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Impact of Multiconstellation on Relative Static GNSS Positioning

Luca Poluzzi, Ph.D.[1]; Luca Tavasci, Ph.D.[2]; Enrica Vecchi[3]; and Stefano Gandolfi, Ph.D.[4]

Abstract: Until a few years ago, a precise survey was only possible using GPS and GLONASS constellations, but the result was not guaranteed under conditions of poor sky visibility, as in urban canyons. Currently, the number of Global Navigation Satellite System (GNSS) satellites in orbit has strongly increased thanks to the great evolution of the Galileo and the Beidou constellations. In this paper, we investigate the impact of using different constellations and their combinations, in static positioning with the classical differencing approach. For this purpose, two distinct baselines of different lengths (10 and 60 km) were processed using commercial software over a period of one year (2018.24–2019.24). Data were acquired by permanent stations belonging to the European Permanent Network (EPN) network providing 24-h observing sessions. Two datasets were tested, one consisting of 24-h Receiver Independent Exchange Format (*RINEX*) files and the other considering only 2-h sessions of data acquisition. In both cases, a one-year-long time span has been considered. The baselines were processed considering each of the four GNSS constellations and a series of combinations, for a total of eight solutions. Results have been evaluated looking at the accuracy and repeatability of the coordinates, together with the main constellation parameters. During the analyzed period the number of contemporary visible satellites of the BeiDou constellation was still too poor over the considered area, and therefore this constellation did not provide comparable precisions in respect to the others. Positioning precision provided by the Galileo constellation has shown to be very close to those given by GPS or GLONASS, with a significant difference only on the height component, especially in the case of processing 2-h data. As for 24-h observing sessions, the use of multiconstellation observables actually leads to small improvements in precision with respect to the use of GPS data only, mainly appreciable considering the vertical component. The GPS-Galileo combination gives quite the same performances of the global positioning system-GLObal NAvigation Satellite System (GPS-GLONASS) one, but it can potentially take advantage of the integrity message provided by the European constellation. **DOI: 10.1061/(ASCE)SU.1943-5428.0000351.**

Introduction

Satellite positioning has become a widely used tool for many civilian and scientific applications thanks to its flexibility in terms of both accuracy and costs. In the era of multiconstellation Global Navigation Satellite Systems (GNSSs), several studies have been done to assess the performances of each constellation and their different combinations. In addition to the NAVSTAR-GPS constellation, the Russian GLObal NAvigation Satellite System (GLONASS), the European Galileo, and the Chinese BeiDou are operational. Other satellite positioning systems like the Japanese Quasi-Zenith satellite system (QZSS) or the Indian regional navigation satellite system (IRNSS) are operating only in their regional areas. Despite these global satellite systems being designed to provide similar accuracies in good operational conditions, the possibility for combining observables from all the constellations should overcome some of the weaknesses of GNSS positioning under suboptimal conditions.

The improvement of GNSS performance in real-time applications, such as navigation, is a widely discussed topic (Bonet et al. 2009; Gaglione et al. 2015); the availability of a large number of contemporary visible satellites allows the reduction of fixing time and improves performances in urban canyons (Angrisano et al. 2009; Gandolfi and La Via 2011).

It is known that precise GNSS positioning can nowadays be performed not only using the differenced approach but also with so-called Precise Point Positioning (PPP) (Geng et al. 2010). The impact of using multi-onstellation observables in PPP calculation has been addressed in several publications (Cai et al. 2015; Martín et al. 2011; Rabbou and El-Rabbany 2015; Yu and Gao 2017).

Nevertheless, most technical applications still rely on the classical differencing approach to GNSS observables. Applications using permanent stations rely on long observing sessions, basically for geodesy and augmentation systems for real-time precise positioning, but also for long terms monitoring. Even in these cases, it would be interesting to be aware of the impact of acquiring multiconstellation GNSS observables instead of the usual GPS or GPS/GLONASS-only approach. This topic has been already addressed in Chu and Yang (2014), who consider very long baselines between International GNSS Service (IGS) permanent stations, processed using well-known scientific software for data processing. Moreover, static observing sessions of a few hours can be performed in other applications where permanent stations cannot be installed.

