Quality Assessment of GNSS Observations from Recent Low-Cost Receivers

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Key words: low-cost receivers, GNSS, measurement noise

SUMMARY

Consequences of technology development and market expectations are cost-reduced versions of instruments designed to track Global Navigation Satellite System (GNSS) signals. GNSS mass-market receivers can be distinguished into the chipsets embedded in smartphone devices and the low-cost modules integrated with application boards. The first group aims to provide an approximate position primarily for personal navigation and applications. The positioning accuracy of smartphone chipsets is limited by factors such as quality of integrated antenna, high suppression to multipath, or duty-cycling effect. The low-cost receivers are, in turn, not constrained by the above limitations and thus can be used in precise applications by industry users. However, a prerequisite of precise positioning with such receivers is a high quality of code and phase GNSS measurements and a correct definition of the stochastic model.

This study aims to assess the noise of GNSS observations collected by the most recent multi-frequency GNSS low-cost receivers. The experiment is based on zero-baseline set-ups built of pairs of the receivers provided by u-blox, Skytraq, and Septentrio. The analysis investigates the stochastic properties of multi-system code and phase data transmitted on all available frequency bands. The code pseudoranges are assessed using a multipath combination, which provides information on the coupled impact of pseudorange noise and the multipath effect. We use double-differenced data derived from a zero-baseline set-up built of homogenous pair of receivers to analyze phase observations. In the study, we take advantage of two kinds of GNSS antennas, namely a patch one dedicated to low-cost receivers and a geodetic one used as a benchmark to contrast the results. The results are also compared with the corresponding dataset recorded with a high-grade geodetic receiver - Trimble Alloy. The experimental results reveal a competing to high-grade receivers quality of the low-cost receiver observations and, thus, the applicability of such receivers to precise positioning.

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1. INTRODUCTION

In the last decade, we could observe a rapid development of the Global Navigation Satellite System (GNSS) technique. Its consequence is a growth of applications that can be supported with GNSS and progress in providing mass-market and low-cost devices. These receivers are primarily delivered in two forms: chipsets embedded in smartphone devices and modules integrated with application boards.

The accuracy of the first group - smartphone built-in sensors - is proved to be lower due to integrated antenna and other issues such as the duty-cycling effect. The low quality of smartphone antennas and related to this strong multipath were reported by Kirkko-Jaakkola et al. (2015) and Siddakatte et al. (2017). Accordingly, the dispersion of code measurements may exceed even 10 meters. Further studies, e.g., Humphreys et al. (2016), also confirmed a poor quality of smartphone phase measurements, including a lot of discontinuities and gradual accumulation of errors. The consequence of these factors is a problem with correct ambiguity fixing and deterioration of feasible performance. As a result, it is believed that such receivers are predestined in less demanding applications.

The second indicated type of receivers, usually called low-cost, are equipped with external supply and antenna connectors and thus, do not suffer from the above-mentioned limitations. Consequently, they should be considered in precise positioning as well. This assumption seems to be confirmed by recent results of satellite positioning, which proved that such devices allow us to reach a centimeter-level accuracy in a real-time kinematic (RTK) mode (Garrido-Carretero et al. 2019, Odolinski and Teunissen 2019, 2020). Nevertheless, such receivers' full potential of applicability is still under investigation.

One of the issues that requires an additional evaluation is the quality of phase and code GNSS measurements recorded by low-cost receivers. Since most of them are dual-frequency, the analysis can be performed in the same way as for high-grade geodetic receivers. Considering the pseudorange data, the most common approach is to use so-called multipath combinations (Cai et al 2016, Paziewski and Sieradzki, 2017). Such methodology allows extraction of the combined impact of all unmodelled effects affecting undifferenced code data (noise and multipath) at a particular signal. Concerning phase noise, the investigations have to be supported by double-differenced (DD) GNSS data. In such case, the estimated stochastic properties of measurements can be obtained using processing of time series of DD observations at zero- or short-baselines (de Bakker et all. 2009, de Bakker et all. 2012) or through analysis of residuals from GNSS positioning (Amiri-Simkooei and Tiberius 2007, Odolinski et al. 2014).

The work demonstrates preliminary results on GNSS measurement noise analysis performed for low-cost receiver data. The research involves processing code and phase data from four satellite systems: GPS, Glonass, Galileo, and BDS. The study is divided into a few sections. The first of them briefly presents an experiment and methodology aimed at the determination of stochastic properties. The following part demonstrates the obtained results. Finally, the conclusions are given in the last section.

