Low-cost GNSS RTK receiver in structure monitoring under demanding conditions

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ABSTRACT

Low-cost GNSS receivers are becoming increasingly popular in monitoring applications. Especially dual-frequency receivers, acquiring signals of all available satellite systems, offer great possibilities. The main goal of this study is to evaluate the accuracy of a position determined using low-cost receiver in different field conditions. The u-blox ZED-F9P receiver was used for testing, with the satellite signal supplied by either a dedicated u-blox ANN-MB-00 low-cost patch antenna or the Leica AS10 high-precision geodetic one. A professional Leica GS18T geodetic receiver was used to acquire reference satellite data. The tests were conducted in two ways. In the first one, the position was determined by low-cost and professional receivers in a typical RTK Network measurement, with a stationary antenna and various field conditions. Reference observations were made using the precise total station. The second test was carried out to check the positioning quality of the u-blox ZED-F9P receiver on the move to recognize its applicability in the automotive industry. A suitable route was proposed, for which reference data was provided by robotic total station and the 360-degree prism, coaxially mounted with the tested patch antenna. Conducted tests showed the advantage of the u-blox ZED-F9P over professional geodetic equipment. As a result, it is concluded that this receiver equipped with a geodetic-grade antenna provides high-quality positioning. In most cases of the partially obscured horizon, precise coordinates were obtained, making the ZED-F9P a valuable alternative to the high-end geodetic receivers in monitoring applications.

I. INTRODUCTION

The diversity of satellite positioning techniques developed over several decades provides sufficient accuracy for many monitoring cases. However, in recent years there has been a significant progress in this field through the increasing availability of low-cost receivers. Among them, especially dual-frequency receivers, available on the market for a short time, have become the subject of a growing number of studies, both in terms of determining the position using the static (Wiśniewski *et al.*, 2013) and kinematic (Takasu and Yasuda, 2009) methods.

A few years ago, the ZED-F9P low-cost dual-frequency GNSS receiver, manufactured by the Swiss company u-blox, appeared on the market. Wielgocka *et al.* (2021) tested the ZED-F9P receiver for positioning accuracy using different methods. In static mode, they obtained RMSE (Root Mean Square Error) values of 11, 17 and 15 mm for north, east and up components, respectively, based on differences from reference data. In contrast, in RTK mode, they found that the manufacturer's parameters were not met and were 20 mm and 53 mm (both RMSE) for horizontal and vertical components, respectively, for a baseline shorter than 0.5 km. In addition, it was noted that the main source of height error was the use of low-cost antennas. Further tests for this receiver were performed by Hamza *et al.* (2021), who used low-cost antennas from various manufacturers to determine position using the static method. Their results allowed them to conclude that low-cost instruments give a coordinate accuracy of a few millimeters, but their precision is four times worse than that of geodetic receivers (based on adjustment of the established geodetic network). A detailed study on the influence of patch antenna was carried out by Krietemeyer *et al.* (2020) by comparing with geodetic-grade antennas, with and without consideration of antenna relative calibrations.

A critical component of the low-cost receivers is the patch antenna, due to the noticeable degradation in positioning accuracy. For this reason, they have been tested using high-precision geodetic antennas. Thus, Tsakiri *et al.* (2017) verified the accuracy of single-frequency u-blox receivers. The results obtained were comparable to geodetic receivers - not exceeding 0.005 m (2σ) in all components (for a baseline shorter than 0.5 km) and 0.02 m (for up to 18 km long baseline). Even better results were obtained by Poluzzi *et al.* (2019), obtaining RMSEs below 2 mm and about 5 mm for the horizontal (Hz) and vertical (V) components, respectively, based on 1-hour static observations. Besides, they estimated the accuracy of the real-time solution as 4 mm (Hz) and 8 mm (V) RMSE. A similar RTK mode study was performed by Semler *et al.* (2019), comparing the ZED-F9P results with a professional geodetic receiver. They obtained a 3D position standard deviation value of 7 mm, which they considered excellent for low-cost GNSS equipment compared to a value of 13 mm obtained with a high-end receiver.

It is worth noting that the tests mentioned above were usually conducted under favorable field conditions, with a large number of available satellites and an open horizon. However, terrain obstacles are a significant handicap in many practical cases, so it seems reasonable to perform tests under such conditions. The tests carried out in this paper take into account different terrain situations, ranging from an open-sky environment, through a horizon obscured from different directions, to the case of an urban canyon.