[1]Postdoctoral Research Fellow, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali–Univ. of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy (corresponding author). ORCID: https://orcid.org/0000-0001-8812-5235. Email: luca.poluzzi5@unibo.it

[2]Postdoctoral Research Fellow, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali–Univ. of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy. Email: luca.tavasci@unibo.it

[3]Ph.D. Candidate, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali–Univ. of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy. ORCID: https://orcid.org/0000-0002-6524-9216. Email: enrica.vecchi@unibo.it

[4]Full Professor, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali–Univ. of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy. Email: stefano.gandolfi@unibo.it

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In this paper, we evaluate the impact of acquiring multiconstellation observables in static positioning with a relative approach. These assessments could be useful for dealing with different practical applications. We considered a scenario where 24-h of data files are available and another scenario where only 2-h observing sessions have been performed. The first case can be interesting for those managing a regional GNSS permanent network for deformation monitoring purposes (Cina and Piras 2015), where the distances between the stations typically range between kilometers and tens of kilometers and instruments are mostly installed in positions where sky visibility is good. The tests shown in this paper may help in choosing the instrumentations to install or eventually modernize. A different scenario can be the monitoring of a GNSS network made of passive benchmarks on which the instruments can be set up only for shorter observing sessions of only a few hours.

The position solutions were obtained using Leica Infinity version 3.2.1 software, which allows baseline computation by selecting one or multiple GNSS constellations. Baseline lengths of about 10 and 60 km have been considered. Results are presented and discussed in terms of repeatability of the coordinates (precision) and their consistency in respect to the formal reference positions (accuracy).

