) and broadcast their signals at different frequencies. GLONASS–K type satellites, in addition to the FDMA signal, broadcast the CDMA signal for interoperability with GPS and Galileo. Basically, the GLONASS constellation consists of 24 active and 3 spare satellites deployed in three orbital planes with inclination 64.8°, at average altitude of 19100 km and an orbital period of 11 hours, 15 minutes, 44 seconds.

1.3 Galileo

Galileo is Europe's own global navigation satellite system under civilian control. The system is funded and owned by the European Commission (EC), design and development of the system was entrusted to the European Space Agency (ESA) while the European GNSS Agency (GSA) officially has taken the responsibility for overseeing the operations and service provision for Galileo (URL 10). The fully deployed Galileo system will consist of 24 operational satellites plus six in-orbit spares, positioned in three circular Medium Earth Orbit (MEO) planes at 23

222 km altitude above the surface of the Earth, and at an inclination of the orbital planes of 56 degrees to the equator and orbital period about 14 hours (URL 11). Experimental satellites GIOVE-A and GIOVE-B (Galileo In-Orbit Validation Element) were launched in 2005 and 2008 respectively, serving to test critical Galileo technologies, while also the securing of the Galileo frequencies within the International Telecommunications Union (ITU). Four operational satellites, belonging to the In-Orbit-Validation (IOV) phase were launched, two in October 2011 and two in October 2012, to validate the basic Galileo space and ground segment. With the constellation consisting of four satellites on March 12th 2013, ESA announced that the first autonomous position fix was achieved (Cameron 2013). The Full Operational Capability (FOC) phase consisting of the deployment of the remaining ground and space infrastructure started in 2014 and is currently ongoing. On November 17th 2016, an Ariane 5 rocket has launched four additional Galileo satellites, accelerating the deployment of the new satellite navigation system (URL 12). On December 15th 2016 'Galileo Initial Services' have officially been declared operational. The Galileo system is designed to provide a range of services, each associated with different radio signals being broadcasted: the “Open Service” (OS) and the “Public Regulated Service” (PRS) which are similar, respectively, to the “Standard Positioning Service” and the “Precise positioning Service” of the GPS system; the “Commercial Service” and the “Search & Rescue” (SAR) service”, part of the wider international Cospas-Sarsat organization, which will provide emergency services to users in case of distress and extreme danger. The “Initial Services” are limited only to certain types of services (Open Service (OS), Public Regulated Service (PRS), Search and Rescue (SAR)) and with limited performance, compatibly with the reduced number of satellites in orbit (Lisi 2017). Galileo signals use four carriers (E5a, E5b, E6 and E2-L1-E1), the system uses CDMA as its access scheme, and will be interoperable with GPS and GLONASS (Van Sickle 2015). The current constellation consists of 18 satellites: 15 operational, 2 under testing and 1 'not available' (URL 14). In 2017 and in 2018 two more quadruple launches with Arianne 5 are expected, which should bring the total number of satellites in service to 24 (Lisi 2017).

1.4 BeiDou

China has started the implementation of a GNSS system known as BeiDou Navigation Satellite System (BDS). The system is being implemented in two phases: the initial phase provides regional coverage (also known as Beidou-1), while the second phase will provide global coverage (BeiDou-2 or Compass as an alternative name). The initial phase of the BeiDou system officially became operational in December 2012, providing coverage for the Asia Pacific region. The regional BeiDou space segment has 5 Geostationary Earth Orbit (GEO) satellites, 5 Inclined Geosynchronous Orbit (IGSO) satellites and 4 Medium Earth Orbit (MEO) satellites. The inclination of both IGSO orbits and MEO orbits are 55°, whereas the orbital radiuses are 35787 km and 21528 km, respectively. The second phase of the BeiDou system is planned to be completed by the end of 2020 and will provide global coverage with enhanced regional coverage. The space segment will consist of a constellation of 5 GEO, 3 IGSO and 27

MEO satellites. Once fully operational, all MEO satellites will be deployed in 3 orbital planes. The BeiDou signals are based on CDMA technology and use three carriers which are in the same area of L-band as other GNSS signals: B1 (open and authorized access), B2 (open access) and B3 (authorized access) (URL 15). BeiDou will deliver two types of global and two types of regional services. Global services are open and authorized services. Regional services are wide area differential and short message services (URL 16). By 2020 when is envisaged the Full Operational Capability, BeiDou orbital constellation will include 35 satellites: 5 BeiDou-G satellites in the geostationary orbit (GEO) (58.75° E, 80° E, 110.5° E, 140° E and 160° E), 27 BeiDou-M satellites in medium Earth orbit (MEO) with nominal period of 12 hours 53 min and 3 BeiDou-I satellites in inclined geosynchronous orbits (IGSO) with the altitude of 35 786 kilometers and an inclination of 55° to the equatorial plane. The currents status of the BeiDou system consists of 23 satellites in constellation: 15 included in operational constellation and the remaining 8 satellites not included in operational constellation (URL 17).

2. REAL TIME KINEMATIC POSITIONING METHOD

Differential positioning with GNSS, abbreviated by DGNSS, is a real-time positioning technique where two or more receivers are used. One receiver, usually at rest, is located at the reference or base station with (assumed) known coordinates and the remote receivers are fixed or roving and their coordinates are to be determined. The reference station commonly calculates pseudorange corrections (PRC) and range rate corrections (RRC) which are transmitted to the remote receiver via a data link sometimes over the Internet, radio signal, or cell phone in real time. The remote receiver applies the corrections to the measured pseudoranges and performs point positioning with the corrected pseudoranges. The use of the corrected pseudoranges improves the position accuracy with respect to the base station. DGNSS with phase ranges, sometimes denoted as carrier phase differential technique, is used for most precise kinematic applications. For this mode of operation, on-the-fly (OTF) techniques are required to resolve the ambiguities. DGNSS with phases converts to relative positioning with phases if the latency becomes zero. This method is usually denoted real-time kinematic (RTK) technique (Hofmann-Wellenhof et al. 2008, Van Sickle 2015).

When processing a baseline, the effects of orbit errors, ionospheric and tropospheric refraction are reduced by forming differences of the observables, e.g., double differences. These effects grow with increasing baseline length. Therefore, it is good practice to use short baselines requiring a reference station close to the rover. RTK ought to have at least five satellites for initialization. Tracking five satellites provides insurance against losing one abruptly; also, it adds considerable strength to the results (Van Sickle 2015). Today, the data combination is no longer be restricted to dual and triple frequencies because more than a single global positioning system is available, i.e, the modernized GPS, GLONASS, in the future fully deployed Galileo and BeiDou. The benefits address the ambiguity resolution itself, the initialization performance, reliability, accuracy, and other aspects. Benefits of the Multiple carrier ambiguity resolution may be summarized as (Hofmann-Wellenhof et al. 2008):

- allowing ambiguity resolution over long distances,
- allowing the fixing of correct integer solutions within much shorter periods,
- achieving highly reliable integer solutions,
- enabling RTK positioning in urban areas (where signal obstruction is an issue).