Furthermore, in testing the accuracy of the devices, it is crucial to provide reliable reference values. Most comparisons utilize results obtained with different GNSS receivers, equipped with various antennas (patch and geodetic), using other positioning methods. In this paper, satellite observations are compared with total station measurements, which provide higher accuracy and are less dependent on random factors such as satellite availability or multipath effect.

The motivation for undertaking the research was to verify the accuracy of low-cost dual-frequency GNSS receiver operating in RTK mode in relation to high-precision observations. An essential element of our work was to create diverse field conditions in which low-cost receivers can be used, such as during vehicle positioning.

Furthermore, expecting worse results for low-cost receivers, a mid-cost solution was conducted in the tests. A high-precision geodetic antenna was combined with a low-cost receiver. Despite the higher cost of the antenna, this combination is still a cost-effective alternative to high-end geodetic equipment in situations where high positioning accuracy is required.

II. TESTED DEVICES

The u-blox ZED-F9P is a 2-frequency, 4-system GNSS receiver - it receives GPS (L1C/A, L2C), GLONASS (L1OF, L2OF), Galileo (E1B/C, E5b) and BeiDou (B1l, B2l) signals. It offers RTK and RTN operation with high frequency (up to 20 Hz) and accuracy (± 1 cm + 1 ppm). In conditions of good satellite visibility, the receiver quickly resolves its position (cold start < 24 s, reacquisition < 2 s). Also, anti-jamming and anti-spoofing algorithms are implemented into the receiver, allowing by the assumption to discard unwanted signals. It has a wide operating temperature range, low power consumption, light weight and a large number of physical I/O and communication capabilities. The parameters of this device declared by the manufacturer, its price, and programming libraries available on the Internet, provide great opportunities for using this receiver. In the presented work the C099-F9P application board was used for testing.

Since the C099-F9P is an application board with the receiver itself, an active GNSS antenna must be connected to it. The manufacturer includes a patch antenna (model ANN-MB-00), which should provide the required accuracy in conditions with good visibility of satellites. It is small (its dimensions are only 60.0 x 82.0 x 22.5 mm) and weather-proof (protection level IP67).

To reduce the number of reflections from other objects and/or the environment reaching the antenna, when mounting the above antenna, it should be ensured that it is placed on a plate made of a well conductive metal (so-called ground plane). For the following tests, a special 4 mm thick disc with a diameter of 200 mm and a bracket for it were self-made of aluminum. The assembly is shown in Figure 1. The whole set provides a coaxial mounting with the second antenna and the Leica GS18T receiver, allowing straightforward interpretation of the results later in the tests.

Figure 1. The u-blox ANN-MB-00 antenna with self-made aluminum ground plane.

To check the performance of the ANN-MB-00 antenna in multipath reduction, measurements were additionally performed with a professional surveying antenna Leica AS10, which was applied in another similar tests (Garrido-Carretero *et al.*, 2019; Xue *et al.*, 2021).

III. STATIONARY EXPERIMENT

A. *Experimental setup*

The details of the conducted experiment have been presented by Janos and Kuras (2021). Measurement stations were planned at locations with different horizon exposure conditions (Figure 2), so that the test would be reliable and different results could be obtained. Measurements were made in May, when trees gather leaves and constitute a barrier for a satellite signal. Pt 1 had a perfect exposure of the horizon, Pts 2-4 had the horizon covered only from one side, Pt 5 had in addition tree branches directly above it, Pt 6 was surrounded by trees and a nearby hill, while Pt 7 was located in an "urban canyon".

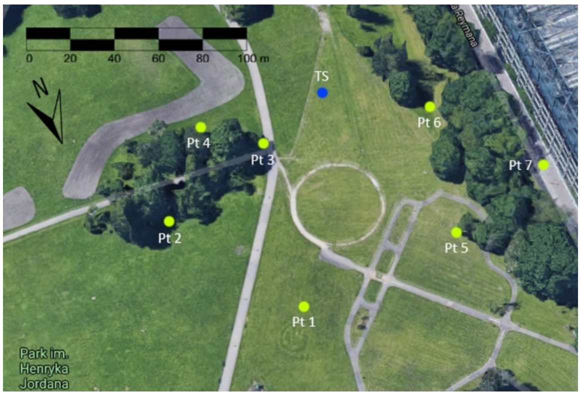

Figure 2. Measurement site for stationary test.