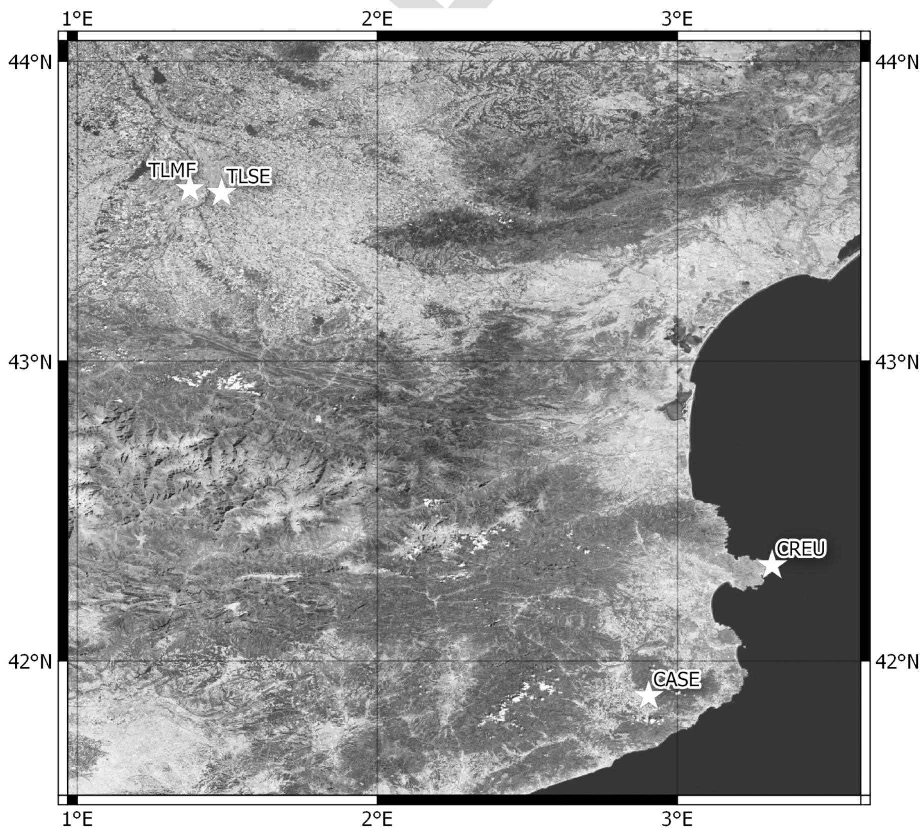
Dataset

GNSS data used for the test were collected by two pairs of permanent stations belonging to the European Permanent Network (EPN) (Bruyninx et al. 2019) and located as shown in Fig. 1. The primary criterion of this choice has been the availability of multiconstellation receivers installed. Moreover, the distances between the selected stations are suitable for the test purpose and are 10 and 60 km for TLSE-TLMF and CREU-CASE respectively. Ten kilometers can be considered a boundary distance for precise surveys with short observing sessions and it is what surveyors may deal with when using GNSS benchmarks to refer their measurements. On the other hand, 60 km is about the maximum distance that one can have from a public permanent station, at least considering national monitoring networks like the Italian Rete Dinamica Nazionale (RDN) (Barbarella et al. 2018). Longer baselines have not been considered because typically these are computed for geodetic purposes using scientific software packages.

Daily Receiver Independent Exchange Format (*RINEX*) files with 30-s rate observations were downloaded for a period ranging from the beginning of March 2018 to the end of February 2019. Starting from these files, a 2-h *RINEX* per day was created for each day, which simulates an independent observing session shorter than 24-h. Table 1 shows the main information about the hardware and the type of provided data for the considered permanent stations.

GNSS Data Processing

The GNSS data processing was performed by Infinity software, which has been recently introduced on the market by Leica Geosystems. Infinity is a geospatial office suite designed to manage, process, and analyze GNSS data and other observations acquired by topographic instruments such as Total Stations, Digital Levels,



Map created with QGIS, map data by ESRI World Imagery © Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Fig. 1. Location of GNSS permanent stations considered for the test. (Map created with QGIS, map data by ESRI World Imagery © Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.)

Table 1. GNSS permanent stations considered for the test: features and equipment

Station	TLSE	TLMF	CREU	CASE
Baseline length	10 km		60 km	
Receiver	TRIMBLE NETR9	LEICA GR25	LEICA GR50	LEICA GR50
Antenna radome	TRM59800.00 NONE	TRM57971.00 NONE	LEIAR25.R4 NONE	LEIAR25.R4 NONE
Data type	Daily, hourly, and real-time	Daily and hourly	Daily, hourly, and real-time	Daily, hourly, and real-time

Table 2. Combinations of GNSS observables and frequencies that Leica Infinity used for each type of solution

ID	Constellations	Used frequencies
G	GPS	L1/L2/L5
R	GLONASS	L1/L2
E	GALILEO	E1/E5a/E5b/E5a+b
C	BEIDOU	B1/B2
G + R	GPS+GLONASS	Combination of the above frequencies
G + E	GPS+GALILEO	
G + R + E	GPS+GLONASS+GALILEO	
G + R + E + C	GPS+GLONASS+GALILEO+BEIDOU	

and Unmanned Aerial Vehicles (UAVs). As for the GNSS data processing, the software allows the processing of the main global constellations, in particular: GPS, GLONASS, Galileo, and BeiDou. Data from different constellations can be combined or independently processed per the user's choice.

The Multi-GNSS Experiment (MGEX) ephemeris were downloaded (sp3 file format) to allow the processing of all the observables (NASA 2021). Absolute antenna calibrations provided by National Geodetic Survey (NGS) were used and a 13° cut-off angle was chosen. As for the troposphere modeling, the Vienna Mapping Function (Kouba 2008) was implemented using Global Pressure and Temperature model (GPT2) files and the Calculated option was selected for the signals delay estimation according to the software user manual in the case of long baselines (≥ 10 km). The impact of the ionosphere is considered in Infinity by using an iono-free frequency combination. The option that enables the application of NGS 14 antenna calibrations was also selected.

Eight types of baseline solutions were calculated to evaluate the impact of a single constellation or a particular combination of these. Table 2 presents the constellations used for each type of solution.

The Earth-Centered Earth-Fixed (ECEF) coordinates (X, Y, Z) expressed in the European Terrestrial Reference Frame (ETRF2000) at the epoch 2010.0, and the related velocities (V_X, V_y, V_Z) for each GNSS station are published in the European Reference Frame website (EUREF 2021). These positions, expressed at each measurement epoch within the considered period, were used as reference positions for the master stations.