Single RTK is referred to the concept featuring at least one base receiver set up at the reference station with known coordinates and at least one rover receiver observing the same satellites. One significant drawback of single base RTK is that the maximum distance between reference station and rover receiver must not exceed 10−20 km in order to be able to rapidly and reliably resolve the carrier-phase ambiguities.

Another important factor affecting efficiency of the RTK method is the necessary time to fix ambiguities (TTFA). The necessary TTFA strongly depends on the behavior of the distance dependent errors. For short distances (a few kilometers), and under favorable conditions, the

TTFA can be as short as only one epoch. A significant limitation of RTK solutions is the fact that the errors and TTFA grow with increasing distance from the base station. A general rule of thumb for the achievable accuracy is 10 mm + 1 to 2 ppm for horizontal coordinates, and 15–20 mm + 2 ppm for the height component. RTK applications are therefore limited to a range of a few kilometers (mostly below 2 km) with a TTFA of just a few seconds (Seeber 2003). This limitation is caused by distance-dependent biases, mainly ionospheric signal refraction but also orbit errors and tropospheric refraction. These errors, however, can be accurately modeled using the measurements of an array of GNSS reference stations surrounding the rover site. Thus, the solution to the distance limitation of RTK lies in multibase techniques which became popular under the name Network RTK (NRTK). In fact, also network RTK has a distance limitation. This limitation refers to the distances between the reference stations. They should not exceed 100−200 km in order to be able to produce highly accurate real-time correction models of the distance-dependent errors (Odijk and Wanninger 2017). A good example of permanent GNSS stations network providing Network RTK solutions as well as the raw GNSS data of the reference stations is the CROatian POsitioning System – CROPOS.

3. CROATIAN POSITIONG SYSTEM – CROPOS

CROPOS is the state network of permanent GNSS reference stations of the Republic of Croatia. The network consists of 33 stations at the average distance of 70 km distributed over the national territory for the purpose of collecting satellite observation data and determination of correction parameters. The inclusion of additional permanent GNSS stations data from neighboring countries into CROPOS enabled a better coverage and reliability of the system as well as the better modelling of corrections in the border areas of the Republic of Croatia. Since its setup in December 2008, in CROPOS were gradually included the data of permanent GNSS stations from the neighboring countries (Slovenia 7, Hungary 4, Bosnia and Herzegovina 5, Monte Negro 2), so today the joint network solution is generated from altogether 51 permanent

GNSS stations. Five stations of the CROPOS network are included in the EUREF Permanent Network (EPN) (Šugar et al 2016; URL 18). The system provides three services which differ in accuracy, availability, way of data transfer, data format and positioning methods. More information about CROPOS, its services and CORS (Continuously Operating Reference Station) permanent GNSS stations may be found on CROPOS's web site (URL 19). High Precise Positioning Service (VPPS in Croatian) is the most frequently used tool by surveyors for every kind of land and cadastral survey in Croatia. The VPPS offers a networked solution of phase measurements in real-time, and the coordinates are determined with declared accuracy 2 cm (2D) and 4 cm (3D). Geodetic Precise Positioning Service (GPPS) provides the GNSS observation data collected at CORSes or at arbitrarily selected Virtual Reference Stations (VRS) with a subcentimeter level of accuracy. Observation data are available for post-processing in Trimble proprietary formats (DAT, TGD, T01, T02) as well as in few versions of RINEX format (2.10, 2.11, 3.02). CROPOS as system of networked permanent GNSS stations is based on the VRS (Virtual Reference Station) concept. That concept was developed by Trimble company whose GNSS equipment and software infrastructure is implemented in CROPOS (Trimble NetR5 GNSS receivers, Trimble Zephyr GNSS Geodetic II antenna, Trimble Pivot Platform 3.5). Currently, the GNSS receivers Trimble NetR5 involved in CROPOS support the observation of only GPS and GLONASS satellites thus, the differential corrections and CORS observation data are available only for those two satellite systems.

4. GEODETIC NETWORK AND STATIC GNSS OBSERVATIONS

For the purpose of testing the availability and feasibility of single base RTK method for coordinates determination using Galileo and BeiDou individually as well as in combination with other GNSS, an appropriate geodetic network was needed. The network initially was composed of altogether 6 stations, one of them was envisaged to serve as base station for subsequent RTK observations (Figure 1). As the goal of testing procedure was the assessment of coordinates accuracy and precision, the coordinates were supposed to be determined by method providing higher level of accuracy – static method. So, the coordinates of the station B and S2 were determined from static observations collected with the receivers *Topcon Hiper SR* (station S2) and *Topcon Hiper HR* (station B). The coordinates of the remaining stations (P1, P2, P3, S1) were envisaged to be determined by terrestrial measurements (total station and digital level) because those stations had partially obstructed horizons. The horizons at the stations B and S2 can be considered as free enabling the unobstructed reception of the GNSS signals (Figure 1).

Figure 1. Stations of the geodetic network where the testing took place (with solid circles are marked the station statically occupied with GNSS, with dashed circles those observed with terrestrial methods)

Static occupation of the stations B and S2 lasted for 44 minutes, the elevation mask was set on 13° and observation interval was 1 second. From the CROPOS GNSS REFERENCE STATION WEB SERVER (CROPOS GPPS) (URL 20) were requested and downloaded the RINEX 3.02 files for three VRS stations evenly distributed around the station B (see Figure 2). Although the nearest CAKO CORS station is distant approximately 1 km from the stations B and S2, the regulations applicable to the determination of coordinates by GPPS CROPOS, namely Regulations on the fundamental geodetic works performance (National Gazette 2009), foresee the usage of three virtual reference stations (VRS) evenly distributed around the stations which coordinates are to be determined. RINEX files along with the **.tps* observation files collected with Topcon GNSS receivers, were imported in *Topcon Magnet Office Tools* where the data were subsequently processed and the network adjustment performed. The coordinates of CROPOS CORS were determined in ETRF2000 (R05) relying on the ellipsoid GRS80, consequently CROPOS provided the coordinates in the same reference frame. As the official *Croatian Terrestrial Reference System 96 / Transverse Mercator* (*in Croatian* HTRS96/TM) is linked to the Transverse Mercator projection, eventually the obtained coordinates are given as plane coordinates (E, N).

The coordinates of the stations B and S2 with associated precision estimations are given in the Table 1, the geodetic network including VRS stations is shown on the Figure 2.

Table 1. Coordinates and associated precisions of the stations B and S2 obtained from static GNSS observations.

