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Detailed assessment of GNSS observation noise based using zero baseline data

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Abstract

In this research, the GNSS observation noise is assessed in details based on zero baseline data. The 24-hour observations are collected from two CORS stations of Curtin University (32.0° S, 115.9° E) on February 8, 2017. The code and carrier phase observation noise is assessed in details for every system of GPS, GLONASS, BeiDou, Galileo, SBAS and QZSS and for every measurement type and every satellite. In addition, the observation noise by two different kinds of receiver is also assessed and compared. From the numerical results, we find that:

1) Among the six GNSS systems, the code noise of Galileo is the smallest, the noise of all observed Galileo code types are no more than 0.1 m and the noise of C8X is only around 1 cm; the GLONASS code noise is the biggest, the noise of code types C1C and C2C are around 0.25 m;

2) The noise can vary greatly for different code measurement types and there is at least one code measurement type in each system with noise smaller than 0.1 m;

3) For carrier phase, Galileo noise is slightly smaller than the other systems, the noise of all carrier phase types are smaller than 1 mm; GLONASS noise is the biggest, the noise of L2C and L2P are all bigger than 1 mm, some can reach about 1.7 mm;

4) Generally, there is no obvious noise difference for different carrier phase measurement types of each system, except for GLONASS, of which the noise of frequency band L2 is obviously bigger than that of L1;

5) For BeiDou, MEO and IGSO have similar carrier phase noise level, but the noise of GEO is clearly related to elevation angle, with the decrease of elevation angle, the noise will increase;

6) The carrier phase noise of different kinds of receiver may vary greatly, in this research, the numerical results show that the noise of JAVAD receiver are generally much smaller than TRIMBLE.

Key words: GNSS, observation noise, zero baseline, carrier phase, code

1. Introduction

For navigation and positioning, there are various GNSS error sources, such as ionospheric delay, tropospheric delay, orbital error, satellite clock error, receiver clock error, wind-up effect, antenna phase center variation, multipath and noise. Observation noise is the most basic and important error source. How well a GNSS receiver performs – that is, how precisely it can measure the pseudorange and carrier phase – largely depends on how much noise accompanies the signals in the receiver's tracking loops. The more noise, the worse the performance. In addition, with model or by differencing between stations and satellites, other error sources can be eliminated, such as receiver clock error, orbital error, satellite clock error, or mitigated, such as ionospheric delay, tropospheric delay, but it is difficult or impossible to remove or mitigate observation noise. Therefore, for better navigation performance, it is important to assess and investigate observation noise level of various GNSS systems in details.

In past research, a lot of research work has been done on observation noise evaluation (Yang et al., 2017), but most of these work is based on single station (Zhang et al., 2017) or short baseline (Amiri-Simkooei and Tiberius, 2007; Nistor and Buda, 2016; Dmitrieva et al., 2017; Geng et al., 2018), which in fact evaluated the mixture of noise and multipath, as multipath cannot be completely avoided during these research works. Zero baseline analysis method is the most proper for noise assessment, but only limited GNSS systems and signals have been analyzed with zero baseline method in past research (De Bakker et al., 2009; Tiberius et al., 2009; Van der Marel et al., 2009; De Bakker et al., 2012).

In recent years, new GNSS systems have been launched and presently, we can observe satellites of four global GNSS systems, including: GPS, GLONASS, BeiDou and Galileo. In addition, there are other regional or augmentation systems available, especially Satellite Based Augmentation Systems (SBAS), such as QZSS, GAGAN, MSAS. In the future, combined use of multi-system will be becoming more and more important for our practical applications. In addition, there exists the IGS MGEX campaign to provide orbits and clocks in the same reference (Montenbruck et al., 2017). There are nearly one hundred GNSS satellites in the sky currently, and for many of these systems, generally no less than three frequency bands are available and there may be more than one navigation signal for one frequency band. So many available satellites and signals do not mean we should use all of them during the positioning and navigation process. In fact, only part of them is enough. In order to facilitate our selection and use of them, it is necessary to assess their observation noise in details.

In this research, with zero baseline analysis method, a detailed assessment of noise is carried out for every GNSS system, every measurement type and every satellite. First, observation noise of every code measurement type is assessed based on combinations between the code and one carrier phase. Second, observation noise of every carrier phase measurement type is assessed based on double-differenced combinations between stations and satellites. Thirdly, carrier phase noise of every satellite is assessed based on combinations between different carrier phase types. Then, observation noise of two different kinds of receivers is assessed and compared. Finally, conclusions are drawn.