Data Analysis and Results

After data processing, the rover solutions were stacked into coordinate time series and analyzed to evaluate the precision in terms of the estimated coordinates repeatability. The time series were cleaned from the outlier solutions by following an automated rejection criterion based on the assumption of linear variation of the coordinates over time and Gaussian distribution of the residuals. We denoted $S_i^j(t)$ to be the value of the geodetic component i (I = North, East, Up) related to the rover station j (j = TLMF, CASE) at epoch t. We set $S_i^j = \{S_i^j(t_1), S_i^j(t_2), \ldots S_i^j(t_n)\}, t_i < t_j$ for $i < j$ to form a time series for each coordinate. The position models mod_i^j were derived using Eq. (1), where m_i^j and q_i^j represent the slope and the intercept of the regression straight line of each time series, respectively. These parameters were estimated using a classical Least Squares approach

$$mod_i^j(t) = q_i^j + t\, m_i^j \tag{1}$$

Table 3. Averaged discards between rover solutions and formal ETRF2000 reference solutions

Time span (h)	Rover solution	Constellations	Accuracy (mm) N	E	U
2	TLMF	C	3.0	8.0	25.2
		E	4.4	3.5	33.4
		R	3.0	0.5	28.8
		G	4.0	0.8	27.1
		G + E	3.6	0.9	26.9
		G + R	3.5	0.7	26.5
		G + R + E	3.5	0.8	26.8
		G + R + E +C	3.4	0.9	26.6
	CASE	C	13.3	16.8	35.4
		E	7.0	0.0	13.8
		R	9.5	0.9	14.9
		G	6.7	1.1	7.8
		G + E	4.8	0.0	7.8
		G + R	4.5	0.1	7.8
		G + R + E	4.8	0.0	6.8
		G + R + E + C	4.7	0.0	6.4
24	TLMF	C	3.5	0.3	24.8
		E	4.4	3.4	31.8
		R	2.8	0.1	27.4
		G	3.3	0.4	26.9
		G + E	3.2	0.5	28.0
		G + R	3.1	0.3	26.8
		G + R + E	3.2	0.4	26.0
		G + R + E + C	3.3	0.3	27.1
	CASE	C	9.1	3.4	6.3
		E	6.2	0.2	13.9
		R	7.4	1.5	14.3
		G	5.5	0.0	7.8
		G + E	5.7	0.1	8.8
		G + R	6.0	0.2	8.3
		G + R + E	6.0	0.1	8.4
		G + R + E + C	6.1	0.1	7.4

We defined the residual $v_i^j(t)$ as the difference between each coordinate and the model at the same epoch

$$v_i^j(t) = S_i^j(t) - mod_i^j(t) \tag{2}$$

Then, σ_i^j was assumed to be the RMS of the residuals v_i^j for each component and station. We adopted an iterative procedure based on the comparison between the maximum residual and the RMS of the related time series to identify possible outliers. Therefore, a residual is an outlier if

$$\max\{v_i^j | abs(v_i^j) > 3\sigma_i^j\} \tag{3}$$

All the three components of a solution were removed if just one of these represented an outlier. The models, the associated residuals and the σ_i^j values were recalculated iteratively after each outlier rejection and the precision parameter of the data series can be represented by the final value of σ_i^j.

In order to evaluate the accuracy of the baseline solutions, the discards between the rover coordinates $S_i^j(t)$ and the related ETRF2000 reference values were also computed. The average of these discards represent the accuracy of the calculated baselines and are reported in Table 3.

By looking at the plan components (i.e. North and East), the estimated baselines seem to be highly accurate in the East direction, with a few mm biases toward the South, that are larger for the 60-km-long baselines. As for the Up direction, the CREU-CASE baselines are coherent with respect to the references within one cm. On the contrary, the TLSE-TLMF baselines show unexpected biases with a magnitude of more than 2 cm. This may be due to some software bugs in the application of metadata concerning the antenna offsets or the antenna calibrations. The only constellation that produces significantly biased solutions in all the components is the Beidou one, especially considering the longer baseline and the 2-h time span. This can be explained by looking at Fig. 2, which shows the percentage of epochs with fixed ambiguities for each baseline solution depending on the GNSS constellation. All solutions were reordered starting from the lower percentages of epochs with fixed ambiguities instead of chronologically to allow an easier evaluation of the results. The Fig. 2 points out how the processing of Beidou data is characterized by a high percentage of solutions estimated with float ambiguities.