Station	E [m]	N[m]	h [m]	σ (E) [m]	σ (N) [m]	σ (h) [m]

B	495292.912	5139611.430	208.107	0.003	0.003	0.006
S2	495397.045	5139630.256	208.340	0.003	0.003	0.006

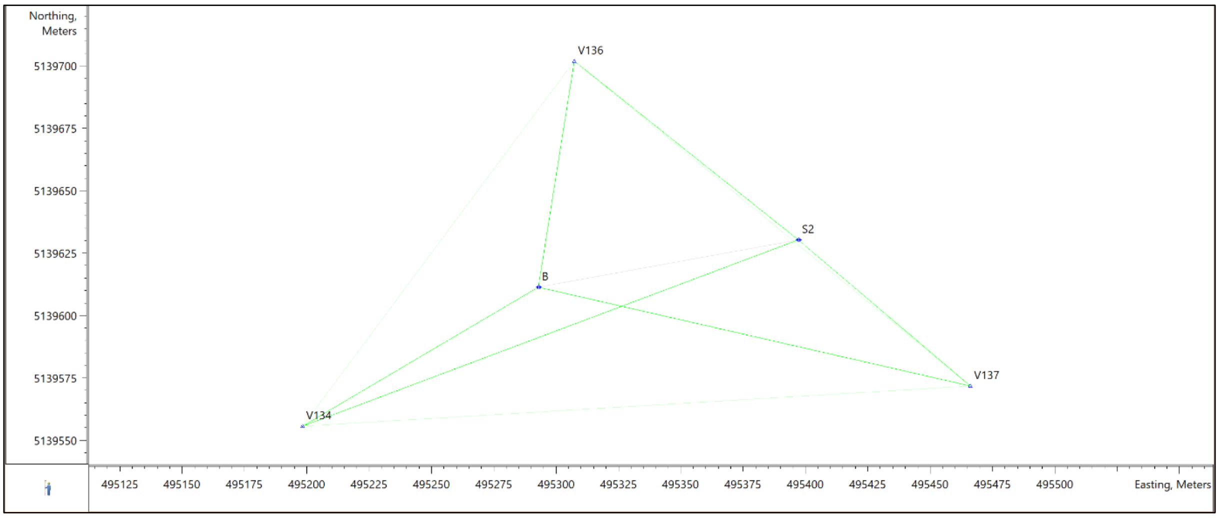


Figure 2. Stations of the geodetic network after baselines processing and network adjustment in Topcon Magnet Office Tools software.

5. RTK MEASUREMENT

5.1 GNSS RTK receivers and equipment

For the sake of implementation of the testing activities, it was necessary to have at disposal two GNSS receivers (base and rover) with the capability of tracking and positioning using Galileo and BeiDou satellite signals. A clear distinction should be made between only tracking and usage of satellite signals for positioning. Indeed, still today many GNSS receivers have the capability of only tracking newer satellite systems (e.g. Galileo and/or BeiDou) whereas the positioning is performed relying on GPS and GLONASS.

For the RTK measurements were used two newest model Topcon Hiper HR GNSS receivers. According to the brochure (URL 21), the receiver is equipped with 452 channels capable of tracking and positioning with all satellites in view (GPS, GLONASS, Galileo, BeiDou, IRNSS, SBAS (EGNOS/WAAS/MSAS) and QZSS) enabling accuracy for static (H: 3.0 mm + 0.1 ppm; V: 5.0 mm + 0.5 ppm) and RTK positioning method (H: 5 mm + 0.5 ppm; V: 10 mm + 0.8 ppm). The communication with other devices is provided through Optional Radio Type (UHF radio), Additional Communications (Internal cellular modem, Wi-Fi, Bluetooth, LongLink) and

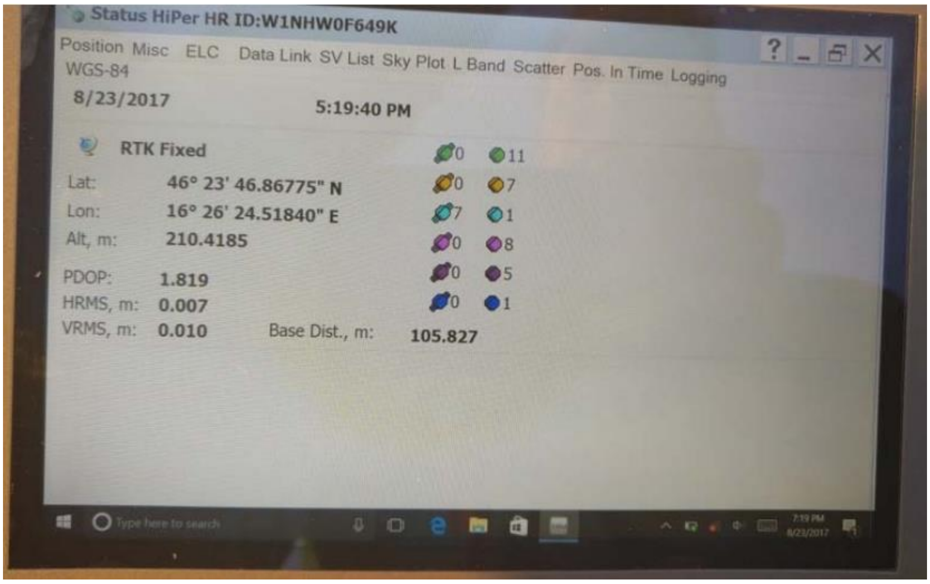
Cellular link (Integrated HSPA+/CDMA). The Real Time Data Output is possible via: TPS, RTCM SC 104 v2.x, 3.x, CMR/CMR+, RINEX (*ibid.*). Along with the receivers, the field controller Topcon FC-5000 with installed *Topcon Receiver Utility* (TRU) software was used too. A conventional (single base) RTK method was used because the CROPOS real-time service (HPPS) does not support newer satellite system signals (e.g. Galileo and BeiDou). For the communication between the base and rover receiver was selected Topcon's *LongLink*, instead of the default radio link. It is about the communication functionality providing 300 m wireless range using Bluetooth Class 1 technology (URL 22).

In addition to the GNSS receiver, an appropriate software for collecting of field measurements was needed. At this point, a problem has arisen because there was no commercially available software supporting the coordinates determination without GPS observation data. The problem was overcome with the usage of the Topcon Receiver Utility (TRU) software which is not a classical software for field surveying activities but, at the other hand, enables a high degree of autonomy in terms of selecting the satellite systems. Although the TRU software is usually used for firmware updating and importing of OAF (Option Authorization File), it allows the GNSS receiver configuration. A drawback of the TRU software is that it does not allow the storage of RTK measurements output but only raw static and kinematic observation data.