2. Experimental data

In this research, we are trying to assess GNSS noise based on zero baseline data. The experimental data are from the GNSS Research Centre of Curtin University (Global Navigation Satellite Systems Research Centre of Curtin University), Australia (http://saegnss2.curtin.edu.au/ldc/). As shown in Figure 1, on the rooftop of one building, there are four station points with four antennas and each antenna is connected to several GNSS receivers. As shown in Figure 2, the antenna (TRM 59800.00 SCIS) on the point CUT00 is connected to four receivers, two TRIMBLE (station names CUT0 and CUT2), one SEPTENTRIO (station name CUT1) and one JAVAD (station name CUT3). And the antenna (TRM 59800.00 SCIS) on the point CUTB0 is connected to three GNSS receivers, two JAVAD (station names CUBB and CUBJ), and one TRIMBLE (station name CUTB). These CORS stations continuously operate and save GNSS observations as RINEX files with a sample interval of 30 seconds.

A zero baseline can be formed by any two stations connected to same antenna. In this research, two zero baselines are taken advantage of, including CUT0-CUT2 and CUBB-CUBJ. They are formed with same type of receiver, CUT0-CUT2 of TRIMBLE, and CUBB-CUBJ of JAVAD, which can benefit to observation noise evaluation and comparison between different receiver types. But CUT0-CUT2 will be mainly used in this research, as TRIMBLE can observe more measurement types than JAVAD. For example, TRIMBLE can collect observations of six GNSS systems, including GPS, GLONASS, BeiDou, Galileo, QZSS and SBAS, while JAVAD can observe only the first five GNSS systems. TRIMBLE can observe all three frequency bands of BeiDou, while JAVAD can only observe L2I and L7I.

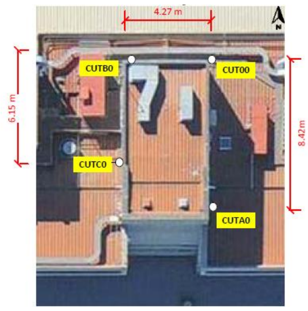

Figure 1 CORS network of Curtin University
(From: http://saegnss2.curtin.edu.au/ldc/CU-GNSS-receivers-setup.pdf)

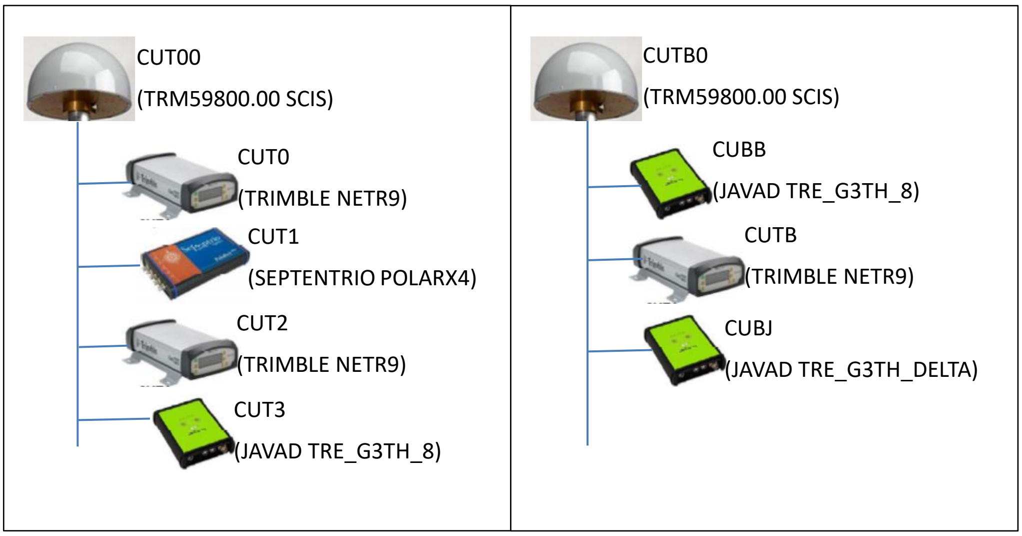

Figure 2 Receivers on station point CUT00 and CUTB0
(Amended from: http://saegnss2.curtin.edu.au/ldc/CU-GNSS-receivers-setup.pdf)

Table 1 is a summary of the observed measurement types of the two zero baselines.

