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THE APPLICABILITY OF LOW-COST MULTI-FREQUENCY MULTI-GNSS RECEIVERS FOR GEODETIC CONTROL SURVEYING

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KEY WORDS: Low-cost GNSS receiver, Geodetic Surveying, RTKLIB, Survey accuracy, Multi-frequency GNSS, Multi-GNSS

ABSTRACT:

In geodetic surveys, survey-grade receivers are conventionally used due to their accuracy. However, expensive survey-grade receivers deter users from performing geodetic surveys utilizing the technology. Considerably, multi-system and multi-frequency low-cost GNSS receivers are available today, which can already provide good positioning accuracy output. This paper evaluates the performance of low-cost GNSS receivers in single-point positioning, relative positioning, and network solutions compared to survey-grade GNSS receivers. The study used a survey-grade antenna to test the u-blox C099-F9P evaluation kit equipped with the ZED-F9P module, a low-cost GNSS receiver. Simultaneously, the survey-grade GNSS receiver utilizes the same antenna using a GPS splitter to ensure simultaneous observation. Based on the results, the low-cost GNSS receiver is comparable to the survey-grade GNSS receiver for single and relative positioning. For single-point positioning, the low-cost GNSS receiver achieved 1- and 1.5-meter accuracy in horizontal and vertical components at a 95% confidence level, respectively. In relative positioning, it achieved an accuracy of 1 millimeter on average at a 95% confidence level. The network solution utilizes four (4) Active Geodetic Stations of the National Mapping and Resource Information Authority within the National Capital Region, used as reference stations. The low-cost GNSS receiver achieved an average accuracy of 8 millimeters. In summary, the ublox C099-F9P low-cost GNSS receiver achieved better than 1:100,000 or first-order survey accuracy stipulated in DAO 2007-29 surveying standards. Results show that the u-blox C099-F9P is possible for geodetic and other land surveying applications, even for high-accuracy requirements surveys.

1. INTRODUCTION

The Global Navigation Satellite System (GNSS) is composed of different satellite systems developed by countries which include the Global Positioning System (GPS) of United States of America, the Global'naya Navigasionnaya Sputnikova Sistema (GLONASS) of Russia, Galileo of European Union, BeiDou of China, Japanese Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS) of India (Teunissen and Montenbruck, 2017). The interoperability of the different systems is valuable for better reliability and multiple satellite signals utilization (Reyes et al., 2018, Rizos, 1997) at any time and anywhere to derive and provide user position, navigation, and timing (Sickle, 2015). The application of GNSS in surveying is widely adopted due to the achievable accuracy and speed in determining geographic position compared to traditional surveying techniques (Ghilani and Wolf, 2015). However, despite the advancement of GNSS in surveying, the price of survey-grade or geodetic kind of GNSS instruments is somehow quite expensive (Antonoglou, 2018). As for the geodetic control establishment, survey-grade receivers were often used due to their capabilities to produce high-accuracy positioning.

As for the GNSS receiver, they can be classified or graded depending on the usage and accuracy it can achieve. Commonly, they can be categorized into two: the geodetic or survey-grade and the low-cost ones. Survey-grade GNSS receiver is optimized to achieve a millimeter accuracy with its multi-system and multi-frequency (MF), recording capability (Hofmann-Wellenhof et al., 2008). On the other side, the low-cost GNSS receivers are portable in size, in the form of a module or board, customizable, and the cost is around 1% of the industry-standard price of a survey-grade GNSS receiver. On the downside, it requires a controller to operate the receiver and an external storage to store observation data on computers or mobile devices. Despite their cost difference, recent low-cost receivers can achieve accuracy comparable to survey-grade receivers (Antonoglou, 2018).