Figure 3. Topcon Hiper HR GNSS receiver (URL 23)

Figure 4. Topcon FC-5000 Field Controller (URL 24)

However, TRU software interface allows the display of solution type (*Standalone*, *Float*, *DGNSS*, *Fixed*), the number of visible satellites and those satellites used for RTK positioning, UTC (Universal Time Coordinated) time, coordinates in WGS84 system (latitude, longitude, height), as well as the PDOP (Position Dilution of Precision), HRMS (Horizontal Root Mean Square) and VRMS (Vertical Root Mean Square) values. The TRU software interface during positioning (RTK Fixed) is shown on the Figure 5.



WGS-84
8/23/2017 5:19:40 PM

RTK Fixed

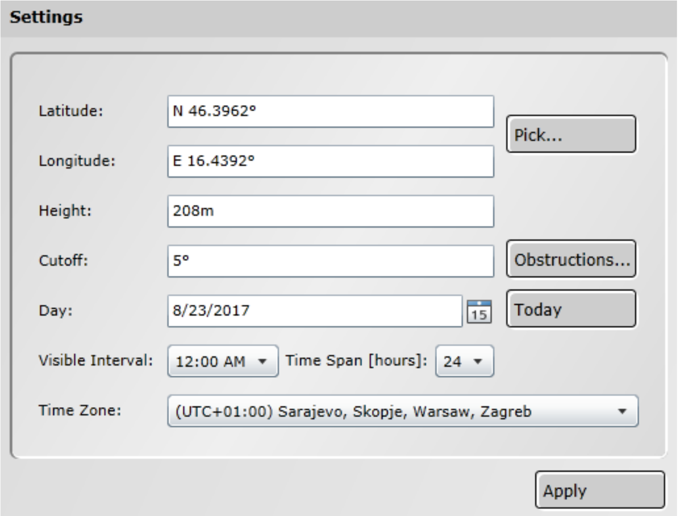
Lat: 46° 23' 46.86775" N
Lon: 16° 26' 24.51840" E
Alt, m: 210.4185

PDOP: 1.819
HRMS, m: 0.007
VRMS, m: 0.010 Base Dist., m: 105.827

Figure 5. TRU sofware interface during the RTK positioning (Photo: V. Mihoković)

For field activities, a tripod with tribrach (base receiver) as well as the range pole with bipod were used (rover receiver) (Figure 9 and Figure 10).

Due to the constellation of Galileo and BeiDou systems still under construction and consequently their limited satellites availability and visibility, it was essential do carry out the mission planning which was carried out using the *GNSS Planning Online* tool (URL 25). Two GNNS receivers Topcon Hiper HR with capability of positioning using Galileo and BeiDou satellites were available for a very limited time, so the field observation had to be performed during two days: 23th and 24th August 2017. Prior to mission planning in GNSS Planning Online tool, it is necessary to select the latitude, longitude and height (approximate ellipsoidal coordinates) as well as to set the cutoff angle (5°), the day of observation, visible interval and Time Zone (Figure 6).



Settings

Latitude: N 46.3962°

Longitude: E 16.4392°

Height: 208m

Cutoff: 5°

Day: 8/23/2017

Visible Interval: 12:00 AM

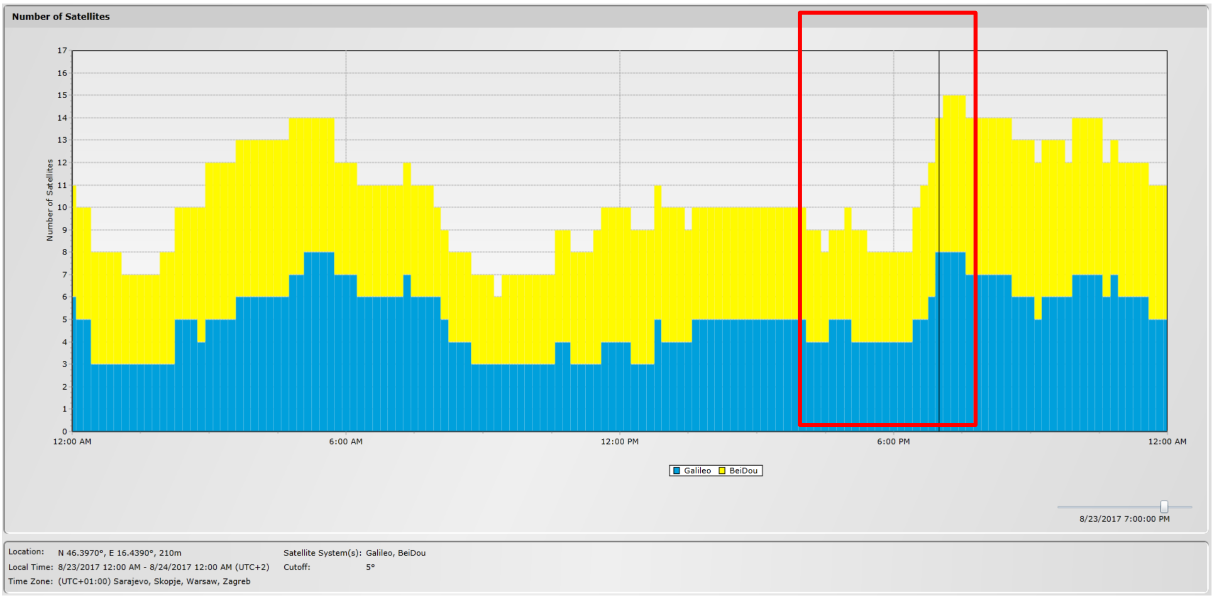
Time Span [hours]: 24

Time Zone: (UTC+01:00) Sarajevo, Skopje, Warsaw, Zagreb

Figure 6. Setting the parameter in GNSS Planning Online tool prior the mission planning (URL 25).

