Multi-constellation GNSS baseline solutions – a perspective from the user's and developer's point of view

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SUMMARY

At the Chair of Satellite Geodesy of the Faculty of Geodesy, University of Zagreb, Croatia, in Satellite Positioning courses and for diploma theses too, the GNSS receivers and software used for processing of static relative observations are provided by Trimble Inc., a company which has a long tradition in GNSS technology, both hardware baseline processing software and workflows. The baseline processing engine (initially having support for GPS-only observations) was deployed with the GPSurvey software, evolved later through the Trimble Geomatics Office (TGO) software, while the combined GPS + GLONASS baseline solution was enabled within Trimble Total Control (TTC) software. In 2005 Trimble company released the Trimble Business Center (TBC) software package with GNSS processing engine including a capability to process GPS-only as well as a combined GPS + GLONASS baseline solution. The updated baseline processor was released within TBC ver. 3.50 in 2015 supporting the independent GNSS constellation solutions including BeiDou-only, GLONASS-only, and BeiDou + GLONASS only combinations. Starting with the TBC, ver. 3.90, Galileo-only post-processing baseline solution was enabled as well. Currently, the sophisticated geodetic GNSS receivers featuring several hundred channels, support a multi-constellation GNSS observations including GPS, GLONASS, Galileo and BeiDou. The fact that TBC is the only commercially available software capable of processing individual constellation information, was a motivation to test and obtain a baseline solution based on GLONASS-only observations and to provide a comparison with the combined GPS + GLONASS solutions which are both supported by CROPOS – CROatian POsitioning System (national network of permanent GNSS stations). Furthermore, at additional three stations were utilized Galileo-enabled GNSS receivers. Upon careful mission planning seeking for favorable time windows, the baselines were processed with GALILEO-only data and subsequently the solutions comparison obtained from different GNSS combinations was given, showing the potential of individual and combined solutions. All computations including baselines processing and network adjustment were carried out utilizing the latest version 4.00 of TBC which was released in September 2017. Currently (February of 2018), GPS and GLONASS are the only two fully operational systems featuring 30 and 24 operational satellites, respectively, whereas the constellations of Galileo and BeiDou systems are still under construction. Approaching their Full Operational Capability (FOC) in the in upcoming years, the availability and reliability of multi-constellation observations will be improved having a direct impact on the reliability of baseline solutions and consequently providing the coordinates of geodetic network stations with improved reliability and accuracy.

Multi-constellation GNSS baseline solutions – a perspective from the user's and developer's point of view

1. INTRODUCTION

Trimble is the synonym for the satellite based positioning since early 1980s. Since then, the company has been the pioneer of geospatial technology and has brought to life many advancements in the GPS, optical, laser scanning and positioning techniques and workflows. Although known for its hardware solutions, Trimble has equally contributed to the advancements in surveying field and office software, offering customers an integrated system solution, from field data collection to final survey deliverables. Trimble Geospatial flagship office software is Trimble Business Center (TBC) office software. TBC is a complete survey office software, enabling field to finish workflows for survey and mapping professionals. TBC enables users to work with a range of geospatial collection methods, ranging from GNSS, total stations, levels, terrestrial laser scanners and UAS in a single office software environment. At the core of TBC, is the GNSS baseline processing engine, which made TBC a household name among surveyors worldwide for its reputation of providing reliable and confident post-processing results and network adjustment. The following chapter provides an overview of the Trimble GNSS post-processing software evolution from the early beginnings to the new generation of GNSS post-processing, introduced in TBC v4.00. The latest version of TBC was used in combination with GPS, GLONASS and Galileo observation data to obtain a multi-constellation GNSS baseline solutions.

1.1 Post-Processing Software Evolution

The history of the baseline processing goes back to the early days of commercial GPS in the mid-1980s. The first major breakthrough in geodetic surveying and commercial GPS happened in 1984 with 4000A receiver. Soon after, in 1986, Trimble released its DOS-based software for post-processing called TrimVec. TrimVec was capable of both static and kinematic GPS data processing and came with TrimNet module for network adjustment. Two years later, TOPAS software with undifferenced processing was introduced (Landau 1988). TOPAS was initially written for VAX, and was adapted later in 1990 to work on DOS operating system. That same year, Günter Hein and Herbert Landau founded TerraSat company. In 1993, TerraSat replaced TOPAS with Geotracer, DOS-based processing software. Geotracer represented a major breaktrough as it came with a graphical user interface, while other GPS processing software at the time were typically executed through a command line. Geotracer allowed users to see the baselines on the screen, enabled on screen selection, editing satellite information, enabling coordinates and graphical interaction with the data. The core principles of baseline processing were similar as today, despite fewer satellites in orbit and less accurate ionosphere and troposphere models available. Around similar time, Trimble introduced its own, GPSurvey post-processing software, which was running on Windows v3.11. GPSurvey still used the TrimNet module for network adjustment. Next, 1994 was a major year for both Trimble and TerraSat. Trimble introduced the first RTK system, paving the path towards more widespread adaption of GPS technology in land surveying. TerraSat went on to introduce the Geotracer RTK system in 1995 and then GeoGenius in 1997. Ashtech adapted GeoGenius as Ashtech Office Software (AOS) and Trimble as Trimble Total Control (TTC). In the same year, Trimble released Trimble Survey Office (TSO) that was running on Window 95. Later, in 1999, Trimble Geomatics Office (TGO) later replaced both GPSurvey and TSO, providing support for both kinematic and static processing. In the same year, TerraSat team went on to introduce another major breakthrough in surveying by releasing the GPSNet software, enabling efficient management of the VRS networks and allowing surveyors to reduce the cost of their equipment. Year 2000 represents a major milestone in Trimble history. That year, Trimble acquired Spectra Precision Group. With TerraSat now being part of Trimble, in 2002 the company decided to combine the legacy Trimble RTK (developed from 1994-2002) with Geotracer RTK (developed from 1995-2002) into a single company-wide used RTK and post-processing engine (internal name Astra) that was released in 2003. Astra was used in receivers as the kinematic (RTK) engine as well as in the office in TBC for kinematic and static data processing. Time evolution of Trimble GNSS processing software is shown on Figure 1.