The low-cost GNSS receivers have the advantage of cost, size, weight, and ease of usage compared to survey-grade receivers (Dabove, 2019). Both these receivers are capable of single and relative positioning methods. Single-frequency (SF) types of low-cost receivers were promising in terms of real-time kinematic (RTK) positioning capabilities compared to the survey-grade receivers (Odolinski and Teunissen, 2018). However, there were drawbacks due to frequent loss of lock, data gap, and low signal-to-noise ratio. Additionally, the capability of detecting cycle slips and the elimination of systematic errors can be difficult for SF (Liu and Li, 2017). Several studies utilized SF low-cost GNSS receivers in applications such as cadastral surveys, deformation monitoring, and performance evaluation (Kosarev et al., 2017, Janssen et al., 2002, Tsakiri et al., 2016, Tsakiri et al., 2017, Caldera et al., 2016, Gebre-Egziabher et al., 2018). Results showed that the receivers tested are comparable to the survey-grade receivers and can attain a centimeter-level positional accuracy. In 2018, the MF multi-band high-precision GNSS module (e.g., u-blox ZED-F9P) was available to the market, which provides faster convergence time and centimeter accuracy (ublox, 2019c). The ublox ZED-F9P module was tested in static measurement and showed comparable results to the survey-grade receiver but suffers on multipath due to the low-grade antenna used (Bredesen and Helder, 2019). Another study for the ublox ZED-F9P attained 1 millimeter to

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1.5 centimeters positional accuracy yet had a low percentage fixed solution for baselines greater than 9 kilometers (Dongen, 2019). Previous studies utilize low-cost receivers and survey-grade receivers. However, both receivers are not evaluated on the identical epoch nor using the same geodetic antenna.

Capabilities of low-cost GNSS receivers in positioning have the potential for geodetic application (Dabove, 2019), such as in isolated surveying and geodetic surveying. The use of GNSS in geodetic surveying is preferable in static mode of observation, as stated in the Department of Environment and Natural Resources (DENR) Administrative Order (DAO) 2007-29 (DENR, 2007). However, a geodetic control survey must be conducted using survey-grade receivers capable of tracking at least four (4) satellites, preferably receiving signals from multi-constellation and either single or dual-frequency (DENR, 2010). Additionally, the Land Management Bureau Memorandum Circular 2015-001 stated guidelines for using RTK-capable GNSS receivers for lot surveys (LMB-DENR, 2015). With stipulated guidelines, low-cost GNSS receivers limit its reach to be used in high-order accuracy surveys.

This study aims to comprehensively evaluate the performance and applicability of the low-cost GNSS receivers for geodetic control surveying. The results from survey-grade receivers were computed for the basis of assessment of the low-cost results. A GPS signal splitter was utilized to synchronize the recording of both receivers from a single geodetic antenna. The positions were derived in geographic and geocentric coordinate systems in WGS 84 ellipsoid and local coordinate positional components. Additionally, the Active Geodetic Stations (AGS) of the Philippine Active Geodetic Network (PAGeNet) under the National Mapping Resource Information Authority (NAMRIA) served as a continuously operating reference station (CORS) in the Philippines (PAGeNet and NAMRIA, 2020). The data obtained from selected active geodetic station (AGS) were incorporated into the post-processing of the data.

2. DATA AND METHODS

2.1 Instruments and software used

The ublox C099-F9P evaluation kit equipped with ZED-F9P high-precision GNSS module (ublox, 2019a) was used as the low-cost GNSS receivers (Figure 1). The receiver has 184 channels and can record multi-frequency and multi-system GNSS signals (ublox, 2019c). A laptop computer for field observation and a desktop computer for office observation were utilized for data collection. In controlling, configuring, and recording observation from the receiver, the u-center (ublox, 2019b) and STR-SVR program of RTKLIB software were used (Takasu, 2013). Using the low-cost GNSS receiver, a modular survey-grade receiver was used as a counterpart during the observation. This modular type of receiver requires a cable to be connected to an antenna, which is preferable for the observation setup. This study used the Trimble SPS 855 and Trimble NET R9 GNSS receivers. In controlling the receiver, an internet browser was used. For its data recording, the receiver automatically logs the data. As for the antenna, the Trimble Zephyr Model 2 was commonly used by both of the receivers. A GPS signal splitter is connected to both receivers from the antenna to ensure synchronized data recording. The Trimble Business Center (TBC) software was used for the network adjustment.

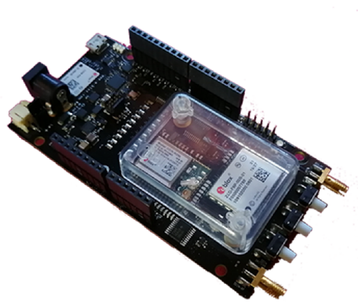

Figure 1. The ublox C099-F9P evaluation kit used in the study.