2. DATA AND METHODS

The GNSS measurements used in the experiment were recorded by three pairs of low-cost receivers, i.e., two UBLOX ZED-F9P, two SEPTENTRIO MOSAIC-X5, and two SKYTRAQ. Additionally, as a reference, we used a pair of geodetic receivers – TRIMBLE ALLOY. All instruments were grouped and connected through splitters to two antennas separated by 1.5 meter. The homogeneous devices worked in a zero-baseline mode, i.e., they received the signals from the same antenna. The test period covered four days: 27-28 February, 2022, and 2-3 March, 2022. During the first two days, the receivers were connected to a high-grade geodetic antenna TRM59800.00 NONE, whereas in the second two-day long period, a UBLOX ANN-MB antenna was installed.

To evaluate the code noise, we used well-known multipath combinations. They are based on dual-frequency undifferenced psuedorange and phase data (P_1, P_2 and L_1, L_2 respectively) and can be written with the formulas (Estey and Meertens 1999):

$$MP1 = P_1 - \left(1 + \frac{2}{\propto -1}\right) L_1 + \left(\frac{2}{\propto -1}\right) L_2 \approx M_{P1} + \varepsilon_{P1} + B_{MP1} \quad (1)$$

$$MP2 = P_2 - \left(\frac{2\alpha}{\propto -1}\right) L_1 + \left(\frac{2\alpha}{\propto -1} - 1\right) L_2 \approx M_{P2} + \varepsilon_{P2} + B_{MP1} \quad (2)$$

where $M_{P1}, M_{P2}, \varepsilon_{P1}, \varepsilon_{P2}$ correspond to multipath and noise at P_1, P_2 data whereas B_{MP1}, B_{MP2} are constant factors related to ambiguity terms in phase measurements and delay biases. As we can read from equations 1 and 2, the selection of multipliers for phase measurements (including frequency coefficient $\alpha = f_1^2/f_2^2$) allows eliminating all variable unknowns except the combined impact of multipath and noise at code data. At this point, it is usually assumed that noise in phase measurements is at least two orders lower and thus can be negligible. Considering the appropriate frequencies, the presented above equations allow the determination of multipath combinations for the remaining code data as well. As Wanninger and Beer (2015) reported, such prepared times series may be affected by long-term variations. To remove this effect, we used third-order polynomial fitting. Finally, a standard deviation of such detrended data was used to characterize the stochastic properties of measured pseudoranges. This computation was performed for all satellite arcs, and its average was used as a final indicator for code data. Due to the dependence of pseudorange noise on elevation and its significant growth at low angles, the final characteristics were computed for elevation higher than 45°.

As mentioned above, the noise of phase data has a very small amplitude. Thus, its evaluation requires eliminating all other factors occurring in phase observations. In our case, we used the most common approach for such analyses, i.e., we connect the homogenous receivers to the same antenna through a signal splitter and create a so-called zero-baseline. In this case, the generation of double-differenced observations eliminates all factors related to the uncertainty of clocks and delays in atmospheric layers. Consequently, all variations in such prepared time series should be considered as phase noise. It should be noted that the results from the zero-baseline solution underestimate the phase noise occurring in real conditions. This is related to the mitigation of all antenna impact and phase multipath. Considering double-differenced data, the observed noise is basically a superposition of this affecting two satellites at different elevations. To provide homogenous results, we computed the standard deviation of phase noise only for DD observations with a similar elevation. The same as for code data, the final indicator is an average value derived from all processed arcs.

3. RESULTS

The experiment consisted of two parts aimed at evaluating pseudorange and phase noise, respectively. Specifically, the main goal was to compare the performance of different low-cost receivers with regard to a high-grade geodetic one. For this purpose, we provide an example time series for selected satellite(s) and a final statistical summary.

3.1. Pseudorange noise

Figure 1 presents example variations of multipath combination. It demonstrates the results obtained for all receivers at code signal C1C using measurements from satellites GPS 14 and 15. The first part (Figure 1a, left panel) depicts time series that corresponded to utilization of geodetic antenna TRM59800.00 NONE. In contrast, the right panel (Figure 1b) provides the equivalent results for patch antenna UBLOX ANN-MB.