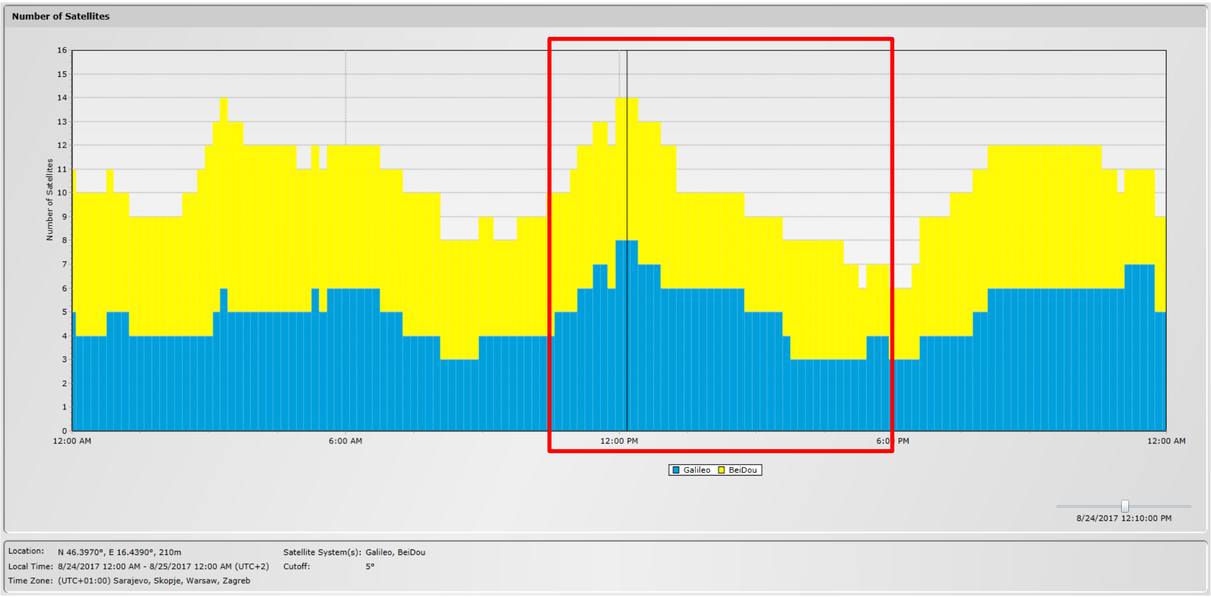
Once the satellite system(s) has (have) been selected (GPS, GLONASS, Galileo, BeiDou, QZSS), the information about Elevation, Number of Satellites, DOPs, Visibility, SkyPlot etc. can be calculated and displayed. During both days, 23th and 24th August 2017 the visibility of GPS satellites were in the range 8-12 satellites and the visibility of GLONASS satellites in the range 6-10. It is worth mentioning that Galileo constellation was composed of 15 operational satellites (altogether 18 satellites), the BeiDou constellation contained 15 operational satellites too. Because both GPS and GLONASS are fully operational and provide enough availability (individually and jointly) for RTK positioning, the subsequent mission planning was performed taking into consideration Galileo and BeiDou systems only. The visibility of Galileo satellites for the days 23th and 24th August 2017 was in the range 3-8 for both days, while the visibility of BeiDou satellites was in the range 3-8 and 3-7, respectively. So, the ultimate goal of mission planning was to select those time windows providing optimal satellite visibility and DOP values as well. The satellite visibility plot for Galileo and BeiDou satellites for 23th August 2017 has pointed out two maximums: around 5:30 (UTC+2) and 19:00 (UTC+2) having visible 8 Galileo and 6 BeiDou as well as 8 Galileo and 7 BeiDou satellites, respectively (Figure 7). Thus, it was decided to select the afternoon time window (session) on 23th August 2017 for RTK field observations: 16:00 (UTC+2) – 19:50 (UTC+2) (on the Figure 7 marked by red rectangle). The Number of satellites plot for the next day, 24th August 2017 has shown the maximum number of visible 8 Galileo and 6 BeiDou satellites around 12:00 (UTC+2): the field RTK observations were performed in the period 10:30 (UTC+2) – 18:00 (UTC+2) (on the Figure 8 marked by red rectangle).

The times for RTK occupations on the station S2 were not optimal, especially on 24th August 2017, because the field activities encompassed the occupation of few additional stations (P1, P2, P3 and S1). Unfortunately, those stations had a partially obstructed horizons, so the results of RTK positioning were not considered nor presented in this paper.



Location: N 46.3970°, E 16.4390°, 210m
Local Time: 8/23/2017 12:00 AM - 8/24/2017 12:00 AM (UTC+2)
Time Zone: (UTC+01:00) Sarajevo, Skopje, Warsaw, Zagreb
Satellite System(s): Galileo, BeiDou
Cutoff: 5°

Figure 7. Number of visible Galileo (blue) and BeiDou (yellow) satellites for August 23th 2017.(GNSS Planning Online – URL 25)



Location: N 46.3970°, E 16.4390°, 210m
Local Time: 8/24/2017 12:00 AM - 8/25/2017 12:00 AM (UTC+2)
Time Zone: (UTC+01:00) Sarajevo, Skopje, Warsaw, Zagreb
Satellite System(s): Galileo, BeiDou
Cutoff: 5°

Figure 8. Number of visible Galileo (blue) and BeiDou (yellow) satellites for August 24th 2017.(GNSS Planning Online – URL 5)

5.2 RTK positioning

As it was previously planned, the RTK field activities were carried out on 23th August 2017 in the period 16:00 (UTC+2) – 19:50 (UTC+2) as well as on the next day, 24th August 2017 in the period 10:30 (UTC+2) – 18:00 (UTC+2). Static occupations on the station B and S2 and the subsequent baseline processing and network adjustment allowed the accuracy estimation of the coordinates obtained by RTK method whereas the two consecutive days of RTK observations enabled the estimation of coordinates precision. In order to assess the accuracy and precision of coordinates obtained with different GNSS constellations, the occupations of the station S2 were performed using 13 different satellite system combinations, namely:

1. GPS+GLONASS+Galiloe+BeiDou (GGGB),
2. GPS+GLONASS+Galileo (GPS.GLO.GAL),
3. GPS+GLONASS+BeiDou (GPS.GLO.BEI),
4. GPS+Galileo+BeiDou (GPS.GAL.BEI),
5. GLONASS+Galileo+BeiDou (GLO.GAL.BEI)
6. GPS+GLONASS (GPS.GLO),
7. GPS+BeiDou (GPS.BEI),
8. GPS+Galileo (GPS.GAL),
9. GLONASS+BeiDou (GLO.BEI),
10. GLONASS+Galileo (GLO.BEI),
11. Galileo+BeiDou (GAL.BEI),
12. Galiloe only (GAL),
13. BeiDou only (BEI).

The base GNSS receiver Topcon Hiper HR was setup on a tripod over the station B (Figure 9). The slant antenna height was measured twice from the station up to the Antenna Reference Point (ARP). The rover GNSS was setup on the range pole with bipod support (Figure 10). The centering of the GNSS receiver (and antenna too) on the station S2 was assured by the range pole itself, the vertical position of the range pole was reached with apposite bubble level. The base GNSS receiver was started as well as the measurements with the rover GNSS receiver were performed by Topcon Receiver Utility software running on the field controller Topcon FC-5000. On the base GNSS receiver were set the ellipsoidal coordinates (GRS80) obtained from the previous static observations, the receiver was set to track all visible and available satellite constellations and finally, the differential corrections were configured to be broadcasted in the format RTCM 3.02 to the rover receiver via the LongLink Bluetooth connection. The base and rover GNSS receivers are shown on the Figure 9 and Figure 10, respectively.