2.2 Study area

The study area covers Metro Manila, Bulacan, Pampanga, Laguna, and Cavite from 14°10'N to 15°08'N in latitude and 120°51'E to 121°30'E in longitude (Figure 2). The selection of the area is due to the abundance of PAGeNet's AGS around the National Capital Region (NCR). Reference geodetic control stations include four (4) AGS, namely PTAG (NAMRIA, Taguig), PSTC (Santa Cruz, Laguna), PSRF (San Rafael, Bulacan, and the UoP (University of the Philippines) base station located at the University of the Philippines Diliman. All of the antennas are roof-based stations. Five (5) ground control points (GCP) test points were established in the network solution. By terrestrial reconnaissance, the GCP locations were selected with having fewer obstructions for clear sky view with stable ground conditions. They are set based on the distance from the UoP station, approximately 10, 20, 30, 40, and 50 kilometers.

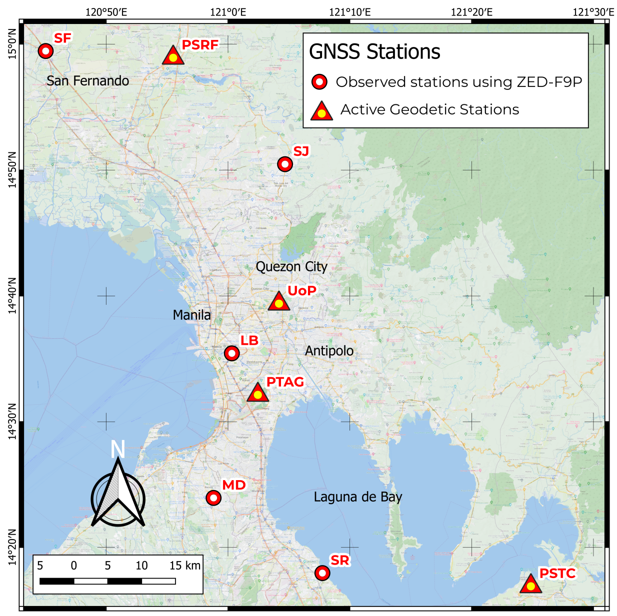

Figure 2. Study area and location of GCP and AGS around NCR.

2.3 GNSS observation

Different tests were conducted by static observation on the selected points or GCPs to determine the low-cost GNSS receiver performance and their positional accuracy. Before the observation, the necessary configuration was set on the receivers, such as the baud rate, logging interval, and the required messages to be recorded for the low-cost GNSS receiver. The low-cost GNSS receiver used the u-center software to configure the receiver. For survey-grade receivers, the configuration includes specifying the logging rate and constellations. Ideally, the results from survey-grade receivers were used as a benchmark for the results from the low-cost receiver.

2.3.1 Single point positioning (SPP): The observation in static mode was done in the UoP base station utilizing low-cost and survey-grade GNSS receivers. Both receivers are connected to a single geodetic antenna by a GPS signal splitter (Figure 3), assuring synchronous observation and recording. Both receivers continuously log data daily for one (1) week using the RTKLIB STR-SVR program.

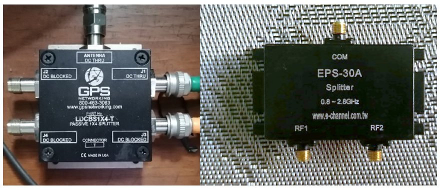

Figure 3. GPS splitter used in the study: at UoP base station in TNC connector type (left); at field observation in SMA connector type (right).

2.3.2 Single baseline/relative positioning (RP): This observation method aims to test the positioning performance and accuracy of the low-cost receiver for a single baseline in static mode. The baseline distance is approximately 13.7 km between station PTAG as the reference station and station UoP as the rover station. At station UoP, the low-cost and survey-grade GNSS receivers were connected to a single geodetic antenna utilizing a GPS signal splitter, ensuring synchronous observation and logging of observation data. In this case, the logging of low-cost GNSS receiver data was recorded using the STR-SVR program. Both receivers continuously log data daily for a week, and the post-processed coordinates from each receiver were compared. For the post-processing data, the base station PTAG observation data was obtained from the IGS website (IGS, 2020).