Looking at example results, we see noticeable differences for utilized receivers. Interestingly, the lowest dispersion is observed for two low-cost devices: SEPTENTRIO MOSAIC-X5 and UBLOX ZED-F9P. In both these cases, the standard deviation for entire arcs does not exceed 0.2m. The characteristic obtained for geodetic receiver TRIMBLE ALLOY is slightly worse (~0.25m). We observe the very poor quality for SKYTRAQ where the deviation of pseudoranges is close to 1 m. What also transpires from the left panel, the application of high-grade geodetic antenna in most cases prevents significant noise growth at low elevations. Only for SKYTRAQ receiver we observe dramatic degradation of code data that for selected epochs exceed 4 meters. Nevertheless, the presented example proves that for the elevation angle above 45° the noise is relatively stable; thus, it justifies the application of such threshold for further analysis. Considering the results obtained for low-cost antenna (UBLOX ANN-MB), we observe a noticeable noise growth that is predominantly visible at low elevations. Analyzing the entire arcs, the corresponding standard deviations are equal to 0.35m, 0.31m, 0,32m, and 1.86m for SEPTENTRIO, TRIMBLE, UBLOX, and SKYTRAQ, respectively. Comparing the results for both antennas, we see that the patch antenna degrades to a less extent the observations of the geodetic receiver. The strongest impact of antenna change is observed for SKYTRAQ receiver.