Depending on the GNSS constellations combination which was planned to be observed, on the rover GNSS receiver with TRU software the chosen satellite systems were turned on or off and subsequently the observations were taken. Due to the fact that that the TRU software does not allow the storage of positioning results, the measurement were carried out as follows. After the rover GNSS receiver was set up over the station S2, it was waited for some seconds until the results became ‘stable’. Further, the photos of the field controller FC-5000 display showing RTK positioning results were taken simulating the recording of three consecutive epochs. The photos were systematically named and stored taking care about the observed GNSS combinations, name of the station and the ‘epoch’ of observation (1-2-3). At the end of the day, all taken photos were transferred to a desktop computer and the ellipsoidal coordinates (latitude, longitude, height) along with the PDOP, HRMS, VRMS and distance to the base were read from the photos and typed in Excel spreadsheet. As it was the most vulnerable step of transferring the results from ‘raster’ to numerical values, a special attention was paid including multiple checks. The average values of three consecutive epochs obtained by a selected GNSS constellations combination were calculated and subsequently imported in *Magnet Office Tools* software where the ellipsoidal coordinates (φ, λ, h) were transformed into the coordinate system HTRS96/TM (E, N, h) enabling the further analysis.

Figure 9. Base GNSS receiver Topcon Hiper HR on a tripod

Figure 10. Rover GNSS receiver Topcon Hiper HR on the ranging pole with a bipod support

6. RTK MEASUREMENT RESULTS

6.1 RTK accuracy estimation

The coordinates of the station S2 determined from static observations enabled the accuracy estimation of the RTK results derived from different GNSS constellation combination during two days of measurements. If the coordinate differences obtained by RTK method (23th August 2017) using different GNSS constellation combinations are compared with the reference coordinates, the coordinate differences (Δ = Measured –Reference) show the values: ΔN (min: -0.003 m; max: 0.007 m; rms: 0.003 m) and ΔE (min: -0.016 m; max: -0.003 m; rms: 0.012 m) leading to the horizontal differences ranging from 4 do 16 mm (rms 13 mm). If the 'measured' base distances (distance between the base and rover receiver) are compared to the base distance calculated from reference coordinates of the stations S2 and B, the following values are derived: min (0.001 m), max (0.013 m), rms (0.006 m).

It is easy to notice that the ΔE coordinate differences show larger values than ΔN. It could be related to the relative position of station S2 compared to the base station B (see Figure 1 or Figure 2). In fact, the rms ΔN (0.003 m) and rms ΔE (0.012 m) are in relation to the stations S2 and B coordinate differences ΔN (-18.826 m) and ΔE (-104.133 m) leading to the approximate ratio 6 ($\Delta E/\Delta N \approx 6$).

Considering the obtained results, it can be figured out that RTK method has provided the fixed solution with all GNSS constellation combinations and subsequently the rover receiver coordinates accuracy at 1-cm level.

If the heights obtained by a single RTK method are compared to the reference, the following values are given: min (-0.007), max (0.042 m), rms (0.013 m). The extreme value (0.042 m) was obtained from BeiDou only combination featuring 5 BeiDou satellites (VRMS = 0.046 m; PDOP = 4.089) (Figure 12). The HRMS values for all combinations were in the range from 0.003 to 0.020 m, in average 0.006 m (worse result was obtained by BeiDou combination). Similarly, The VRMS values for all combinations were in the range from 0.004 to 0.046 m, in average 0.010 m (if the maximum 0.046 m is excluded, a new maximum value is 0.019 (GLO.BEI combination) with average value now 0.007 m). Another solution with significant vertical deviation was obtained with GLO.BEI combination showing the values: Δh = 0.015 m, VRMS = 0.007 m; PDOP = 1.473. The remaining solution have shown differences less than 1 cm (see Figure 12).

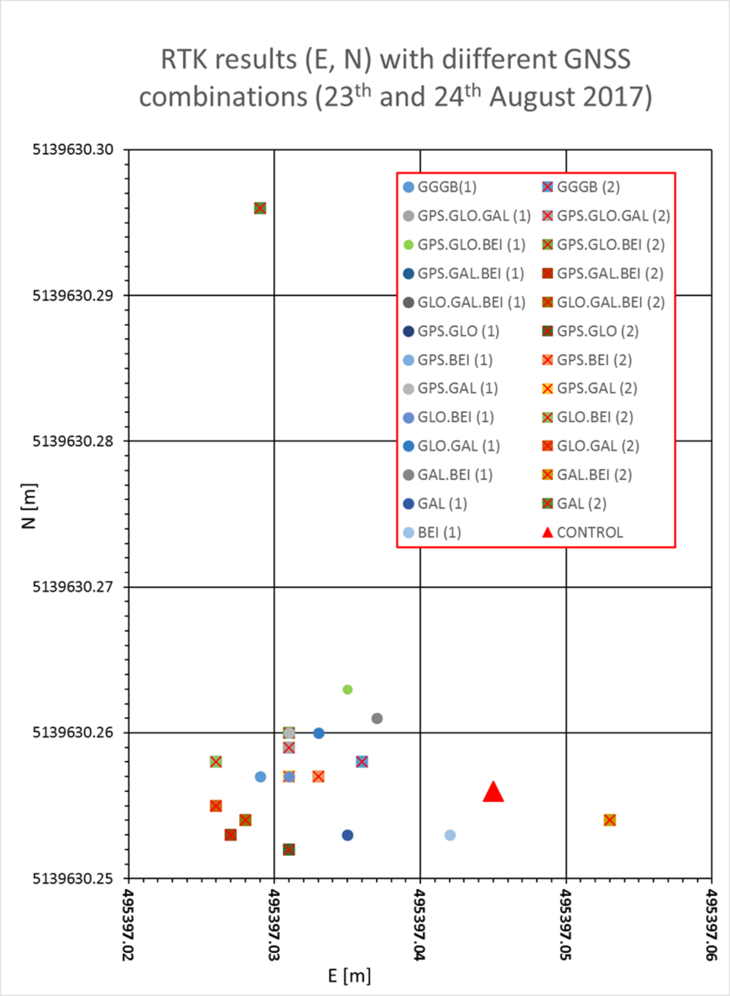


Figure 11. RTK results (E, N)obtained with 13 different GNSS constellation combination during both days of observation: 23th and 24th August 2017.