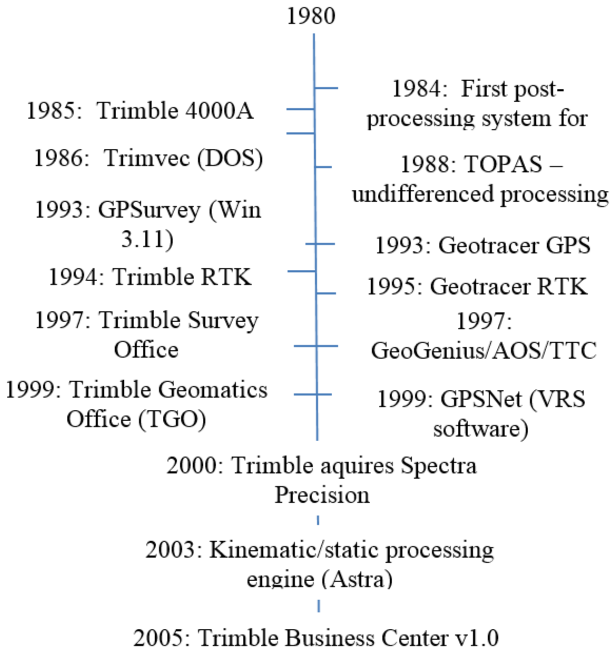

Figure 1: Trimble GNSS processing software in chronological order.

In years to follow, Astra engine and baseline processing workflows continued to evolve with each software release introducing workflow simplification, productivity, accuracy and precision optimization with releases of TBC. In 2006, TBC was enhanced to support GNSS data and network adjustment. In May of 2007, the software was enhanced by adding the Session Editor, Time-Based View and Interned Download simplifying the baseline processing workflows significantly. With release of TBC v2.00, in addition to integrating the optical data (total station and level), TBC was enhanced to process the GNSS trajectories and handle event markers. TBC v2.11 in May of 2009 introduced processing of .T02 data (L5 and Galileo information was not yet supported). TBC v2.40, release in September of 2010 introduced multiple frequency (L1/L2/L5) baseline processing option, in addition to the L1-only option and dual frequency (L1 and L2) option. In TBC v2.60 (September 2011), the Baseline Processor has been enhanced to fully utilize multi-core CPUs by processing independent baselines simultaneously, resulting in faster overall processing times. TBC v2.70 (April 2012), brought improved accuracy and support for RINEX 3.0 and the ANTEX antenna model. In October of 2012, Trimble released the new R10 receiver with the Trimble HD-GNSS™ technology capabilities as well as tilt measurement and Trimble xFill™. In addition, with support for the Trimble R10, TBC v2.80 came with completely new ribbon based user interface and support for the QZSS satellites. TBC v3.00 in May of 2013 was the first 64-bit version of TBC introducing the UAS processing capabilities on Windows 7 and 8 operating systems. TBC v3.20 in April of 2014 introduces new point cloud engine (from TRW) and baseline processor was enhanced with improved code outlier detection and support for RINEX Galileo Ephemeris. TBC v3.50 in 2015, represented an important release for baseline processing users as the software allowed for independent GNSS constellation processing including GLONASS-only, Beidou-only and BeiDou and GLONASS only combinations with GPS no longer being required for baseline processing. Somewhere around this time, the idea of a static-only processor was born.

1.2 TBC v4.00 - New Generation of Static Baseline Processing

Fast forward to recent history, in September of 2017, TBC v4.00 introduced a new generation of baseline processing software (internal Trimble name “Pantea”). While Astra served a dual purpose of being the engine for both kinematc and static data processing, Pantea was fully optimized for static data processing. Instead of using Kalman Filter with additional constraints, the engine uses a sequential least square with time independent unknowns. The testing process involved processing over 10,000 baselines internally and leveraging worldwide Beta group to verify and confirm the results. University of Zagreb, Faculty of Geodesy has been one of these contributing beta members. Some of the main new capabilities that Pantea introduces in TBC v4.00 are:

- support for Differential Code Biases (DCB) for satellites via the Internet Downloads command; accounting for DCBs when processing static GNSS baselines in TBC supplements receivers that may or may not track all signals and modulation types from a certain frequency,
- support for Earth Orientation/Rotation Parameter (EOP) models via the Internet Downloads command,
- automatic dynamic parameters that adjust depending on the baseline length; the new engine handles baseline lengths in three classes, short (0 – 20 km), medium (20 – 200 km), and long (200+ km). For each of these classes, processing parameters and settings are automatically adjusted to improve the processing result,
- support for the Galileo E5A, E5B, and E5AltBOC signals; more high-quality Galileo satellite signals improves the accuracy and reliability of the processed baseline solution,

- more fixed solutions for all baseline lengths, especially long baselines - those greater than 200km; Pantea has refined processing algorithms using a number of different techniques, such as selecting the optimal linear combination based on baseline length, and a refined error modeling algorithm, to achieve more fixed solutions for long baselines.