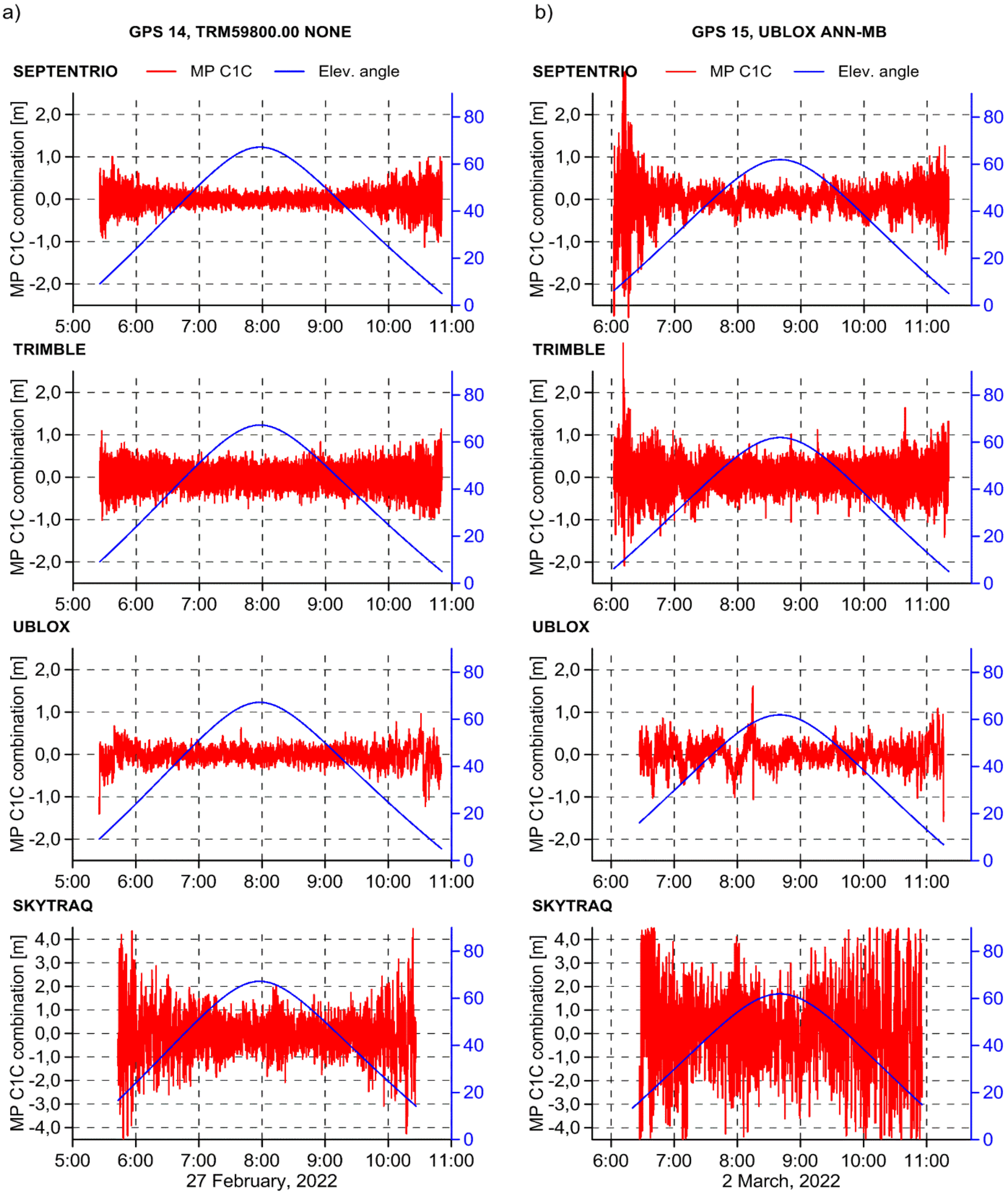

Fig. 1 The example variations of multipath combination for C1C data.

Table 1 The standard deviation of multipath combinations for SEPTENTRIO MOSAIC-X5 [units – m].

GPS	C1C	C1W	C2W	C2L	C5Q
TRM59800.00	0.09	0.09	0.07	0.09	0.04
UBLOX ANN-MB	0.17	0.17	0.32	0.30	0.18
Glonass	**C1C**	**C2P**	**C2C**	**C3Q**	
TRM59800.00	0.19	0.08	0.11	0.04	
UBLOX ANN-MB	0.32	0.31	0.36	0.20	
Galileo	**C1C**	**C5Q**	**C7Q**	**C8Q**	
TRM59800.00	0.06	0.04	0.04	0.03	
UBLOX ANN-MB	0.14	0.16	0.18	0.13	
BDS (MEO)	**C1P**	**C2I**	**C5P**	**C6I**	**C7I**
TRM59800.00	0.07	0.11	0.04	0.04	0.08
UBLOX ANN-MB	0.17	0.26	0.16	0.16	0.24

Table 2 The standard deviation of multipath combinations for TRIMBLE ALLOY [units – m].

GPS	C1C	C1X	C2W	C2X	C5X
TRM59800.00	0.16	0.10	0.09	0.15	0.06
UBLOX ANN-MB	0.23	0.22	0.35	0.38	0.27
Glonass	**C1C**	**C1P**	**C2C**	**C3X**	
TRM59800.00	0.25	0.14	0.26	0.08	
UBLOX ANN-MB	0.37	0.28	0.60	0.31	
Galileo	**C1X**	**C5X**	**C6X**	**C7X**	**C8X**
TRM59800.00	0.09	0.06	0.09	0.07	0.06
UBLOX ANN-MB	0.19	0.27	0.28	0.28	0.17
BDS (MEO)	**C2I**	**C6I**	**C7I**		
TRM59800.00	0.10	0.05	0.08		
UBLOX ANN-MB	0.17	0.20	0.25		

Table 1 presents the summary of results for all available signals and systems available in SEPTENTRIO receiver. Before analyzing the results, it should be noted that this low-cost device is the only one that can fully benefit from multi signals transmitted by particular systems. Furthermore, according to Table 1, the code observations of this instrument are characterized by the lowest noise. In most cases, the standard deviation is below 0.1 m. Considering the new signals, such as C3Q for Glonass or all Galileo data, the accuracy is even twice as good. What can also be read from the table, the level of degradation caused by the application of UBLOX ANN-MB significantly depends on the system and signal. Nevertheless, the characteristics between 0.13 – 0.36 m obtained for the SEPTENTRIO receiver should be considered satisfying.

Table 3 The standard deviation of multipath combinations for UBLOX ZED-F9P [units – m].

GPS	**C1C**	**C2L**
TRM59800.00	0.12	0.11
UBLOX ANN-MB	0.23	0.33
Glonass	**C1C**	**C2C**
TRM59800.00	0.15	0.13
UBLOX ANN-MB	0.28	0.35
Galileo	**C1C**	**C7Q**
TRM59800.00	0.13	0.06
UBLOX ANN-MB	0.26	0.23
BDS (MEO)	**C2I**	**C7I**
TRM59800.00	0.14	0.07
UBLOX ANN-MB	0.24	0.20

Table 4 The standard deviation of multipath combinations for SKYTRAQ [units – m].