The main results are summarized in Table 4, concerning both the length of the baseline and both the observing session time spans considered for the test. These results confirm the well-known dependency of the precision on the baseline length (Eckl et al. 2001; Anjasmara et al. 2019), where the longest baseline has a scattering about the double concerning the shorter one.

The GPS still provides the most precise results among the single constellations, especially looking at the height component. Nevertheless, the GLONASS system gives very similar precisions in the horizontal components, and also the Galileo constellation shows repeatability of the position solutions close to the previous ones.

Despite the good values of the dilution of precision (DOP) parameters, a high percentage of Galileo solutions calculated from the 2-h files were rejected. Moreover, these solutions are highly scattered along the Up direction, showing σ_{Up}^j values that are

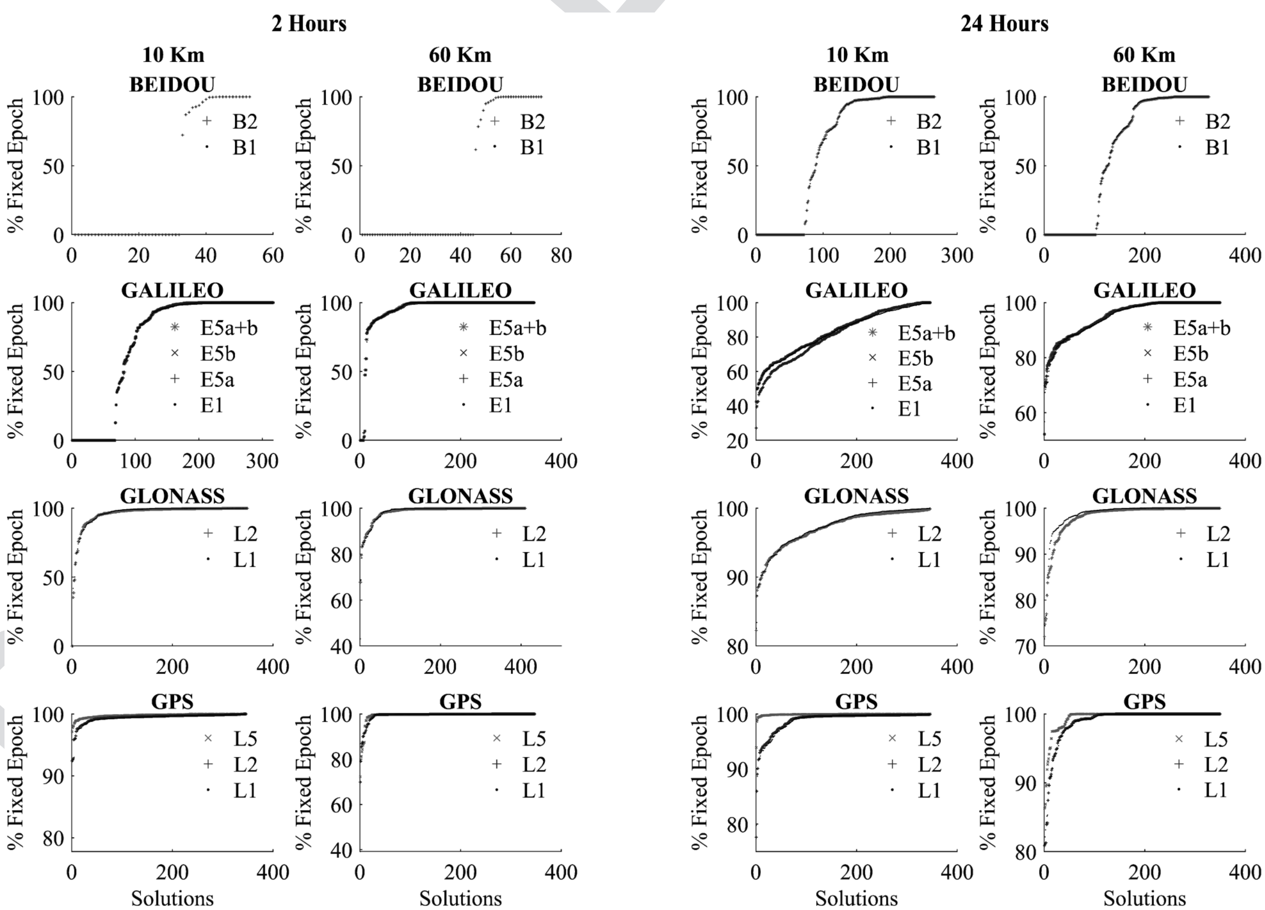


Fig. 2. Charts of the percentage of fixed epochs for each solution for 2- and 24-h time spans. Values on the x-axis are sorted in order to have increasing percentage of fixed epochs.