As described in Schütz (2017), Pantea represents the future of baseline processing as its optimization and use in other Trimble products and services is continue to expand over the next years.

2. CROPOS – CROatian Positioning System

CROPOS is a national permanent network of GNSS stations owned and administrated by the State Geodetic Administration (SGA) of the Republic of Croatia. The network is composed of 33 stations evenly distributed over the national territory at average distance between stations of 70 km. In order to provide a reliable differential correction of GNSS observations in border areas, the networked solution includes the data from the stations belonging to Slovenian SIGNAL (7 stations), Hungarian GNSSnet.hu (4 stations), Montenegrin MontePOS (2 stations) and Bosnian FBiHPOS (3 stations) with SRPOS (2 stations). This results in CROPOS system consisting of data from 51 permanent GNSS stations. The networked solution is based on the Trimble's Virtual Reference Station (VRS) concept. The GNSS stations are equipped with Trimble's equipment: Trimble NetR5 receivers and Zephyr Geodetic 2 w/Dome antennas. In the appropriate receiver's Datasheet (Trimble 2006-2009), can be found that NetR5 receiver has 76 channels for tracking GPS, GLONASS and SBAS signals. Similarly, in the antenna's Datasheet (Trimble 2007) can be found that the Zephyr Geodetic 2 w/Dome has a capability for tracking GPS, GLONASS, Galileo and SBAS signals. As the consequence of the receiver's features installed in CROPOS, the system collects and processes GPS and GLONASS observations. The system provides three services, namely: DPS (*Differential Positioning Service*), HPPS (*High Precision Positioning Service*) and GPPS (*Geodetic Precision Positioning Service*). The last two services are being used by surveyors: HPPS for real time applications (2 cm horizontal precision), whereas the GPPS is used for post-processing (sub-cm precision). The observations collected using any of the Continuously Operation Reference Stations (CORS) or generated using arbitrarily selected Virtual Reference Station can be downloaded in Trimble's native formats (T01, T02) or in few versions of RINEX format (2.10, 2.11, 3.02). The coordinates of CORSes were determined using Bernese GPS Software ver. 5.0 in ETRF 2000 (R05), epoch 2008.83, so the coordinated determined by CROPOS are obtained in that reference frame. More details about CROPOS can be found on the official web site (URL 1) as well as in several papers like Bačić et al. (2011), Šugar et al. (2016a), Šugar et al. (2016b).

2.1 Baselines processing with GPS-only, GLONASS-only and combined GPS+GLONASS data using CROPOS GPPS

GNSS observations data (GPS and GLONASS) was downloaded for the permanent stations ZABO, KARL, SISA and ZAGR from the CROPOS GNSS REFERENCE STATION WEB SERVER (URL 4) in T02 format (with logging interval 5 seconds) for the time window May

2nd 2017, 13:00 – May 4th 2017, 01:00 GPST (GPS Time). For baselines post-processing, precise ephemeris given as IGS Final Orbits for GPS and GLONASS satellites were used. Precise orbit data in SP3 format were downloaded from the CDDIS (Crustal Dynamics Data Information System) web server for GPS (URL 5) and GLONASS satellites (URL 6). Data about Earth Orientation Parameters (EOP) (given as IGS Final Earth Rotation Parameters) was downloaded from the CDDIS web server too (URL 5) and used for baselines processing. IGS final orbits are expressed in IGS14 reference frame, which is aligned to the ITRF2014. The new reference frame, called IGS14, was adopted on 29 January 2017 (GPSWeek 1934) (Rebischung et al. 2017). Updating to IGS14, aligning of IGS products to ITRF2014, and increasing the precision of that alignment by integrating additional available reference frame stations with more precise and up-to-date coordinates was announced in Rebischung et al. (2016). Since the IGS Final orbits were used for baseline processing, the coordinates of CROPOS CORSes were transformed from ETRF 2000 (R05), epoch 2008.83 to the reference frame ITRF2014, epoch 2014.33 (May 3rd, 2017) using web-based tool available at EUREF Permanent Network (EPN) web site (URL 7). The use of the tool was strongly advised in EUREF Technical Note 1 (Altamimi 2017) enabling the transformation between any ITRS and ETRS89 frames, at any epoch.

Subsequent baseline processing was carried out in the newest version of TBC, v4.00.4 (released on January 16, 2018). Prior to importing data in TBC, each project was created with the following settings: coordinate system HTRS96/TM (Croatian Terrestrial Reference System 1996/ Transverse Mercator), ellipsoid GRS80, time system GPS (GPS Time), ephemeris precise. Data collected at CROPOS stations ZABO, KARL, SISA and ZAGR was imported in TBC along with the data collected at two additional stations: GEOM and ZZFP. GEOM station is a permanent GNSS station with installed receiver Trimble NetR9, station ZZFP is monumented with the mast atop the building roof where the GNSS receiver Trimble R10 was setup.

The baselines were processed with three different data combinations (GPS-only, GLONASS-only, GPS+GLONASS). The procedure for all three combinations (projects) was the same: after all baselines were processed (15 baselines), a fixed solutions were obtained and minimally constrained adjustment was performed keeping fixed coordinates of station ZABO. Since there were no baselines burdened with outliers, a fully constrained network adjustment with three fixed stations and disabled correlated vectors was performed. The fully contrained network adjustment after processing baselines with GPS and GLONASS data combination is shown in Figure 2.