2.3.3 Network solutions: The network solution uses multiple reference stations, AGS (Figure 2), for each session. Every session utilizes two low-cost receivers to observe GCPs at different locations. The observation time of each GCP in every session is set to a minimum of one (1) hour. At the end of each session, the two low-cost receivers are transferred to another GCP, which is not previously observed until all the planned sessions are realized. An essential part of the planning is the redundancy of the baselines (Sickle, 2015, DENR, 2010, DTMR, 2019). In this test, the performance of the low-cost GNSS receiver was evaluated in terms of network solution cases. It primarily determines the position of the established GCP, especially in greater baseline distances, e.g., over 50 kilometers. In the recording of data using the low-cost GNSS receiver, the u-center software was used. In this study, GCPs were placed at LB (Liwasang Balagtas, Pandacan, Manila), SJ (San Jose Del Monte, Bulacan), MD (Molino Dam, Cavite), SR (Santa Rosa, Laguna), and SF (San Fernando, Pampanga).

2.4 Data processing and analysis

After the observations, the receiver's data was checked and analyzed through satellite visibility, signal strength, and the number of signals received. The observation data were then downloaded and converted using RTKCONV into receiver-independent exchange (RINEX) format for later GNSS processing. All RINEX data were converted in the 3.02 version. The post-processing was done using the RTKLIB-RTKPOST software.

The post-processing setting includes the following: the elevation mask to 15°, frequencies to dual (L1 and L2), single (pseudoranging) and static (carrier) for positioning mode, ionospheric correction from the broadcast ephemeris, tropospheric using the Saastamoinen model, satellite ephemeris from broadcast messages, ambiguity validation threshold of 3 was used for relative positioning as it is the values used most on software as the minimum ratio for fix solution (Hofmann-Wellenhof et al., 2008, Dongen, 2019). The processed single and static solutions were in geographic, Earth-centered, Earth-fixed (ECEF) XYZ coordinates in WGS 84 reference system. Local coordinate systems in north (N) and east (E), as horizontal components, and up (U) for the vertical component were also produced. The post-processed data includes 15-minute results, 30 minutes, 45 minutes, and hourly data up to 24 hours. This is to test the performance of the solutions produced in different time durations considered in post-processing. A programming method was employed using the Spyder integrated development environment (IDE) in Python programming to automate reading, parsing, computing, and summarizing the data solution. The root-mean-square (RMS) error was also determined for each receiver and their differences to analyze the result. Furthermore, the position dilution of precision (PDOP) was evaluated. To verify its comparability to the survey grade receivers, the F-test statistical test (Equation 1) was employed:

$$F_0 = \frac{S_{lc}^2}{S_{sg}^2}, \tag{1}$$

where F_0 = F-test value
S_{lc}^2 = variance of low-cost
S_{sg}^2 = variance of survey grade

The network solution's post-processing and network adjustment (DTMR, 2019) were done using the Trimble Business Center software. Additional AGS RINEX data needed were obtained from PAGeNet. The workflow of the network adjustment comprises baseline processing, minimally constrained network adjustment, and fully constrained network adjustment. In all the adjustments, the 95% confidence level was used. The baseline processing is the first step in determining the quality of each baseline. As for the baseline selection, independent baselines were only considered in the network for survey-grade and low-cost GNSS network data adjustment. Per session, the required number of independent baselines were selected. After all the baselines were processed and error-free, loop closure was checked, and minimally constrained adjustment was made. A single AGS was held fixed for the adjustment, both the horizontal components and the height. This reduces the high correlation observations in the network (Tsakiri et al., 2016). After the adjustment, a check was done on the other AGS that were not held fixed to see their differences in coordinates from the entered values and the adjustment results, which one AGS is only held fixed. The results of low-cost receiver adjustment were compared to the survey-grade receiver adjustment result in WGS 84 ECEF coordinates, and their differences were evaluated. After the adjustment, the fully constrained adjustment was performed, where all AGS was held fixed in the adjustment. Furthermore, the values of the adjustments were referenced from reports of network adjustment, baseline processing, and point derivation.

3. RESULTS AND DISCUSSION

3.1 Sky-plot of the observed data and SPP at station UoP

The visibility analysis of raw data on low-cost and survey grade was evaluated (Figure 4). Both receivers collect numerous satellites from different constellations and various signal frequencies. A total of 102 satellites and 106 satellites were recorded for low-cost and survey-grade, respectively. For the satellite frequencies, the survey-grade GNSS receiver captures more frequencies on each GNSS, recording pseudoranges, carrier phase observation, Doppler, and signal strength. Few frequencies were recorded for the low-cost receiver except for L5 signals.