Table 4. Overall statistics for each type of baseline and time span: precisions (columns 4–6), DOP values (columns 7 and 8), mean number of satellites (column 9), total number of processed solution (column 10), and percentage of rejected solutions (column 11)

Time span (h)	Baseline (km)	Constellations	σ_N (mm)	σ_E (mm)	σ_U (mm)	HDOP	VDOP	MNS	n° sol	% rej
24	10	C	4.8	5.9	18.3	6.2	8.3	3.6	266	39.8
		E	1.3	2.4	6.4	2.1	2.7	5.8	346	4
		R	0.9	1.8	4.2	1.0	1.5	8.4	346	3.2
		G	0.9	1.9	2.9	0.9	1.2	11.0	346	2.0
		G + E	0.8	1.8	2.5	0.7	0.9	16.8	346	3.5
		G + R	0.8	1.8	2.4	0.6	0.8	19.3	346	2.6
		G+R+E	0.8	1.8	2.5	0.5	0.7	25.1	346	2.0
		G+R+E+C	0.8	1.9	2.6	0.4	0.6	28.7	346	2.0
	60	C	27.5	35.6	51.1	6.2	8.3	3.8	327	33.5
		E	2.8	2.0	7.8	1.9	2.5	7.2	349	10
		R	2.2	2.0	6.6	1.0	1.5	8.6	349	10.9
		G	2.5	1.8	5.1	0.9	1.2	11.0	349	4.9
		G+E	2.5	1.9	4.6	0.7	0.9	18.2	349	5.7
		G+R	2.4	1.9	4.5	0.6	0.8	19.6	349	5.2
		G+R+E	2.4	2.0	4.5	0.5	0.7	26.8	349	8.6
		G+R+E+C	2.5	2.1	5.0	0.4	0.6	30.6	349	7.2
2	10	C	26.6	40.0	38.0	4.1	5.4	3.0	53	38.9
		E	2.8	3.8	19.7	1.8	2.6	5.0	318	26.1
		R	1.7	2.4	10.9	0.9	1.4	7.1	349	7.7
		G	1.9	2.4	6.5	0.8	1.2	9.2	346	5.8
		G+E	1.9	2.4	5.8	0.7	0.9	14.2	346	4.3
		G+R	1.6	2.3	5.2	0.6	0.8	16.3	349	7.2
		G+R+E	1.5	2.2	4.9	0.5	0.7	21.3	349	5.2
		G+R+E+C	1.5	2.3	4.8	0.5	0.7	24.3	349	5.7
	60	C	66.2	118.5	124.4	2.5	4.6	2.9	72	23.7
		E	5.4	3.9	27.8	1.4	2.0	6.1	338	17.5
		R	4.6	3.7	22.3	1.0	1.5	7.1	347	4.3
		G	4.3	3.2	12.4	0.9	1.2	9.7	347	9.0
		G+E	4.2	3.3	11.4	0.6	0.9	15.8	347	8.4
		G+R	4.2	3.2	10.5	0.6	0.8	16.8	347	8.9
		G+R+E	4.2	3.2	10.4	0.5	0.7	22.9	347	8.1
		G+R+E+C	4.1	3.2	10.1	0.4	0.6	25.7	347	9.2

up to triple the GPS ones. Note that in most cases the BeiDou constellation shows a dispersion of the solutions one order of magnitude higher than the other GNSS constellations, also presenting the highest percentages of outliers. These results are certainly not due to a malfunction of the Chinese positioning system but they depend on the low number of acquired satellites and their geometry considering the chosen cut-off angle. The weakness of the Beidou satellite geometry is also evidenced by the DOP parameters and probably is the cause of the low percentage of fixed solutions shown in Fig. 2 and the consequent poor accuracy of the solutions. Nevertheless, it could also be due to some problem with the MGEX ephemeris, which are not verifiable using our dataset.