By analysis of the results obtained during second day of measurements (24th August 2017) it can be easily seen that the results are worse due to longer observation time window and worse Galileo and BeiDou satellites availability and visibility (Figure 7 and Figure 8). First of all, it should be noted that the BeiDou only combination has not gained a fixed solution, actually an *Autonomous* solution was obtained. If this solution is neglected, other solutions were *Fixed* with coordinate differences (Δ = Measured – Reference) showing the values as follows: ΔN (min: -0.004 m; max: 0.040 m; rms: 0.012 m) and ΔE (min: -0.019 m; max: 0.008 m; rms: 0.015 m) leading to the horizontal differences ranging from 8 do 43 mm (in average 17 mm). The largest coordinate difference (ΔN = 0.040 m) was obtained with Galileo only combination (6 Galileo satellites visible; HRMS = 0.024 m; VRMS = 0.021 m; PDOP = 2.375). This result is quite well visible in the Figure 11 as an outlier. If this largest value is neglected, the statistical parameters of the coordinate differences are given as follows: Δ*N* (min: -0.004 m; max: 0.004 m; rms: -0.003 m) and Δ*E* (min: -0.019 m; max: 0.008m; rms: 0.015 m) leading to the horizontal differences ranging from 8 to 19 mm (in average 15 mm).

On the Figure 11 are reported all results obtained during both days of observation. Two results that significantly deviate from the other results, were obtained with GAL(2) only and with GAL.BEI (2), both gathered during the second day of observations (24th August 2017).

Similarly to the first day of observations, if the 'measured' base distances (distance between the base and rover receiver) are compared to the base distance calculated from reference coordinates of the stations S2 and B, the following values are displayed: min (-0.002 m), max (0.024 m), rms (0.008 m).

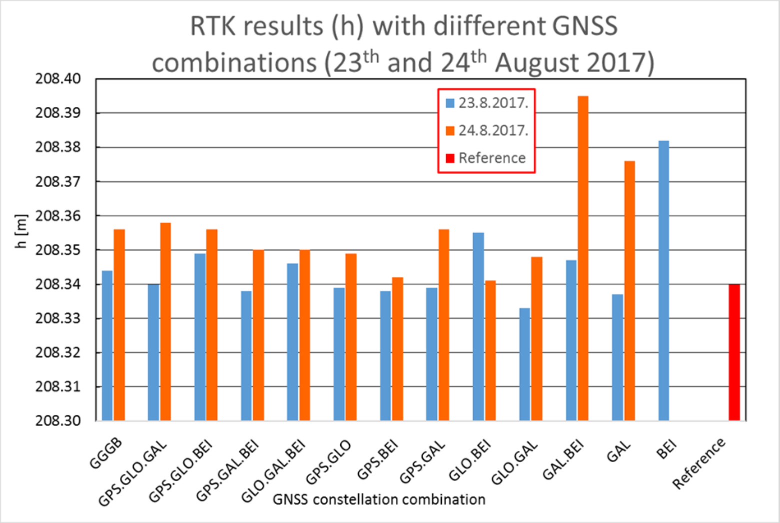


Figure 12. Ellipsoidal heights (GRS80) obtained from 13 different GNSS constallation combinations during both days of observation: 23th and 24th August 2017. REMARK: an Autonomous solution was gained with BEI combination (24th August 2017) thus the numerical value is not shown.

Generally, on the Figure 11 can be seen that the results obtained during the first day of observations (23th August 2017) show smaller deviations from the reference coordinate in comparison to the results obtained during the second day (24th August 2017). The average horizontal deviation for the first day was 12 mm, for the second day 17 mm (GAL only combination included. Additionally, on the second day an *Autonomous* solution occurred.

The height differences (Δ = Measured – Reference) obtained from observations taken on the second day of measurement have shown the following statistical parameter values: min (0.001 m), max (0.055 m), rms (0.022 m). Two largest differences were gained from the GAL.BEI combination (Δ*h* = 0.055 m; VRMS = 0.064 m; visible 4 Galileo and 4 BeiDou satellites) and from GAL only combination (Δh = 0.036 m; VRMS = 0.021 m; visible 6 Galileo satellites). Generally, it can be seen and concluded from the Figure 12 that the heights determined during the second day of measurements (24th August 2017) show worse accuracy in comparison to the results gained during the first day of measurements (23th August 2017).

6.2 RTK precision estimation

Two consecutive days of observations with the same GNSS receivers have enabled the precision estimation of the RTK results. If each GNSS constellation combination the result obtained from the first day of measurements (23th August 2017) is compared to the corresponding result obtained from the second day of measurements, the coordinate differences with the following statistical parameters are given: ΔN (min: -0.007 m; max: 0.043 m; rms: 0.013 m) and ΔE (min: -0.007 m; max: 0.016 m; rms: 0.006 m) leading to the horizontal differences ranging from 0 to 43 mm (rms 14 mm). The largest horizontal differences were shown from the GAL only and GAL.BEI combinations (43 mm and 17 mm, respectively). If this two combinations are excluded from the further analysis, the following statistical parameters about coordinate differences are given: ΔN (min: -0.006 m; max: 0.004 m; rms: -0.004 m) and ΔE (min: -0.007 m; max: 0.007m; rms: 0.004 m) leading to the horizontal differences ranging from 2 to 9 mm (rms 6 mm).

The height differences between from consecutive station occupations using the same GNSS constellation combination show the similar behavior: Δh (min: -0.014 m; max: 0.048 m; rms: 0.021 m). Two largest difference values occurred for the combinations GAL. BEI (Δh = 0.048 m) and GAL only (Δh = 0.039 m). If this two GNSS constellation combinations are excluded from the further consideration, the following statistical parameters about height differences are given: Δh (min: -0.014 m; max: 0.018 m; rms: 0.012 m).

Taking into consideration what was above stated, and considering the results shown on the Figure 12, it can be concluded that combinations that include at least one fully operational GNSS (GPS or GLONASS) can provide the consecutive results (thus precision) within 2 cm.

CONCLUSION

In this paper were presented the very first results of the single base RTK positioning method obtained with 13 different GNSS constellation combinations, among which were individual and joint combinations consisting of Galileo and BeiDou observation data. Although on the market are available the latest GNSS receivers with the capability of tracking the Galileo and BeiDou satellites, it is not straightforward to obtain a RTK solution without the usage of GPS observation data. The problem was overcome by using two newest GNSS receivers Topcon Hiper HR (base and rover) along with the Topcon Receiver Utility (TRU) running on the Filed Controller Topcon FC-5000. The TRU software enabled the selection of 13 different GNSS constellation combinations, including individually and jointly Galileo and Beidou. Due to the status of the Galileo and BeiDou systems under construction and development, it turned out that the mission planning was essential in selection of suitable time windows with optimal number of available and visible satellites. Despite the mission planning, the results obtained during two consecutive days of measurements have shown that Galileo and BeiDou satellites (individually or jointly) cannot provide a reliable solution. Although almost all GNSS constellation combinations have provided the RTK Fixed solution (with one exception: BEI only combination on 24th August 2017), the errors were up to 43 mm horizontally and up to 55 mm vertically. If the GNSS constellation combinations featuring at least one fully operational GNSS (GPS or GLONASS) were used, the errors were up to 2 cm horizontally and 2 cm vertically. This had led to the conclusion that the RTK solution using Galileo and BeiDou satellites although can provide a Fixed solution, it still cannot be considered reliable. The coordinates obtained with combinations of few GNSS constellations (3 or 4) haven't shown a significant improvement in terms of accuracy and precision, confirming that the multi-constellation observations will provide a faster and more reliable phase ambiguity solutions. The assessment of precision inferred from two days of measurement has shown that it can be estimated to 1 cm horizontally and 2 cm vertically using the same GNSS constellation combination. The future of the RTK method is in the multi-constellation solutions which will provide numerous benefits, and one day (when the FOC of Galileo and BeiDou will be achieved) will become a standard for a single base as well as for the Network RTK.