Furthermore, the recorded signals from the low-cost receiver align with the declared supported GNSS signals on the ZED-F9P module (ublox, 2019c). Generally, the multiple-frequency recording was seen on the skyplot on both receivers. Noticeably, the J01 (QZSS Satellite No. 1) satellite data of survey grade is full of cycle slips. However, the J01 satellite data received by the low-cost receiver tends to have less cycle slip occurrence than the survey-grade receiver.

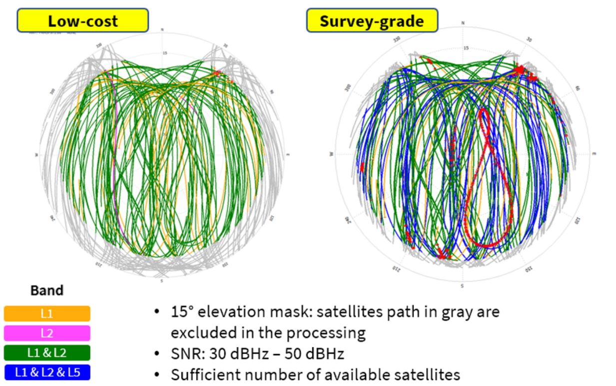

Figure 4. Skyplot of the satellites observed.

Table 1 shows the average and difference of positions in local projection in meters of SPP solution from low-cost and survey-grade receiver data. The average number of satellites observed for the low-cost receiver is 30, and the PDOP value is four (4) on average. On the other side, the survey-grade receiver observed 35 satellites on average, and the PDOP value ranges from 3 to 5. The average difference in position obtained from the low-cost and survey grade in N and E components achieved less than 0.5 meters difference. However, the average difference between the receivers reaches about a meter for the U component. Furthermore, a 2.50 meters maximum difference for the U component for short observation post-processing, like 15-minute observation data, compared to more extended post-processing time coverage. The results imply that a low-cost receiver must observe for at least an hour or more to achieve similar results to the survey-grade receiver, as shown in Figure 5. However, there was no convergence between the two results from two receivers per ECEF component. There were minimal changes to the output solution when the processing length was increased, starting from the 12th hour to the 24th hour. The RMS error at the 95% confidence level of positional components in horizontal and vertical for low-cost and survey-grade receivers was less than 1.00 meter for at least an hour of post-processed observation. Both receivers achieved a pseudoranging result better than 2 meters at a 95% confidence level.

GNSS Receiver	Difference in meters		
	N	E	U
low-cost - survey-grade	-0.137	0.076	-1.340

Table 1. Mean coordinate difference between low-cost and survey-grade receivers' derived positions in SPP.

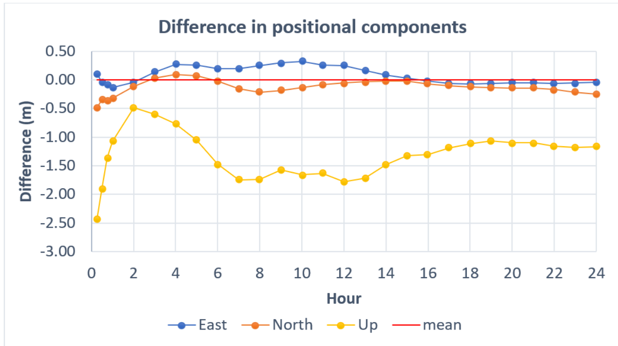

Figure 5. The difference in meters between the low-cost receiver and survey-grade receiver SPP solution in local coordinates components.

Although the low-cost receiver is comparable based on the results to the survey-grade receivers as shown on graphs and their difference, they were verified statistically using the two-tailed F-test. Equal variances signify equal performance on both receivers. Otherwise, the low-cost GNSS receiver is not on par with the survey grade. The study of Tsakiri et al. (2017) used the same method in verifying the low-cost GNSS receiver performance. The horizontal and vertical component of the low-cost receiver is compared to the survey grade. The variances of each horizontal and vertical component were pooled to determine the variance (S_0^2) of the 27 results (e.g., 15 minutes, 1 hour, and so on). The test used a 95% confidence level with 26 degrees of freedom (DOF) to verify if the receivers have equal performance (H_0: null hypothesis) or differ in performance (H_A: alternative hypothesis). Based on the results, the $F_H = 1.128$ and $F_V = 1.351$ were inside the confidence region computed for horizontal and vertical, respectively. In this case, the null hypothesis cannot be rejected, and both receivers, low-cost and survey grade, performed equally.