GPS	**C1C**	**C2L**
TRM59800.00	0.56	0.54
UBLOX ANN-MB	1.30	1.92
Glonass	**C1C**	**C2C**
TRM59800.00	0.75	0.75
UBLOX ANN-MB	1.66	2.15
Galileo	**C1C**	**C7Q**
TRM59800.00	0.71	0.09
UBLOX ANN-MB	1.05	0.25
BDS (MEO)	**C2I**	**C7I**
TRM59800.00	0.19	0.19
UBLOX ANN-MB	0.75	0.60

The results for TRIMBLE and UBLOX receivers are at a similar accuracy level (Tables 2 and 3). The characteristics for GPS and Glonass are mostly in the range of 0.1 and 0.2 m. The results are slightly better for the newest systems (BDS, Galileo) (0.06 - 0.09 m). In the case of the TRIMBLE receiver, the same improvement one can observe for new signals of GPS and Glonass. Considering UBLOX and TRIMBLE receivers, the antenna exchange results in a similar degradation to a few tenths of meters. The only exception is the C2C signal recorded by TRIMBLE, where the dispersion equals to 0.6 m.

The summary given in Table 4 confirms the conclusion from the analysis of Figure 1. The quality of SKYTRAQ code data is the worst. In the case of GPS and Glonass, the standard deviations exceed 0.5 m, and after replacing the antenna, it even goes beyond 2 meters (C2C Glonass signal). Interestingly, the results for Galileo and BDS are significantly better. In the case of C7Q signal, the obtained values are comparable to those observed for TRIMBLE and UBLOX. The characteristics for BDS are worse than for C7Q but still outperform these observed for GPS and Glonass.

3.2. Phase noise

The second part demonstrates the equivalent results for DD phase data. The same as for code data we start with providing an example time series for a single arc (Figure 2). For this purpose we use differential data of L1C signal between GPS satellites 10 and 27. To clarify view, the obtained results are overplotted with corresponding variations of elevation angles.