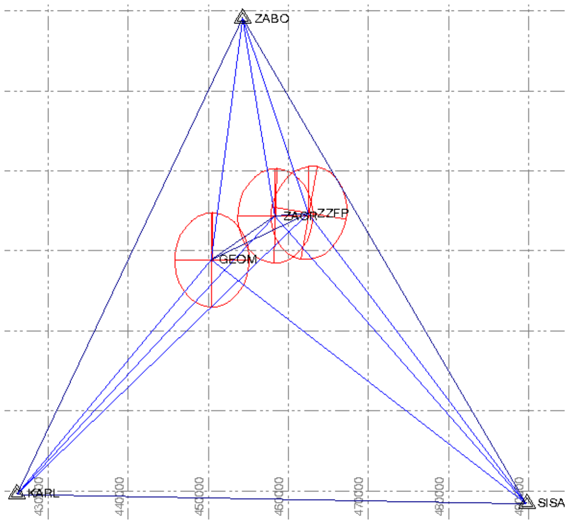

Figure 2. Network with baselines processed with GPS + GLONASS combination after a fully constrained adjustment; the adjustment was performed with uncorrelated vectors.

All unknown coordinates have been determined with homogeneous accuracy with error ellipse having major and minor axes in the range 8–9 mm, and 6–7 mm, respectively. Ellipsoid height error was in range 27–30 mm. All results have been computed with default precision confidence level 95%. The coordinates of ZAGR station obtained with three different solutions were compared with the official coordinates originally determined in ETRF 2000 (R05), epoch 2008.83 and subsequently transformed in ITRF2014, epoch 2017.33. These coordinates were considered as 'Reference' and the differences given as 'Measured – Reference are presented in Table 1. Along with the coordinate differences (ΔE, ΔN, Δh), are presented the coordinates precision estimation (σE, σN, σh) as well as the horizontal (2D) and spatial (3D) deviations from the 'Reference' values.

Table 1. Comparison of coordinates (E, N, h) determined from different data combinations with official coordinates transformed from ETRF 2000 (R05), epoch = 2008.83 to ITRF2014, epoch = 2017.33. For each coordinate is given the precision estimation along with the estimated 2D and 3D deviations of the computed coordinates from the 'Reference'.

Combination	ΔE [m]	ΔN [m]	Δh [m]	σE [m]	σN [m]	σh [m]	2D [m]	3D [m]
GPS only	-0.002	0.008	0.005	0.005	0.007	0.027	0.008	0.009
GLONASS only	0.001	0.008	0.001	0.006	0.006	0.032	0.008	0.008
GPS+GLONASS	-0.001	0.008	0.004	0.005	0.006	0.027	0.008	0.009

Although the coordinate differences ΔE are lower than the coordinate precision estimation σE, the coordinate differences ΔN almost match the precision estimation σN. The height differences (Δh) are lower than height precision estimation σh. All combinations have led to uniform horizontal (2D) and spatial (3D) deviations below 1 cm. The differences (ΔE, ΔN, Δh) can be considered as consequence of coordinates transformation inaccuracies as well as coordinates precision. Nevertheless, the solution obtained from GPS+GLONASS combination can be considered as the most reliable.

The coordinates for the station GEOM and ZZFP haven't been determined previously therefore the accuracy estimation cannot be given. Instead, the precision estimation resulting from three solution combinations was assessed. Table 2 shows the coordinate differences between two solutions (data combinations). Moreover, for each solution marked with bold letters (GPS, GLONASS, GPS+GLONASS) are given the coordinates precision estimations, in last two columns are given the horizontal (2D) and spatial (3D) differences between solutions.

Table 2. Differences between solutions for GEOM station; precision is given for each solution marked with bold letters; with 2D and 3D are presented horizontal and spatial deviations, respectively.

GEOM station								
Combination difference	Δ*E* [m]	Δ*N* [m]	Δ*h* [m]	σE [m]	σN [m]	σh [m]	2D [m]	3D [m]
GPS-GLONASS	-0.005	-0.001	-0.011	0.005	0.007	0.028	0.005	0.012
GPS-(GPS+**GLONASS**)	-0.001	0.000	-0.002	0.006	0.006	0.032	0.001	0.002
GLONASS-(**GPS+GLONASS**)	0.004	0.001	0.009	0.005	0.007	0.027	0.004	0.010

The smallest coordinates differences (Δ*E*, Δ*N*, Δ*h*) are obtained for the difference (GPS only – (GPS+GLONASS)) leading to the smallest differences in 2D and 3D. Therefore, the combination (GPS+GLONASS) can be considered as the most reliable, and the coordinates of the station GEOM obtained from (GPS+GLONASS) solution will be considered fixed in the further analysis. Similar analysis was performed for the station ZZFP. Table 3 shows the corresponding numerical values, the most reliable solution was obtained from the GPS+GLONASS data combination.

Table 3. Difference between different data combination for ZZFP station; precision is given for each solution combination marked with bold letters; with 2D and 3D are presented horizontal and spatial deviations, respectively.

ZZFP station								
Combination difference	Δ*E* [m]	Δ*N* [m]	Δ*h* [m]	σ*E* [m]	σ*N* [m]	σ*h* [m]	2D [m]	3D [m]
GPS-GLONASS	-0.003	0.007	-0.017	0.006	0.007	0.031	0.008	0.019
GPS-(GPS+**GLONASS**)	-0.001	0.001	-0.004	0.006	0.007	0.034	0.002	0.004
GLONASS-(**GPS+GLONASS**)	0.003	-0.006	0.014	0.006	0.007	0.030	0.007	0.015

3. SUBNETWORK baseline processing using Galileo data combinations

3.1 Mission planning with Galileo satellites

Since Galileo satellite navigation system is still under development with currently 22 satellites in orbit (February 2018; URL 2), at the beginning of May 2017 there were 18 satellites in orbit, 11 of them producing usable data (URL 2, URL 3). For the purpose of this investigation, it was essential to have at disposal Galileo-enabled GNSS receivers. The equipment consisted of one

Trimble NetR9 receiver and two Trimble R10 receivers (both tracking 440 channels with the capability of observing GPS, GLONASS, Galileo, BeiDou, QZSS and SBAS signals).
Having at disposal three Trimble Galileo-enabled GNSS receivers and 13 operational satellites in Galileo constellation, a careful mission planning had to be carried out prior to the field campaign. Trimble Planning Tool was used, along with the updated almanac data. According to the availability of the GNSS receivers and favorable weather conditions, the field activities were planned for May 3rd 2017. After setting the time span for the entire day (May 3rd, 2017) and the elevation mask to 10°, GNSS visibility plot for Galileo satellites was obtained as shown on Figure 3.