3.2 RP of UoP-PTAG baseline

The post-processed results for the survey-grade receiver observed an average of 18 satellites and a PDOP value of less than 2 millimeters. Identically, the low-cost receiver achieved a PDOP value of fewer than 2 millimeters for 18 average satellites observed. Table 2 summarizes the average coordinate difference of fixed solution obtained from low-cost and survey grade determined from 27 post-processed baselines. The maximum difference in ECEF between low-cost and survey-grade receivers is about 3, 6, and 2.00 millimeters for X, Y, and Z components, respectively. The results of the low-cost receiver are comparable to the survey-grade receiver in terms of their difference in coordinates with at least a millimeter difference (Figure 6). The average for the fixed solution is 98.6% and 98.1% for the low-cost and survey-grade receivers, respectively.

GNSS Receiver	Difference in mm		
	N	E	U
low-cost - survey-grade	1.0	0.7	-3.8

Table 2. Mean coordinate difference between low-cost and survey-grade receivers' derived positions in RP.

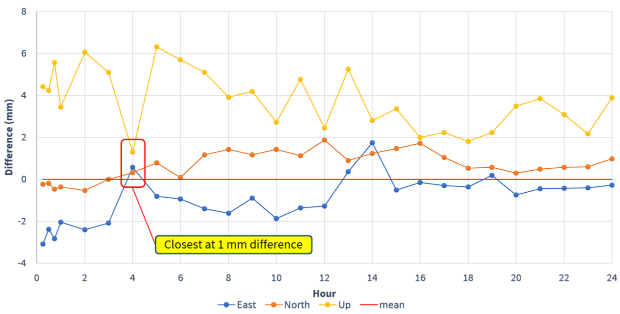

Figure 6. The millimeter difference between the low-cost receiver and survey-grade receiver the RP solution in local coordinates components.

The closest difference between low-cost and survey-grade receivers for the three components was achieved at the 4th-hour processing length, which differs by only 1 millimeter. The maximum differences between the two results were about 6 millimeters for the up component. As the post-processing length was increased from 1 hour to 24 hours, the coordinate difference was less than 2 millimeters for low-cost and survey-grade receivers. For the RMS at 95% confidence level, the horizontal component is less than 2 millimeter. As expected, the vertical component is more significant than the horizontal. Related to the study of Dongen (2019), using the same type of low-cost GNSS receiver, a millimeter accuracy is achievable in a post-processed kinematic solution for a 9 kilometer baseline. Furthermore, the number of valid satellites in the solution for both receivers is 18. The low-cost fix solution is 97% and 96% fix solution for the survey grade. Based on the results, the fixed solution rate was high for the low-cost and quite the same as the solutions in the survey grade. However, most float solutions occurred on the low-cost receiver on the same instance on the survey-grade receiver at around 11 to 12 hours. Comparably, both receivers achieved a PDOP value of less than 1.

With the identical results and performance of both receivers, the two-tailed F-test was used to check the comparability of the two receivers. The process was similar to the SPP procedure. Based on the results, the $F_H = 1.165$ and $F_V = 1.396$ were inside the confidence region for horizontal and vertical, respectively. In this case, the null hypothesis cannot be rejected, and both receivers, low-cost and survey grade, performed equally.

3.3 Network solution

Two networks were created for the network solution. It includes the network consisting of a low-cost receiver and the network consisting of survey-grade receivers. A total of 20 independent baselines were processed (Figure 7), with five independent baselines per session. The network is also comprised of AGS included in the post-process. These baselines ranged from 7.20 to 72.00 kilometers in baseline vector length. For all the baselines processed, the PDOP values were below 3.25 for both networks consisting of survey-grade and low-cost receivers. The average satellites observed were 15 and 26 for low-cost and survey-grade receivers, respectively. The loop closure was checked for errors before further processing. The error of closure of loops on the network was checked in horizontal and vertical components. The criteria used for the loop check is one part per million (ppm) relative error. The output shows that the worst loop for the low-cost receiver has an error of 1.764 ppm, while the survey-grade receiver's worst loop has an error of 2.531 ppm. As per evaluation, the vertical component contributes the most to the error.