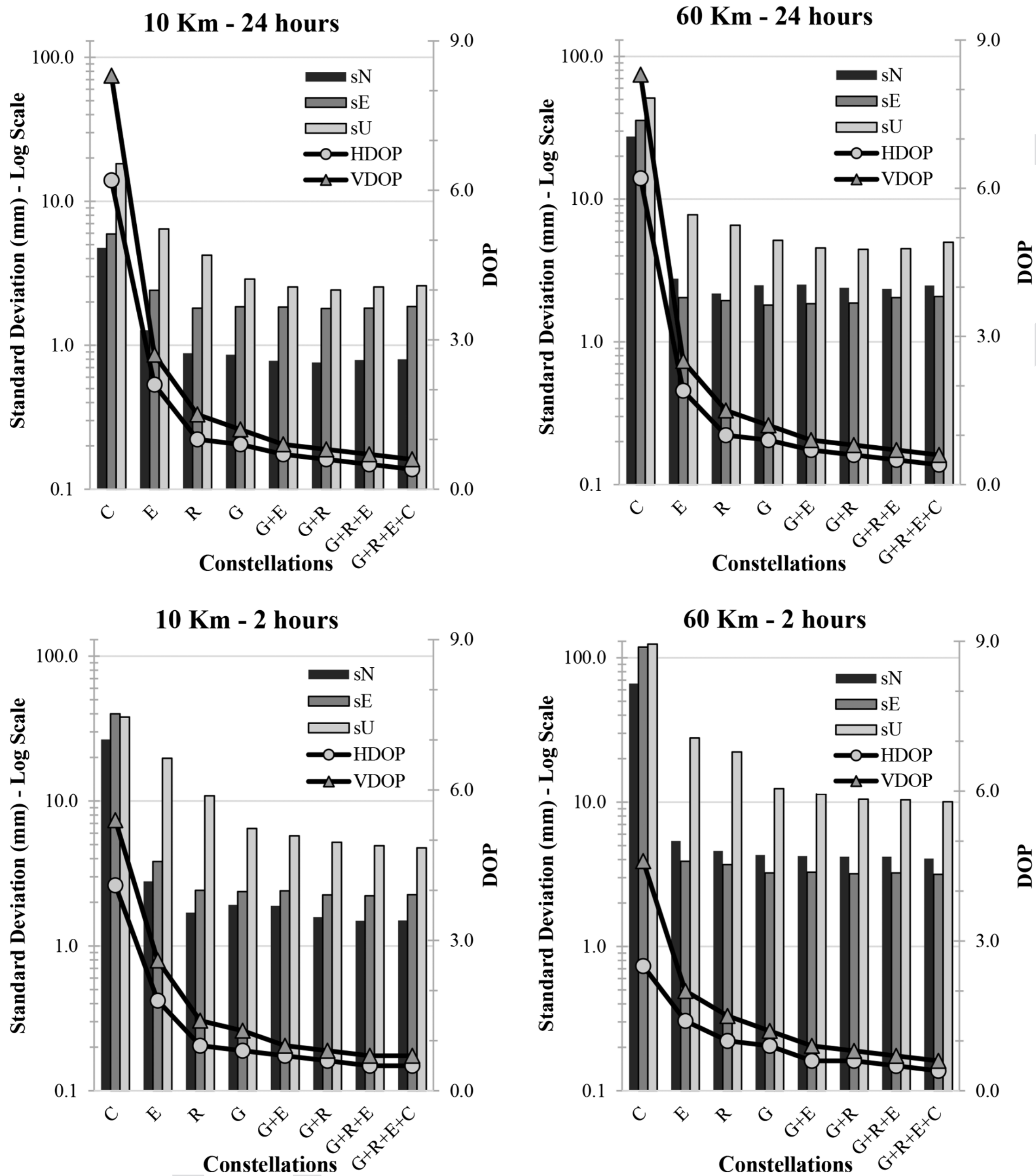
Fig. 3 emphasizes the results in terms of precision of the baselines and their correlation with the quality of the satellite geometry, represented through the DOP parameters. As for the results obtained from 24-h data files, the use of all constellations does not produce significant improvement of the precision. The GPS-GLONASS combination is the one giving the best results, but the difference concerning the other combinations seems to be negligible. The only improvement due to the use of the multiconstellation is on the height component, which is slightly more precise than the single GPS.