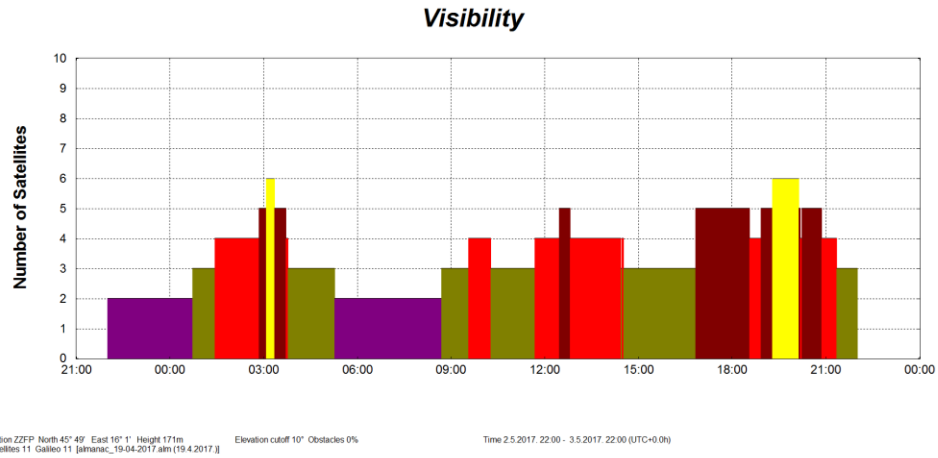

Figure 3. Galileo satellites visibility at the station ZZFP, for May 3rd 2017 in period 0-24 CET (22 – 22 UTC).

From the Galileo visibility plot can be noticed that there were three longer time windows where 4 or more Galileo satellites were visible. Those three time windows are summarized in Table 4.

Table 4. Time Windows with visible 4 or more Galileo satellites at the station ZZFP for May 3rd 2017.

Time window	PDOP range (min-max)	Number of SV	Duration (minutes)
01:26 – 03:45 UTC	2.98 – 582.64	4, 5, 6	140
11:41 – 14:25 UTC	7.37 – 828.78	4, 5	165
16:50 – 20:51 UTC	1.96 – 137.33	4, 5, 6	242

3.2. Subnetwork stations

The subnetwork consists of three stations: GEOM, ZZFP and MRGJ (Figure 4). The station MRGJ makes a part of the 'GPS network of the City of Zagreb' and is monumented by a concrete pillar and was planned to be occupied in three sessions with additional Trimble R10 GNSS receiver according to the time windows shown in Table 4. On each receiver were set up the same observation settings: elevation mask 10° and logging interval 5 seconds. Since GEOM and ZZFP stations were occupied continuously for more than 24 hours, and the station MRGJ was occupied in three sessions, the baselines in the subnetwork were processed in three processing sessions using 7 different data combinations: GPS-only, GLONASS-only, Galileo-only, GPS+GLONASS, GPS+Galileo, GLONASS+Galileo, GPS+GLONASS+Galileo.

3.3 Baseline processing with Galileo and different constellation data combinations and subnetwork adjustment results comparison

As described earlier, the station MRGJ was occupied in three different sessions with 4 or more Galileo satellites visible during the time window longer than 90 minutes. Considering the longest baseline (GEOM-ZZF) length being 13.4 km, the previous field investigations carried out through the diploma thesis (Matika 2017) have led to the conclusion that 90-minutes long time window could be long enough for reliable ambiguity resolution and subsequent baseline determination with Galileo-only observations. After the baseline processing, the coordinates of stations ZZFP and MRGJ were obtained (where possible) using minimally constrained adjustment with station GEOM having fixed coordinates. The coordinates of GEOM station were previously determined from GPS+GLONASS data combination using CROPOS GPPS (see section 2.1). Table 5 provides the start and stop observation times during the occupations of station MRGJ in the 1st, 2nd and 3rd session.

Table 5. Session duration with start and stop times of occupations on station MRGJ.

Station MRGJ	START – STOP (GPST)	Duration
1. SESSION	00:57:40 – 03:53:35	02:56
2. SESSION	11:18:50 – 14:30:45	03:12
3. SESSION	16:38:25 – 20:45:50	04:07

Realized occupation times at station MRGJ (Table 5) closely match the planned time windows having visible 4 or more Galileo satellites (Table 4) in order to allow the subsequent baseline determination based on Galileo-only observations.