The reference coordinates were measured with the Leica MS50 precision total station (angle accuracy 1", distance accuracy ± 1 mm + 1.5 ppm) in combination with the Leica GPR1 surveying prism. The total station was referenced to 2 points, the coordinates of which had previously been determined using a static GNSS technique. The session lasted 45 minutes. The observation data were collected with Leica GS16 geodetic receivers (GPS + GLONASS) and calculated with commercial software. The final accuracy of the reference points is estimated to be a maximum of $\sigma_{2D} = \pm$ 2.4 mm and $\sigma_H = \pm$ 2.6 mm. For further considerations, the obtained coordinates are considered constant and error-free.

The measurements with both receivers – Leica GS18T and u-blox ZED-F9P – were performed in RTK Network mode. In this mode Leica declares a slightly higher measurement accuracy of its receiver due to the distance to the base. To obtain consistent results, in both cases, RTCM corrections to the observations were provided by the same CORS network (Leica SmartNet Poland).

The measurement at the station consisted of at least five measurement series (the exception was station Pt 7) for each hardware configuration. Measurements in successive configurations (Leica GS18T, u-blox ZED-F9P + Leica AS10, u-blox ZED-F9P + ANN-MB-00) were performed alternately to ensure that each receiver had the most similar measurement conditions (access to the same satellites). The scheme of one measurement series on the station was as follows:

- Receiver initialization - maximum 30 seconds.
- Measurement - 30 seconds.
- Change of antenna/receiver.

The collected observations in one 30-second measurement were averaged. After completing the measurement at the station, at least five separate (averaged) measurements of each antenna were obtained and taken for further analysis.

B. *Results*

The test of the ZED-F9P receiver started with measurements under good satellite visibility conditions. The Pt 1 measurement station had no significant obstacles around it. The next measurement stations were located in places with one side of the horizon obscured by tall trees. Those sides was the southern, eastern, and northern for Pt 2, Pt 3 and Pt 4 stations, respectively. The subsequent measurement stations were located in even more demanding conditions. Point Pt 5 was planned with the horizon obscured from the west (by trees and a football stadium). Additionally, the tripod was set up directly under the tree branches. The Pt 6 station, on the other hand, was located in the surroundings of trees, less dense, however, on all sides. Additionally, on the southern side the horizon was limited by a nearby mound and on the western side by the football stadium.

The last station was located in difficult measuring conditions for GNSS technology. On the west side the horizon was directly limited by a building, while on the east side by a line of tall trees - the tripod was set up along an alley running between a park and a large football stadium. It is worth mentioning the problems that were encountered during the measurements. As many as 8 series of measurements were performed on this station. The Leica GS18T receiver had a fixed solution only in half of the series. The ZED-F9P receiver with the Leica AS10 antenna had even fewer fixed solutions - only 3. The same receiver, but with the ANN-MB-00 antenna, had fixed solutions in 4 series. Unfortunately, the result of one of them differed considerably from the reference coordinates - by as much as 13 meters on the vertical coordinate. This measurement was removed from further considerations, nevertheless the result is still not satisfactory.

The results are summarized for different hardware configurations and for all measurement stations. Table 1 contains the differences of the measured coordinates in relation to the reference values, averaged from the five measurement series. Similarly, Table 2 contains standard deviations calculated based on the five measurement series.

The following values were used to compare the results: the summed coordinate differences (Eq. 1) and the mean standard deviation (Eq. 2):

$$sum_{XYH} = |d_X| + |d_Y| + |d_Z| \tag{1}$$

where d_X, d_Y, d_Z = differences from reference values

$$MSD = \sqrt{(\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2)/3} \tag{2}$$

where $\sigma_X, \sigma_Y, \sigma_Z$ = standard deviations of coordinates

An increasing trend of sum_{XYH} values can be seen in Figure 3. Surprisingly, better results were obtained at station Pt 6 than at the station Pt 1 with a fully open horizon. It can be assumed that despite many obstacles on the horizon from different sides, there were also free gaps that made it possible to create a good-quality angular resection of signals coming from the satellites of all constellations.