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REFERENCES

Cameron, A. (2013): Galileo Logs First Autonomous Fix, GPS World - The Business & Technology of GNSS, Vol. 24, number 4, pp. 14.

Hofmann-Wellenhof, B.,Lichtenegger, H., Wasle, E. (2008): GNSS – Global Navigation Satellite Systems - GPS, GLONASS, Galileo, and more, Springer-Verlag, Wien, New York

Janssen, V. (2009): A comparison of the VRS and MAC principles for network RTK, IGNSS Symposium 2009, Queensland, Australia, pp. 1-13.

Lisi, M. (2017): “Initial Services”, the new phase of the Galileo program, Coordinates - the monthly magazine on positioning, navigation and beyond, Volume XIII, Issue 03, March 2017, pp 7-17, Delhi, India.

National Gazette (2009): Regulations on the fundamental geodetic works performance, NN 87/2009, State Geodetic Administration of the Republic of Croatia, Zagreb (in Croatian).

Odijk, D. and Wanninger, L. (2017): Differential Positioning, chapter in Springer Handbook of Global Navigation Satellite Systems, pp. 753-778, Peter J.G. Teunissen and Oliver Montenbruck (Eds.), Springer International Publishing AG, Cham, Switzerland

Seeber, G. (2003): Satellite Geodesy, 2nd completely revised and extended edition, Walter de Gruyter, Berlin, New York

Šugar, D., Gabela, J., Bačić, Ž. (2016): The impact of nonstandard CROPOS network configuration on the accuracy of High Precision Positioning Service, International Scientific Conference GEO2016 & XXIX Meeting of Serbian Surveyors "Professional Practice and Education in Geodesy and Geoinformatics" / Aleksić, Ivan R. (editor-in-chief) (ur.). - Kopaonik, Serbia : University of Belgrade - Faculty of Civil Engineering, pp. 2-9.

Van Sickle, J. (2015): GPSfor Land Surveyors - Fourth Edition, Taylor & Francis Group, Broken Sound Parkway NW, Boca Raton, FL.

Torge, W. And Müller, J. (2012): Geodesy – 4th Edition, Walter De Gruyter GmbH & Co. KG, Berlin/Boston

URL1: Trimble Tracks Galileo Test Satellite Signal , http://www.trimble.com/news/release.aspx?id=072106a (last access October 5th 2017.)

URL 2: Track Galileo Test Signals, http://www.businesswire.com/news/home/20060929005686/en/Topcon-GR-3-NetG3-Receivers-Track-Galileo-Test (last access October 5th 2017.)

URL 3: Capacity for galileo and other future signals, http://gpsworld.com/launchpad-galileo-ready-receivers/ (last access October 5th 2017.)

URL 4: Current GPS constellation, http://www.usno.navy.mil/USNO/time/gps/current-gps-constellation (last access October 5th 2017.)

URL 5: GPS Space Segment, http://www.gps.gov/systems/gps/space/ (access October 5th 2017.)

URL 6: GPS current status, https://www.glonass-iac.ru/en/GPS/index.php (access October 5th 2017.)

URL 7: An introduction to GNSS – GPS, https://www.novatel.com/an-introduction-to-gnss/chapter-3-satellite-systems/gps/, (access October 5th 2017.)

URL 8: An introduction to GNSS – GLONASS, https://www.novatel.com/an-introduction-to-gnss/chapter-3-satellite-systems/glonass/, (last access October 5th 2017.)

URL 9: GLONASS Constellation Status, https://www.glonass-iac.ru/en/GLONASS/, (last access October 5th 2017.)

URL 10: The GSA takes up its responsibilities for Galileo, http://galileognss.eu/the-gsa-takes-up-its-responsibilities-for-galileo/ (last access October 5th 2017.)

URL 11: What is Galileo?, http://www.esa.int/Our_Activities/Navigation/Galileo/What_is_Galileo (last access October 5th 2017.)

URL 12: Galileo system - European Commission, https://ec.europa.eu/growth/sectors/space/galileo/launches_en (last access October 6th 2017.)

URL 13: GALILEO constellation status, http://esamultimedia.esa.int/docs/technology/Constellation_status.pdf (last access October 6th 2017.)

URL 14: GALILEO Constellation Information, https://www.gsc-europa.eu/system-status/Constellation-Information (last access October 6th 2017.)

URL 15: An Introduction to GNSS – BeiDou, https://www.novatel.com/an-introduction-to-gnss/chapter-3-satellite-systems/beidou/ (last access October 6th 2017.)

URL 16: BEIDOU GLOBAL NAVIGATION SATELLITE SYSTEM, https://www.glonass-iac.ru/en/guide/beidou.php (last access October 6th 2017.)

URL 17: BEIDOU constellation status, https://www.glonass-iac.ru/en/BEIDOU/index.php, (last access October 6th 2017.)

URL 18: CROPOS national network of permanent stations, http://cropos.hr/o-sustavu/cropos-drzavna-mreza-referentnih-stanica-republike-hrvatske, (last access October 7th 2017.)

URL 19: services of CROPOS, http://cropos.hr/servisi, (last access October 7th 2017.)

URL 20: CROPOS GNSS REFERENCE STATION WEB SERVER , http://195.29.118.122/Map/SensorMap.aspx, (last access October 7th 2017.)

URL 21: Topcon Hiper HR GNSS receiver brochure, https://www.topconpositioning.com/sites/default/files/product_files/hiper_hr_broch_7010_2199_revb_sm.pdf, (last access October 7th 2017.)

URL 22: LongLink communication functionality, https://www.topconpositioning.com/sites/default/files/product_files/topcon_es_series_brochure_a_us_us_low.pdf, (last access October 7th 2017.)

URL 23: Topcon Hiper HR, http://www.topconsolutions.com/site/cart/productdetail.exc?cmd=view_cart_product&co_id=1074&item_id=126239&prod_id=10827, (last access October 7th 2017.)

URL 24: Topcon FC-5000 Field Controller, https://www.topconpositioning.com/support/products/fc-5000-field-controller,

URL 25: GNSS Planning Online, http://www.gnssplanningonline.com/#/Settings, (last access October 8th 2017.)

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