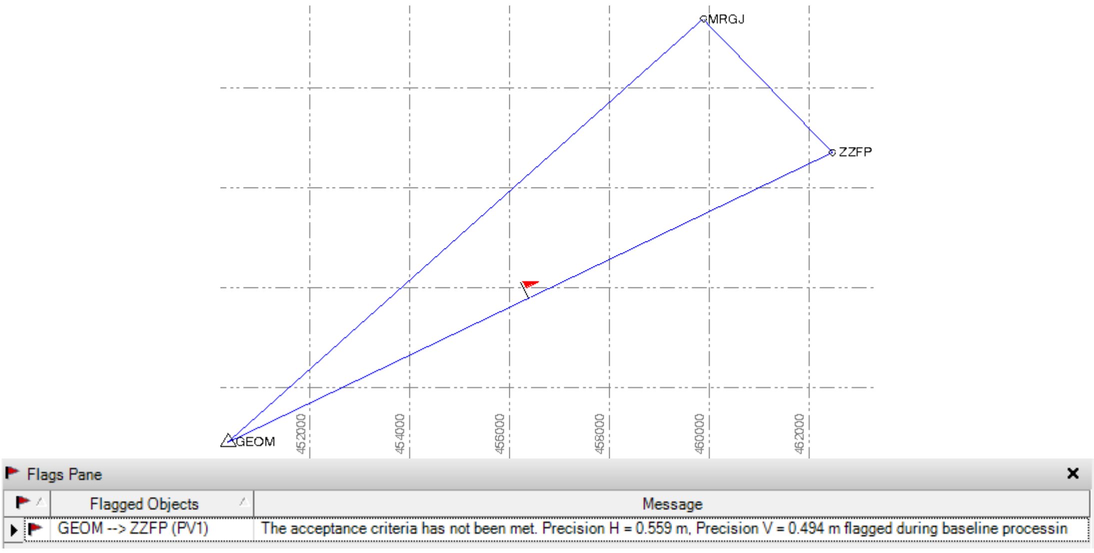

Figure 4. Subnetwork with baselines between stations GEOM, MRGJ and ZZFP processed with Galileo-only satellites observations during the 2nd session; a float solution was obtained for the baseline GEOM → ZZFP having not met the Horizontal and Vertical precision acceptance criteria.

For each session (1st, 2nd, 3rd) and each data combination (7 combinations) have been created altogether 21 individual projects in TBC, where baselines were processed using exclusively broadcast ephemeris. As can be found in TBC Help system, it is recommended to download and use precise orbit data when processing baselines exceeding 50 km. Since the longest baseline was 13.4 km long, broadcast ephemerides were used.
Fixed baseline solutions were obtained in all projects with only one exception: the baseline GEOM → ZZFP observed in the 2nd session (Galileo-only). The ambiguities haven’t been fixed resulting in a float baseline solution. Since the horizontal as well as the vertical precision haven’t been met, the baseline was flagged as failed (red flag set on the baseline; see Figure 4). Along with the *float* solution, the statistical parameters were calculated as follows: Horizontal Precision 0.559 m, Vertical Precision 0.494 m, RMS 0.028 m

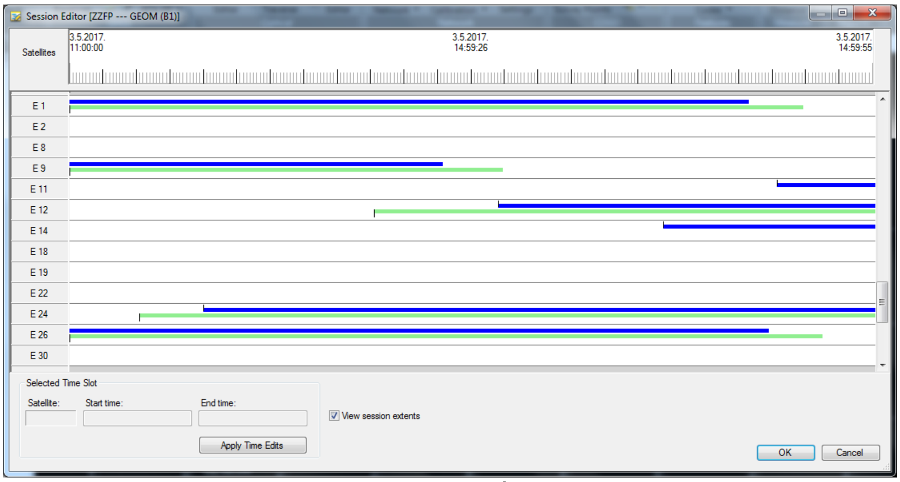

Figure 5. Session editor for the baseline ZZFP → GEOM (2nd session); a gap in the visibility of satellites E9 and E12 has most likely prevented a fixed solution.

The reason why the ambiguities haven’t been fixed during the baseline processing can be assessed by examination of the baseline GEOM→ ZZFP session editor (Figure 5). Although the session lasted for more than four hours (04:07), four or more satellites needed for ambiguity determination were not continuously visible. Although the distance between the station GEOM and ZZF is about 13.4 km, each Galileo satellite was visible for a longer period on the station GEOM than on the station ZZFP indicating that the horizon on the station ZZFP isn’t completely free above the elevation mask 10°. The baseline was processed for the time window 11:40:00 – 14:21:30 GPST, with the maximum PDOP 1714.209 and altogether 5 satellites tracked at both stations. The gap in visibility of the satellites E9 and E12 at both stations has most likely prevented the possibility of reliable ambiguity determination. At the same time, the longer continuous visibility of four Galileo satellites has enabled a fixed solution for the baseline GEOM → MRGJ. Although, the length of the baseline GEOM → MRGJ is a little bit shorter (12.7 km), a different (shorter) visibility of some satellites on the station MRGJ may indicate a non-perfection of its horizon (Figure 6).