Table 1. Differences from the reference values [mm]

Rec.		Pt1	Pt2	Pt3	Pt4	Pt5	Pt6	Pt7
GS18T	X	-10	-6	0	-1	18	4	-4
	Y	2	7	27	11	-24	-8	1
	H	19	5	14	5	31	-4	-32
ZED+AS10	X	-7	-6	-4	3	15	-4	-64
	Y	-2	1	20	10	-26	-9	-33
	H	11	6	11	-1	9	-10	38
ZED+ANN-MB-00	X	-9	-9	-11	8	13	-2	21
	Y	0	0	20	8	-26	-10	69
	H	27	14	30	4	35	9	237

Table 2. Std. deviations based on measurement series [mm]

Rec.		Pt1	Pt2	Pt3	Pt4	Pt5	Pt6	Pt7
GS18T	X	8	9	9	7	5	21	29
	Y	6	13	9	6	15	25	47
	H	14	12	34	29	20	38	57
ZED+AS10	X	8	9	6	14	18	11	75
	Y	14	6	10	8	9	16	106
	H	21	29	23	31	32	31	15
ZED+ANN-MB-00	X	10	16	9	5	11	18	110
	Y	6	7	10	6	17	22	147
	H	17	16	30	36	42	31	392

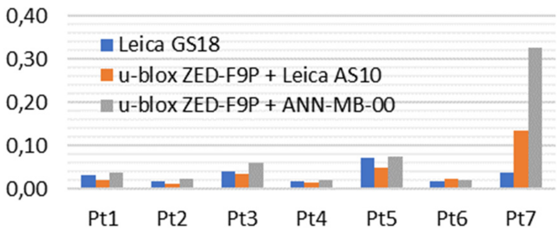

Figure 3. Values of sum_{XYH} [m] on each station point.

Considering the conditions at all measurement stations, it can be concluded that both receivers performed well. The u-blox ZED-F9P, equipped with the Leica AS10 antenna, had a slight advantage in the clear areas, while its rival excelled in the very demanding "urban canyon" type conditions at the last station.

In Figure 4 the increasing tendency of the *MSD* values can be clearly seen. It is a result of measurement difficulties at subsequent stations (more and more obscured horizon, access to less satellites of a given constellation, as well as more reflected signals and interferences). This proves a good choice of successive measurement stations in order to increase the difficulty of measurement.

IV. EXPERIMENT IN MOTION

A. *Experimental setup*

The second experiment consists in checking the quality of the calculated position of the antenna being in motion (in contrast to the static tests carried out by Janos and Kuras (2021)) determined by the GNSS receiver u-blox ZED-F9P. To ensure the highest possible accuracy of the reference data, a total station measurement was performed simultaneously. To facilitate the processing of the measurement data, a 360° prism was mounted coaxially with the GNSS antenna. The plan was implemented by mounting a surveying pole to the fork and handlebars of the bicycle (Figure 5). The aforementioned prism and antenna were mounted on the pole. Acquisition of both GNSS and total station data was done continuously at a frequency of about 10 Hz and about 7 Hz, respectively. Measurement data from the ZED-F9P was sent to the tablet via a USB cable and saved via an application written for this purpose. The Leica MS50 instrument collected the observations on board. With the system thus assembled, two passes were made, in opposite directions of travel.

Figure 4. Values of *MSD* [m] on each station point.

Figure 5. Measuring equipment on a bicycle.

The measurements were made in a city park - in an area with varied satellite visibility. The rides were made through alleys leading both through open spaces, half-obscured, and with the horizon completely obscured by bushes and trees. Layout of the survey points on the satellite images background are presented in Figure 6. The obstacles can be clearly seen. The measurement campaign was performed in May when trees already have been covered with leaves and together with their branches represent a real obstacle for the GNSS satellite signal.

Figure 6. Measurement site for the experiment in motion with markings of positioning quality.

B. *Preliminary results*

The reference data was determined based on two control points occupied by geodetic GNSS receivers in 45-minute static session. Then the reference observations were acquired using the Leica MS50 robotic total station set up on the control points.

To compare coordinates obtained from two devices (total station and low-cost receiver), a special script has been written, which performs spline interpolation by reference points and calculation of distances from measurement points to this spline.