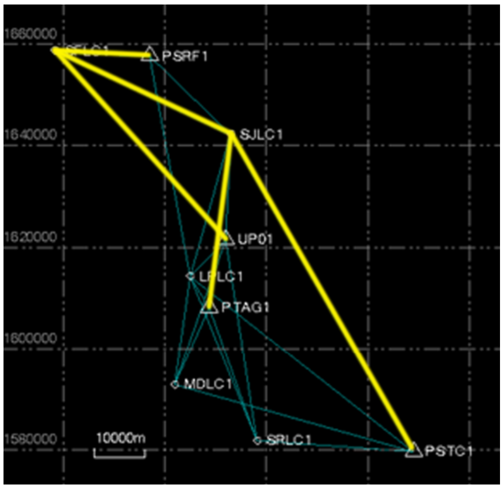

Figure 7. Baselines of one of the sessions (yellow line) conducted with other independent baselines from other sessions.

The differences in baseline components between the low-cost and survey-grade receivers and their differences in standard deviations are 8, 14, and 6 centimeters for X, Y, and Z, respectively. The maximum horizontal RMS for the low-cost receiver is 2.30 centimeters, and the survey-grade receiver is 1.20 centimeters. In the vertical component, the low-cost and survey-grade receivers achieved a maximum RMS of 9 centimeters and 7.80 centimeters, respectively. The survey-grade receiver had better horizontal precision with an average difference of 3 millimeters.

The network adjustment was performed, setting the PTAG station coordinates fixed for a minimally constrained adjustment. The network adjustment for low-cost receiver consists of 20 baselines and 36 DOF, and the computed posteriori variance factor is one (1) after applying weights on the a priori scalar of 0.56. For the survey-grade receiver solution, the posteriori variance factor is 1, and the a priori scalar of 0.47. The differences between the low-cost and survey-grade results show an average of 2 centimeters. The horizontal components have differences not exceeding 2 centimeters, and the vertical is up to 6 centimeters. Both network adjustment solutions passed the Chi-square test.

A fully constrained solution was performed after checking the previously conducted minimally constrained solution. PTAG's latitude, longitude, and height were held fixed for the adjustment. For PSTC and PSRF stations, only their latitude and longitude were held fixed. There are 20 observations and 38

DOF for both networks, the posteriori variance factor is 1, the a priori scalar of 0.55 for low cost, and the a priori scale of 0.47 for survey grade was set. Both networks passed the Chi-square test. The Z component difference for all the stations was within 1 centimeter between low-cost and survey-grade receivers. For stations LP, MD, and SF, the difference is below 1 centimeter. Stations SR and SJ had a maximum difference of 6 centimeters. This is due to the survey-grade receiver capturing additional L5 signals, which the low-cost receiver hasn't during observation. Despite a similar skyplot of satellites, the survey-grade receiver showed few cycle slips on one of its tracked satellite vehicles (SV) of BeiDou, which was not tracked by the low-cost receiver. Station PSRF had a difference of up to 4 centimeters for the X and Y coordinates. The UoP base station was not included in the fully constrained solution. The reason is that the network reference factor is more than 3; thus, the Chi-square test failed. UoP was excluded as a fixed station because the UoP coordinates were not derived using Bernese processing software as the 3 AGS were.

The solution difference between low-cost and survey-grade coordinates in planar projection (NEU) was computed. Results show that the horizontal component varies within a 1-centimeter difference. The north component of SJ had a maximum difference of 1.6 centimeters. The up-component difference for SJ and SR is 6 and 4 centimeters, respectively. The rest of the station is in sub-centimeter difference. For the PSRF and PSTC, their up component differs by 5.30 centimeters and 9 millimeters, respectively. However, the UoP station coordinates in the east, north, and up are 1 centimeter, 8 millimeters, and 4 millimeters, respectively. Based on the solution of the post-processed UoP-PTAG baseline relative positioning, the reported average difference from the known and computed coordinates of the UoP station for the east, north, and up components is 17.50 centimeters, 3 centimeters, and 11 centimeters, respectively. For the network adjustment solution, the difference of the UoP station between the known and computed coordinates for the E, N, and U components is 26, 7, and 9 centimeters, respectively. At station PSRF, the calculated coordinates differ by 5 centimeters for the U component in a network of low-cost receivers compared to the survey-grade receiver. With said station recording only GPS and GLONASS, this affects the result.