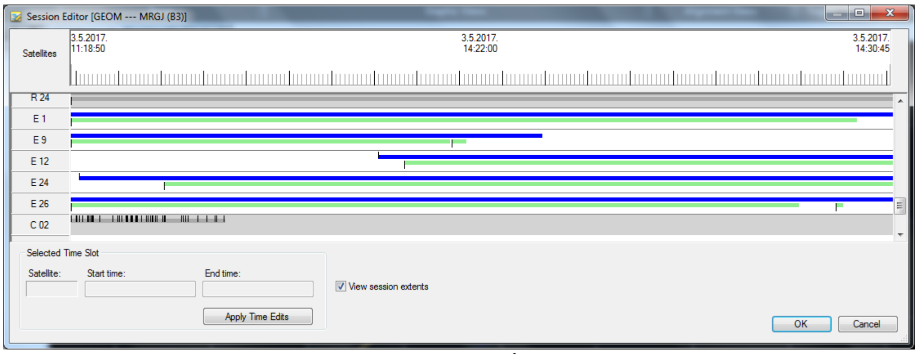

Figure 6. Session editor for the baseline GEOM → ZZFP (2nd session); continuous visibility of 4-6 satellites has allowed the determination of a fixed solution.

In all project the baselines were not optimized, the baseline processing results were saved (including the float solution) and subsequently a minimally constrained network adjustment was carried out. In the project where a float solution occurred (Galileo-only), the network adjustment hasn't been performed. Station GEOM with coordinates obtained from the previous network adjustment (GPS+GLONASS) in ITRF2014, epoch 2017.33 was held fixed in network adjustment leading to the determination of the coordinates of stations ZZFP and MRGJ. Another purpose of network adjustment was to determine any potential outliers. In each network adjustment a Tau criterion has been met as a consequence of acceptable standardized residual values and absence of outliers. In most cases the Chi-square test (95%) (overall statistical test of the network adjustment) failed but after the application of scalar multiplying the reference factor from the last adjustment, the Chi square test (95%) passed and the Network Reference Factor has achieved its ideal value 1.00. The coordinates obtained from different network adjustments (baselines computed from 7 different data combinations observed in three independent sessions) will be discussed in the following section. All results were determined with precision confidence level 95%, Chi square test PASSED and Network Reference Factor equal or close to 1.00.

In each session, the coordinates were assessed and compared to the most reliable coordinates (obtained from GPS+GLONASS combination). Generally, the largest individual deviation from reference solution (GPS+GLONASS combination) was achieved for the solutions encompassing individual GALILEO and GLONASS or combined observations leading to 2D and Δh deviations as presented in Table 6. Horizontal deviations 2D were calculated from the relation SQRT$((\Delta E)^2 + (\Delta N)^2)$ where ΔE and ΔN present a difference of the individual solution from the reference.

Table 6. Largest 2D and Δh deviations of each solution from the reference values obtained for stations MRGJ and ZZFP resulting from the 1st, 2nd and 3rd session.

Session	Station	Data combination	2D	Δh
1.	MRGJ	Galileo_only	0.026 m	0.071 m
	ZZFP	Galileo_only	0.032 m	0.104 m
2.	MRGJ	GLONASS+Galileo	0.008 m	0.013 m
	ZZFP	GLONASS+Galileo	0.008 m	0.014 m
3	MRGJ	GLONASS_only	0.012 m	0.013 m
	ZZFP	Galileo_only	0.010 m	-0.025 m

The coordinates of station ZZFP determined from all observation combinations in 1st, 2nd and 3rd session are shown on Figure 7 (left and right). Light green represents the solution obtained from Galileo_only combination in 1st and 3rd session. Coordinates from the combinations GPS-only, GPS+GLONASS and GPS+GLONASS+Galileo exhibit similar behavior. Since the observations were collected throughout three sessions, the results obtained in each session are presented separately on the Figure 7 on the right hand side. Results obtained in each individual session show similar behavior (results are grouped) as a consequence of specific satellite availability in that session. Maximum deviations among results have been achieved during the 1st session, which is in accordance with the session duration, number of visible Galileo satellites and PDOP range values presented in Table 4. Finally, all solutions were compared with the reference values of ZZFP station obtained from GPS+GLONASS combination and CROPOS network: the results obtained from GPS+GLONASS+Galileo combination (in all three sessions) have shown the smallest sum of 2D departure from the reference position.