Two rides, in opposite directions of travel, were made in a city park to check the repeatability of the results. Graphs illustrating the preliminary experimental results are presented in Figure 7.

Figure 6 illustrates the results of the rides. It is noticeable where the receiver had a limited horizon and where it had problems with the fixed solution. The location of the total station is also marked. Efforts were made to have it as central as possible to the whole survey, because of the better distribution of the positioning error, caused by the increasing influence of the measurement error in horizontal and vertical angles, as well as distance. It can also be seen why in some places on the route GNSS measurements are missing - then the total station's line-of-sight was interrupted by bushes, trees or other objects. However, the ride through sensitive places - bushes obscuring the horizon from the east, as well as tall trees located in the centre of the sketch, was captured. Hence, the given location of the total station was considered to be the most favourable.

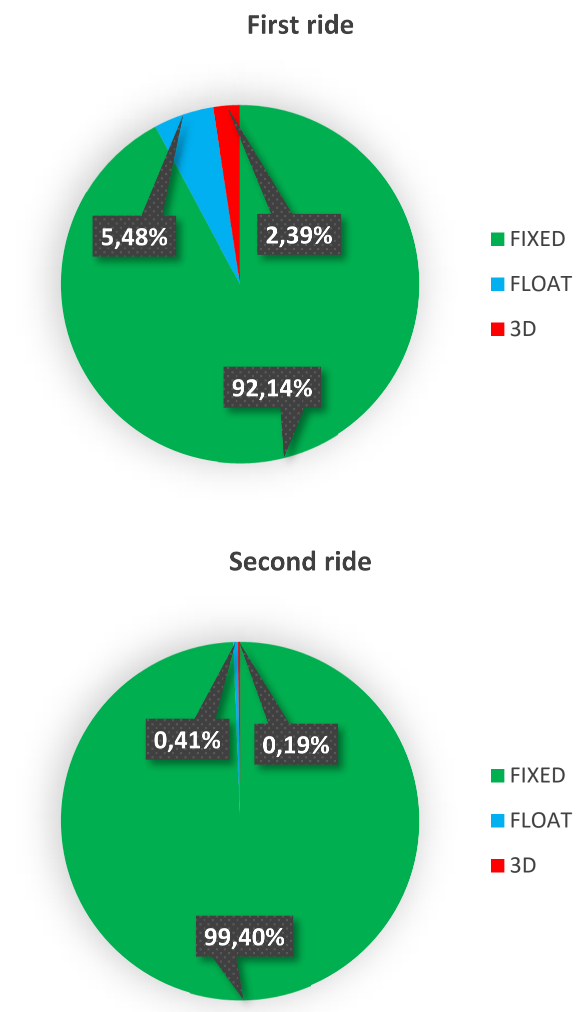

Figure 7. Pie charts showing the quality of GNSS positioning for the first and second test rides, respectively.

The receiver copes very well with positioning an antenna that is in motion. This happens both in places with a fully exposed horizon and those obscured from one of the sides. This is evidenced particularly by the results of the second ride (99.40% of fixed solutions). The first ride was more challenging - the route led through a place with a fully obscured horizon, hence the lower percentage of the highest precision measurements (92.14%).

The preliminary results indicate a high quality of positioning under demanding field conditions, however, a comparison with the observations collected by the total station will be the subject of further detailed analysis.

It is worth noting that the reference coordinates were determined at a different time, with a different satellite constellation, which also ensures the independence of the results obtained.

As expected, the receiver lost the fixed solution in places where the horizon is completely covered by tree crowns. Despite this, the accuracy of position determination did not drop drastically. However, these results may not be reliable due to the definitely low number of float positions. It is also not a satisfactory value, *e.g.* for precise monitoring of buildings or standard geodetic measurements. On the other hand, changes in the conditions of GNSS satellite signal reception and loss of good positioning quality are signalled correctly.

The 3D quality solutions look not bad either. The receiver, while moving, jumps quickly from areas with good satellite visibility to areas with poor signal quality (and vice versa). Due to the lack of such information in the technical documentation of the device, it can only be supposed that some algorithms are used to predict the movement of the receiver and maintain the accuracy of its position. The duration of the float and 3D quality position was short, so the results may not be completely reliable, and it would be necessary to conduct additional research on this aspect only.