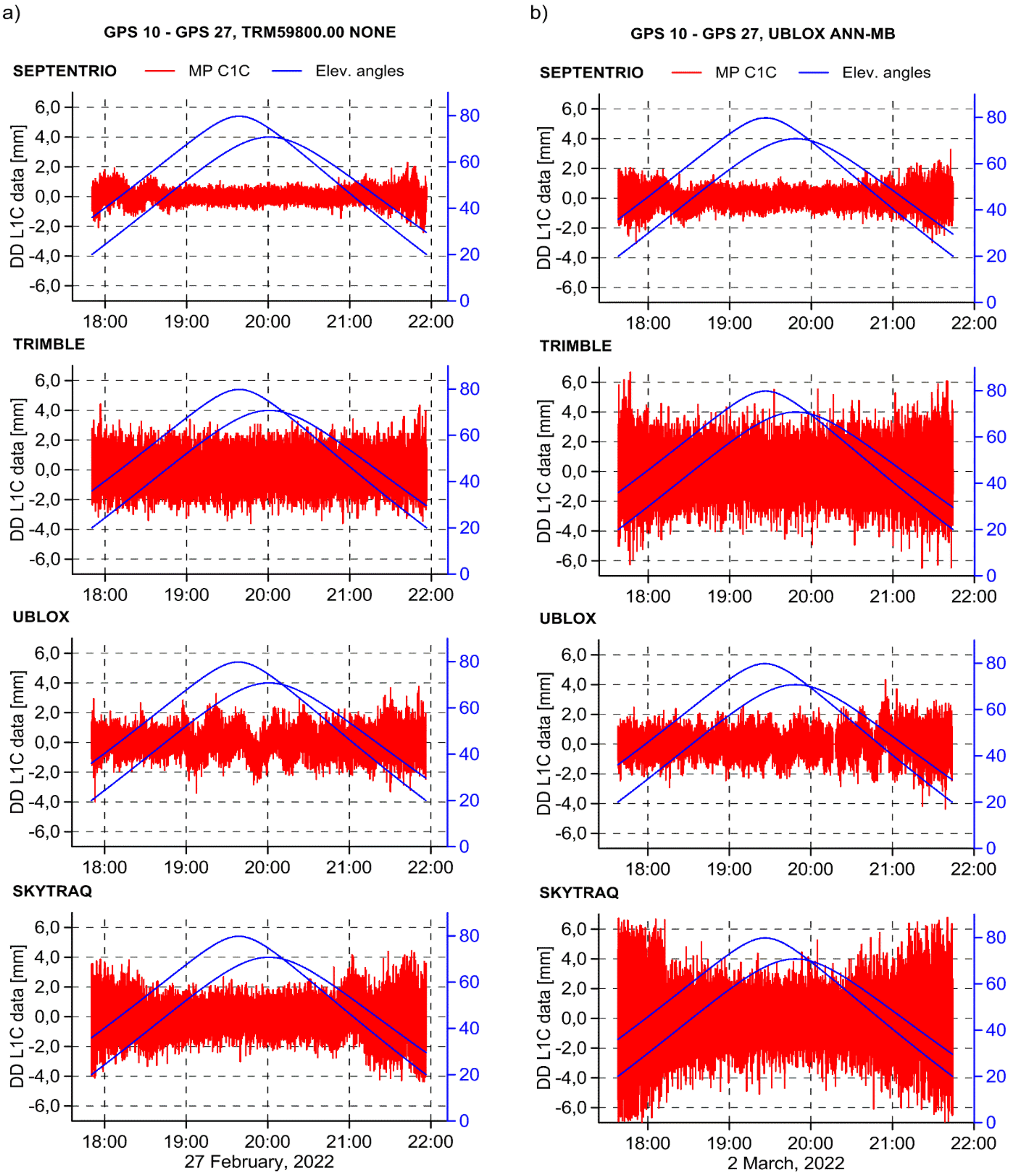

Fig. 2 The example variations of zero-baseline double-differential L1C data.

The demonstrated examples should be considered as at least a bit unexpected. First of all, a very low dispersion observed for SEPTENTRIO confirms that devices of this manufacturer are of very good quality. We find the performance of low-cost MOSAIC-X5, with a standard deviation slightly exceeding 0.4 mm for TRIMBLE antenna, as very high. On the other hand, the remaining tested low-cost receivers also outeperform the high-end geodetic instrument. In the presented example the standard deviations equal to 0.8 mm, 1.0 mm and 1.1 mm for UBLOX, SKYTRAQ and TRIMBLE respectively. It basically proves that phase data derived from low-cost receivers predestine them to high-precision applications as well. Neverthless, comparing the presented in Figure 2 time series, we can observe a longer-term oscillations that are particularly clear for UBLOX. They are similar to a phase multipath effect but this factor cannot occur for zero-baseline differential data. Another possible exaplnation of such oscillations is an implementation of some smoothing algorithms. This could explain a very low phase noise for low-cost receivers, but to be more precise comprehensive investigations of this issue are needed.

The exchange of antenna decreases the quality of phase data, what confirms the time series given in the right panel of Figure 2. This effect, however, strongly depends on reciver. The lowest degradation (~0.2 mm) is observed for SEPTENTRIO and UBLOX, whereas the strongest for SKYTRAQ. In the latter case the standard deviation for the entire arc dropped to 2.0 mm, but such poor quality is related to high growth of phase noise for low-elevated data. On the other hand, it should be noted that for UBLOX there are no noticeable changes in double differenced residuals.

Table 5 The standard deviation of DD phase data for SEPTENTRIO MOSAIC-X5 [units – mm].

GPS	**L1C**	**L2W**	**L2L**	**L5Q**	
TRM59800.00	0.4	0.4	0.6	0.4	
UBLOX ANN-MB	0.8	0.9	1.1	1.1	
Glonass	**L1C**	**L2P**	**L2C**		
TRM59800.00	0.8	0.6	0.8		
UBLOX ANN-MB	1.1	1.4	1.9		
Galileo	**L1C**	**L5Q**	**L7Q**	**L8Q**	
TRM59800.00	0.4	0.5	0.5	0.4	
UBLOX ANN-MB	0.7	1.6	0.8	0.8	
BDS (MEO)	**L1P**	**L2I**	**L5P**	**L6I**	**L7I**
TRM59800.00	0.4	0.4	0.4	0.4	0.5
UBLOX ANN-MB	0.6	0.7	1.4	1.2	0.7

Table 6 The standard deviation of DD phase data for TRIMBLE ALLOY [units – mm].