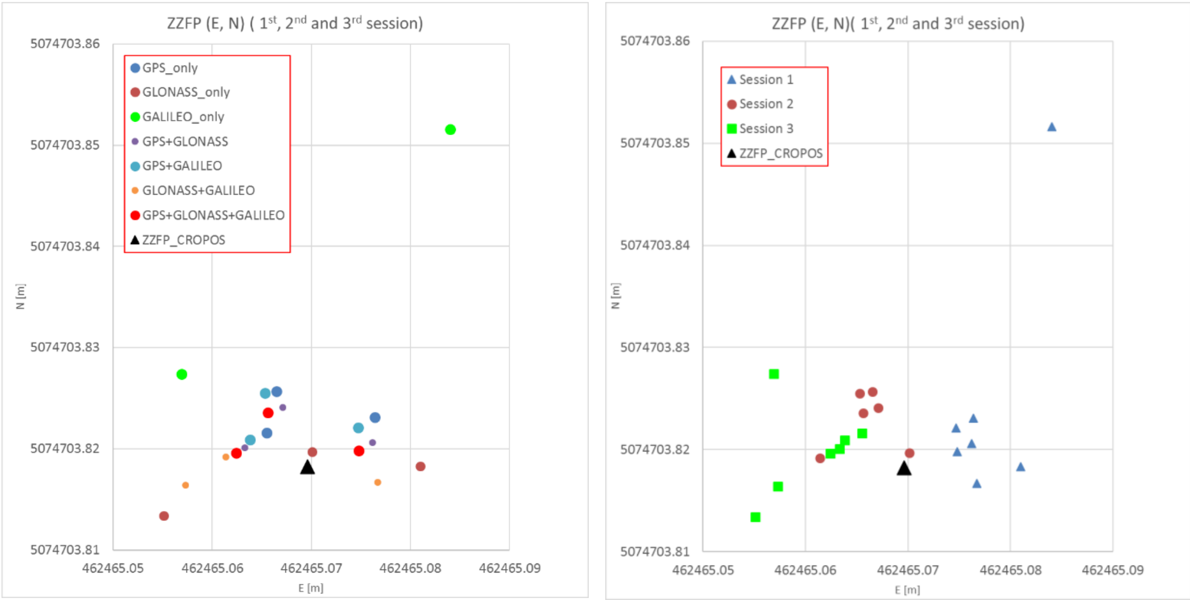

Figure 7. (left): Coordinates of station ZZFP obtained from different data combinations in 3 different sessions; (right): Coordinates of station ZZFP obtained from different data combinations, individually presented for each session (right).

Ellipsoidal heights of the station ZZFP presented per session and per constellation combination are shown in Figure 8 below.

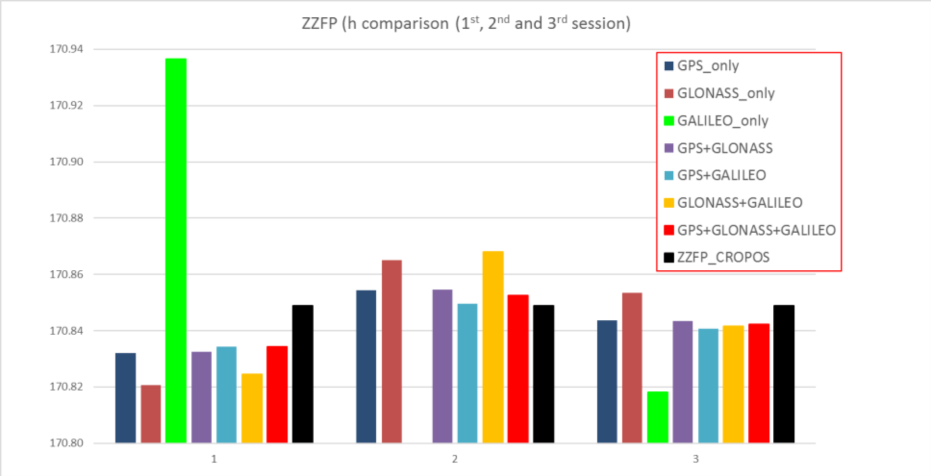

Figure 8. Ellipsoidal heights of station ZZFP obtained from different data combination in 1st, 2nd and 3rd session.

Maximum deviation shows the value determined in the 1st session from the Galileo_only combination. In the 2nd session there are no Galileo_only solutions, the 3rd session once again shows maximum deviation. Generally, can be noticed that Galileo_only and GLONASS_only combinations show largest departure from other solutions. Furthermore, the 3rd session being the longest in duration, with better satellite visibility and consequently lesser PDOP values range, shows overall better results. The reference ellipsoidal height of ZZFP station (obtained from GPS+GLONASS combination and CROPOS network) is shown on Figure 8 for comparison reasons. The sum of absolute values of all differences between the individual solution and the reference value has been calculated: the smallest value was obtained for the GPS+GLONASS+Galileo combination (0.019 m).

4. CONCLUSIONS

Since the beginning of usage of GPS for surveying purposes, Trimble has been providing a solution for the post-processing of static and kinematic data. The latest version of TBC provides a multi-constellation and multi-frequencies baseline solutions supporting GPS, GLONASS, GALILEO and BeiDou observations individually and jointly. The capabilities of the latest TBC v4.00 were tested by processing baselines between the CROPOS CORSes ZABO, KARL, SISA and ZAGR based on GPS only, GLONASS only and GPS+GLONASS combinations. The station ZAGR being previously determined, has served as a ground truth for the coordinates accuracy comparison. Since the reference coordinates of ZAGR station were determined using Bernese GPS Software ver. 5.0, a sub-centimeter 2D difference of coordinates determined with the latest version of TBC has shown its great potential. Furthermore, a subnetwork featuring three stations GEOM, ZZFP and MRGJ has been occupied in three sessions with the Trimble's Galileo-enabled GNSS receivers allowing baseline processing with 7 different constellation combinations. All combination have provided a fixed baseline solutions except Galileo_only combination during the 2nd session. Although, all session were carefully planned, due to the baseline length (13.4 km) and imperfections of the horizon of station ZZFP, the baseline GEOM → ZZFP hasn't achieved a fixed solution. Generally, the best precision estimation values have been obtained from GPS+GLONASS combination, with largest deviations coming from the results obtained with Galileo_only combination. This is true for 2D as well as for height precision. The coordinates of station ZZFP have been determined from three sessions and 7 data combinations and finally compared to the reference values: the smallest overall deviations have been revealed for the combination GPS+GLONASS+Galileo in terms of position and height as well. The baselines processing has shown the interoperability among different systems, better results are to be expected approaching the FOC of Galileo satellite system (expected by 2020). Since Galileo constellation hasn't been fully developed, mission planning has shown to be an essential step in reaching a fixed baseline solution. Prior to field testing activities it was expected that the multi-constellation solution including Galileo data would provide an improvement in terms of availability, accuracy and reliability what was confirmed by the obtained results.

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