V. CONCLUSIONS

In stationary test the u-blox ZED-F9P receiver performs well for a GNSS receiver in this price range. The ANN-MB-00 antenna is suitable for precise measurements and provides centimeter accuracy, but only in conditions with sufficient horizon exposure.

The ZED-F9P configuration with the ANN-MB-00 antenna provides an excellent relation of positioning quality to price, as well as size, weight or power consumption. This makes the u-blox a very versatile receiver and can be used in many industries, such as autonomous vehicles, building monitoring, surveying, robotics and marine.

In the case of positioning in more demanding conditions and/or with greater accuracy, a replacement for the patch antenna with a model of the survey-grade type would be worth considering. In the test the Leica AS10 antenna has significantly improved the measurement performance of the u-blox ZED-F9P, with smaller PCV (Phase Centre Variations) and more efficient multipath reduction. This configuration turned out to be better than a professional geodetic receiver in most field cases. It can be assumed as promising outcome, considering the price gap between both devices.

The u-blox ZED-F9P performs well also in mobile GNSS surveys. It achieves the fixed solution type in the conditions of limited horizon visibility. In order to assess the positioning accuracy, a detailed comparison with the observations collected by the total station will be performed in further work.

Thanks to its small size, low power requirements, and the multitude of ways to communicate and exchange data with the device, the u-blox ZED-F9P receiver is a very good option for all kinds of applications where high GNSS positioning accuracy is needed. Based on the comprehensive static tests, this receiver can be successfully applied in the projects requiring accuracy of approximately ±2 cm.

VI. ACKNOWLEDGEMENTS

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References

Garrido-Carretero, M.S., M.C. de Lacy-Pérez de los Cobos, M.J. Borque-Arancón, A.M. Ruiz-Armenteros, R. Moreno-Guerrero, and A.J. Gil-Cruz (2019). Low-cost GNSS receiver in RTK positioning under the standard ISO-17123-8: A feasible option in geomatics. *Measurement*, Vol. 137

Hamza, V., B. Stopar, and O. Sterle (2021). Testing the Performance of Multi-Frequency Low-Cost GNSS Receivers and Antennas. *Sensors*, Vol. 21, No. 6

Janos, D., and P. Kuras (2021). Evaluation of Low-Cost GNSS Receiver under Demanding Conditions in RTK Network Mode. *Sensors*, Vol. 21, No. 16

Krietemeyer, A., H. van der Marel, N. van de Giesen, and M.-C. ten Veldhuis (2020). High Quality Zenith Tropospheric Delay Estimation Using a Low-Cost Dual-Frequency Receiver and Relative Antenna Calibration. *Remote Sensing*, Vol. 12, No. 9

Poluzzi, L., L. Tavasci, F. Corsini, M. Barbarella, and S. Gandolfi (2019). Low-cost GNSS sensors for monitoring applications. *Applied Geomatics*, Vol. 12

Semler, Q., L. Mangin, A. Moussaoui, and E. Semin (2019). Development of a low-cost centimetric GNSS positioning solution for Android applications. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, Vol. XLII-2/W17

Takasu, T., and A. Yasuda (2009). Development of the low-cost RTK-GPS receiver with an open source program package RTKLIB. In *Proc. of the International Symposium on GPS/GNSS*, Jeju, Korea.

Tsakiri, M., A. Sioulis, and G. Piniotis (2017). Compliance of low-cost, single-frequency GNSS receivers to standards consistent with ISO for control surveying. *International Journal of Metrology and Quality Engineering*, Vol. 8, No. 11

Wielgocka, N., T. Hadas, A. Kaczmarek, and G. Marut (2021). Feasibility of Using Low-Cost Dual-Frequency GNSS Receivers for Land Surveying. *Sensors*, Vol. 21, No. 6

Wiśniewski, B., K. Bruniecki, and M. Moszyński (2013). Evaluation of RTKLIB's Positioning Accuracy Using low-cost GNSS Receiver and ASG-EUPOS. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 7, No. 1

Xue, C., P. Psimoulis, Q. Zhang, and X. Meng (2021). Analysis of the performance of closely spaced low-cost multi-GNSS receivers. *Applied Geomatics*, Vol. 13