A comparison of the results obtained shows that the use of GPS with Galileo improves the precision on the height component and reduces the percentages of outlier solutions with respect to only the Galileo constellation. Very similar considerations can also be done for the GLONASS with respect to the GPS-GLONASS combination.

As for the test concerning 2-h *RINEX* files, the baseline solutions are significantly less precise with respect to those estimated with 24-h observations. The reduced amount of data strongly impacts mainly on the Beidou results for the 60-km baseline. It is worth noting that in the case of 2-h processing, even the Beidou constellation slightly improves the precision of the full constellation combined solution, despite its own performances being scattered. Galileo performances are a bit worsened by the reduced observing session, especially considering the height component with respect to GPS ones. Nevertheless, Galileo allows precisions of the same order of magnitude of what GPS and GLONASS do, and can help improve the performances in the case of combining multiconstellation observables. This is not the case when considering 24-h observations, where the most precise solution is achieved by using GPS and GLONASS constellations only.

Discussion and Conclusion

The impact of using different GNSS constellations and their different combinations has been investigated in this paper by computing two baselines of different lengths over a period of one year using daily and 2-h *RINEX* files. A possible application of the test results is to help surveyors dealing with regional GNSS networks evaluating the advantages of using new full-constellation instrumentations instead of older ones. Two pairs of CORS stations of the EUREF network define these baselines (TLSE-TLMF, CREU-CASE). Each station acquires data from four constellations (GPS,



F3:1 **Fig. 3.** Charts and histograms of the precision and DOP parameters for each analyzed solution.

Glonass, Galileo, and Beoidou) with a 30-s sampling rate. Data processing was performed using the Leica Infinity commercial software.

The test results show that the use of multiple constellations does not have a strong impact on the precision of solutions based on 24-h of observations, at least for the considered baseline lengths that are 10 and 60 km. Indeed the main advantage of using multiconstellation is to increase the number of observables acquired by the receivers, which is not a critical aspect for very long observing sessions but has been observed to impact positively on 2-h acquisitions. In this case, adding the observables of constellations such as Beidou to the combined processing, which does not provide suitable results by itself, helps to improve the precisions.

Considering single-constellation solutions, the GPS one is still providing the best precision, especially on the height component. Nevertheless, both the GLONASS and the Galileo constellations provide just slightly less precise results, so they can certainly be considered alternatively to GPS for the presented application. The European constellation shows a weakness in the height component with respect to the GPS, which is enhanced in the case of processing 2-h observations. The BeiDou constellation shows significantly worse precisions with respect to the others, but its performances actually cannot be criticized given that they were affected by a poor number of satellites and a weak geometry over the considered area.

Bearing in mind that multiple constellations would probably have higher impact in more demanding situations with respect to the test scenarios, such as very long baselines or poor sky visibility, we can conclude that the use of multiconstellation GNSS instead of GPS-only provides a slight advantage in terms of precision in the case of 24-h data processing, typical of permanent stations. In this case, adding the Galileo observables in the computation of daily static solutions does not provide any advantage in terms of precision at the time, at least when using Leica Infinity software. Additionally, for the applications involving shorter observing sessions, the combined use of Galileo observables together with others improves the baseline precision. Moreover, the availability of the Galileo constellation may be a major advantage thanks to the civilian vocation of the European GNSS because it can provide integrity services that may be fundamental for survey certification.

Data Availability Statement

All GNSS data (*RINEX* and *ephemeris* files) used during the study are available in a repository or online in accordance with funder data retention policies (*RINEX:* ftp://ftp.epncb.oma.be/pub/obs/; *ephemeris*: ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/). The GNSS processing code used during the study was provided by a third party (Infinity–Leica Geosystems); direct request for these materials may be made to the provider as indicated in the Acknowledgments. All the data analysis codes that support the findings of this study are available from the corresponding author upon reasonable request.

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