Its horizontal and vertical accuracy evaluated the adjusted network. The horizontal precision of the adjusted network is in ppm. The results show a positive trend of horizontal accuracy, which improves as the distance increases due to the small error (Figure 8). The ppm measured for low-cost GNSS receivers ranges from 0.245 to 1.534, and its equivalent ratio of 0.025/100,00 to 0.1534/100,000, respectively. Article 7 of DAO 2007-29 indicates that the first-order accuracy for establishing geodetic control in the Philippines is 1/100,000. For a nominal distance of 50 km and above, the accuracy obtained from both receivers achieved better than the required standard. Thus, the low-cost receiver can achieve first-order survey accuracy using static observation.

4. CONCLUSION AND RECOMMENDATION

The performance of the low-cost GNSS receiver, ublox C099-F9P, was tested and compared to that of the survey-grade receiver. The results showed that the low-cost receiver is comparable with the survey-grade receiver in terms of their minimal millimeter positional difference. Thus, it can be used for geodetic surveying requiring first-order accuracy. Based on the

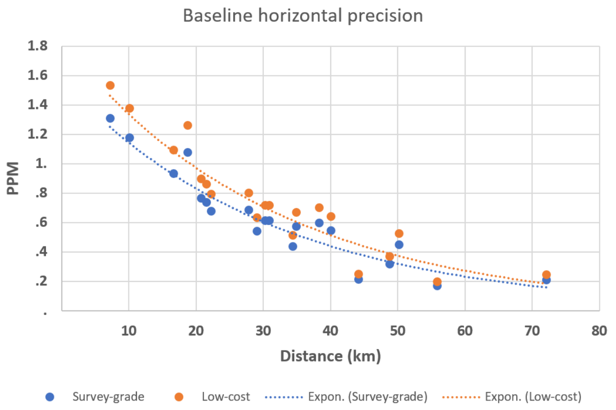

Figure 8. Baselines horizontal precision of over distance and its trendline.

coordinate differences between low-cost and survey-grade receivers in SPP, they are comparable, given that their average differences are 14, 8, and 1.30 centimeters for the N, E, and U, respectively. The position dilution of precision (PDOP) values on both receivers achieved better than 4, which is considered a good observation. At the 95% confidence level, the local coordinates components are 0.70, 0.60, and 1.50 meters for the N, E, and U components, respectively. These values were within the declared accuracy of ublox C099-F9P, a 1.50-meter circular error probable for horizontal. The F-test statistics show that the performance of a low-cost receiver is comparable to the survey-grade receiver for horizontal and vertical positioning.

In the 13.70-kilometer baseline RP test, the average difference between the two receivers for the three components, N, E, and U, are 0, 1, and 4 millimeters, respectively. This showed that the low-cost receiver could achieve competitive results with the survey-grade receiver—additionally, the RMS at 95%

The network adjustment results between low-cost receivers and a network with survey-grade receivers showed comparable performance based on their differences in coordinates obtained. The differences differ by about 1 centimeter on average for the horizontal components and about 6 centimeters for the vertical component. In terms of the horizontal accuracy of the network, the network of low-cost receivers achieves first-order accuracy or 1/100,000 relative error. For the vertical component, test results illustrate good performance in which, at a 7.20-kilometer distance, the RMS at 95% confidence is 4 centimeters, which is better than the required first-order accuracy, as stated in Article 7 of DAO 2007-29. Thus, low-cost receivers can be utilized for geodetic surveying applications that require high positional accuracy.

In terms of performance, the ublox C099-F9P application kit GNSS receiver, which was used in the study, is expected to improve once the additional frequency is available through the firmware update of the ZED-F9P module. As the advancement of technology in the surveying application evolves, consideration of the inclusion of low-cost GNSS receivers for geodetic surveying and isolated surveying in revising the surveying standards and policies in the Philippines might be possible. Since said receivers are affordable, survey practitioners can now maximize the benefits of the GNSS technology in their practice. Furthermore, schools/universities offering Geodetic Engineering will be unrestricted by a limited number of GNSS receivers for teaching.

Since there were yet to be standards in surveying applications for using low-cost GNSS receivers specifically, further tests should be conducted. The test includes an assessment of the same low-cost GNSS receiver in a real-time kinematic mode of positioning in different scenarios and field conditions. It is also suggested that a performance assessment of the multi-band antenna be included in the C099-F9P application kit in the positioning test. The wireless connectivity of these receivers must be explored and assessed to minimize the use of cables during field observation. Aside from surveying, these receivers can be used as an alternative device for monitoring purposes in construction, ground deformation, navigation, and other applications that require accurate positioning.

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