GPS	**L1C**	**L1X**	**L2W**	**L2X**	**L5X**
TRM59800.00	1.1	1.1	1.4	1.3	1.3
UBLOX ANN-MB	1.5	1.6	2.7	2.0	2.4
Glonass	**L1C**	**L1P**	**L2C**		
TRM59800.00	1.3	1.4	1.4		
UBLOX ANN-MB	2.1	2.1	2.9		
Galileo	**L1X**	**L5X**	**L6X**	**L7X**	
TRM59800.00	1.0	1.3	1.2	1.3	
UBLOX ANN-MB	1.4	3.3	1.8	2.1	
BDS (MEO)	**L2I**	**L6I**	**L7I**		
TRM59800.00	1.0	1.2	1.3		
UBLOX ANN-MB	2.4	2.6	3.0		

Table 7 The standard deviation of DD phase data for UBLOX ZED-F9P [units – mm].

GPS	**L1C**	**L2X**
TRM59800.00	0.7	0.8
UBLOX ANN-MB	0.9	1.3
Glonass	**L1C**	**L2C**
TRM59800.00	0.6	0.7
UBLOX ANN-MB	1.1	1.8
Galileo	**L1X**	**L7X**
TRM59800.00	0.7	0.7
UBLOX ANN-MB	0.7	0.9
BDS (MEO)	**L2I**	**L7I**
TRM59800.00	0.4	0.7
UBLOX ANN-MB	0.9	0.8

Table 8: The standard deviation of DD phase data for SKYTRAQ [units – mm].

GPS	**L1C**	**L2L**
TRM59800.00	1.5	1.2
UBLOX ANN-MB	2.5	3.3
Glonass	**L1C**	**L2C**
TRM59800.00	1.8	2.2
UBLOX ANN-MB	3.6	3.9
Galileo	**L1C**	**L7Q**
TRM59800.00	6.1	1.7
UBLOX ANN-MB	7.2	3.5
BDS (MEO)	**L2I**	**L7I**
TRM59800.00	1.3	1.0
UBLOX ANN-MB	3.3	1.8

The tables 5-8 provide a summary of statistics for DD phase measurements. The overall results for SEPTENTRIO receiver (Table 5) are consistent with those given in Figure 2. Considering sessions with TRIMBLE antenna the obtained standard deviations are mostly in the range of 0.4 – 0.5 mm. The only exception, in this case, is noise for Glonass measurements characterized by values 0.6 – 0.8 mm. After replacing the anetenna we can observe two/threefold increase in dispersion. Excluding GPS system, the characteristics obtained for the UBLOX ANN-MB antenna are much more variable between signals. Such effect is the most pronounced for Galileo and BDS satellites. For example, the noise for Galileo L1C equals to 0.7 mm, whereas at L5Q reaches even 1.6 mm.

The phase measurements from TRIMBLE ALLOY (Table 6) are characterized by a much higher noise than SEPTENTRIO. Analyzing the results for TRIMBLE antenna the corresponding values of standard deviation vary between 1.0 mm and 1.4 mm and are comparable between particular signals. For low-cost UBLOX antenna we observe the same effect as in the case of SEPTENTRIO, i.e. a significant disproportion between obtained characteristics. For this session, they range between 1.4 mm and 3.3 mm. Comparing these results with phase data derived from low-cost receivers, it should be remarked for TRIMBLE the clock was steered by the receiver, whereas for the remaining devices was synchronized to GPS.

The statistics for UBLOX (Table 7) outperforms TRIMBLE and are slightly worse than for SEPTENTRIO. It is worth noticing that the deterioration of phase data caused by low-cost antenna is in the case the lowest and reaches a few tenth of mm. The quality of SKYTRAQ measurements is definitely the poorest (Table 8). The obtained characteristics are in the range of 1.0 – 6.1 mm and 1.8 – 7.2 mm for geodetic and patch antenna, respectively. Particularly high dispersion we detect for Galileo L1C signal.

4. CONCLUSIONS

The study was devoted to an assessment of code and phase measurement noise affecting data recorded by low-cost receivers as well as a comparison with that of geodetic receiver. The analysis indicated that observations from SEPTENTRIO MOSAIC-X5 and UBLOX ZED-F9P are of very good quality, and there is no doubt they can be used in precise positioning and applications. According to the initial analysis, the former significantly outperforms the reference geodetic receiver in the precision of the GNSS observations. The last tested device - SKYTRAQ - has a much worse quality of observations. This is particularly true with regard to code pseudoranges.

The performed tests based on two different grades of antennas showed significant growth of noise for the low-cost one. Nevertheless, our results also revealed that such antennas can still be used in precise applications.

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BIOGRAPHICAL NOTES

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