Table 1 Summary of observed measurement types

	code						carrier phase					
GPS	C1C	C1W	C2W	C2X	C5X		L1C	L1W	L2W	L2X	L5X	
GLONASS	C1C	C1P	C2C	C2P			L1C	L1P	L2C	L2P		
BeiDou	C2I	C6I	C7I				L2I	L6I	L7I			
Galileo	C1X	C5X	C7X	C8X			L1X	L5X	L7X	L8X		
QZSS	C1C	C1X	C1Z	C2X	C5X	C6L	L1C	L1X	L1Z	L2X	L5X	L6L
SBAS	C1C	C5I					L1C	L5I				

3. Detailed noise assessment results

In this section, a detailed noise assessment is carrier out based on observations on February 8, 2017. Based on zero baseline CUT0-CUT2, first, code noise of different GNSS systems are assessed and compared, then carrier phase noise is assessed for every measurement type of each system, thirdly, carrier phase noise is assessed for every satellite of each system, and finally, noise of GPS and GLONASS of CUBB-CUBJ is compared to that of CUT0-CUT2. In order to avoid abnormal measurements of low elevation angle as much as possible, a cutoff elevation angle of 20° is used.

1) Code noise assessment

In order to assess code noise, geometry-free combinations are formed by differencing between code and one carrier phase observations (Leick, 2015). As compared to code noise, carrier phase noise is very small, about 1% of code noise (Leick, 2015), so it can be neglected, therefore, the change of these geometry-free combinations over time can reflect the size of code noise. First, the Standard Deviation (SD) of the time-series data of the geometry-free combinations is calculated, denoted as SD_{sd}. Note that the subscript sd represents single-difference, that is, SD_{sd} indicates the size of code noise after differencing between stations. Then, the size of original code observation nosie, denoted as SD_{zd}, can be acquired according to error propagation rules:

$$SD_{zd} = SD_{sd}/\sqrt{2}$$

Figure 3 is SD_{zd} of GPS satellites. From the figure, we can see that C2W has the highest noise level, which are between 0.15 and 0.2 m. C1C noise is the second high, around 0.15 m, C2X noise is slightly smaller than C2W, generally between 0.1 and 0.15 m and C5X noise is the smallest, around 3 cm.

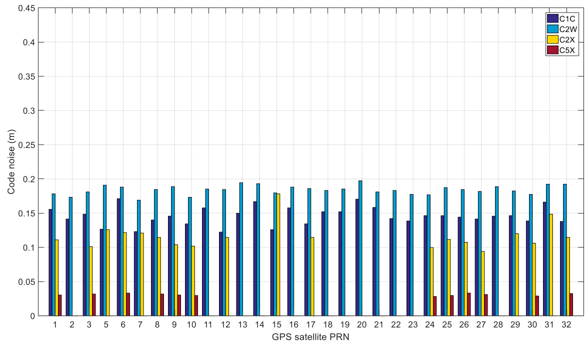

Figure 3 GPS code noise

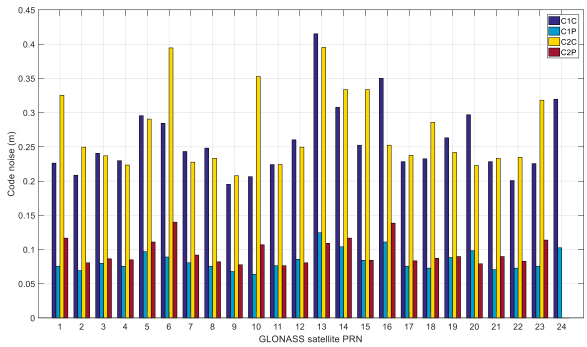

Figure 4 GLONASS code noise

Figure 4 is SD_{zd} of GLONASS satellites. From the figure, we can see that C1C and C2C have a noise level around 0.25 m, much higher than that of C1P and C2P, which are generally between 0.05 and 0.1m.

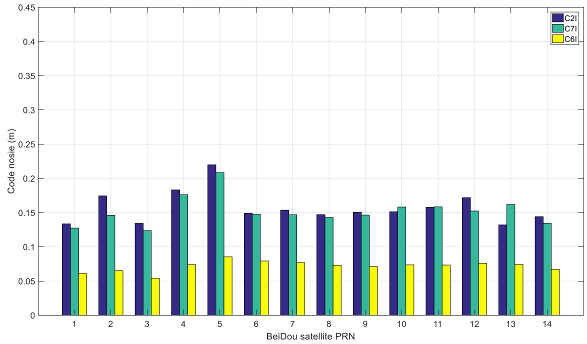

Figure 5 BeiDou code noise

Figure 5 is SD_{zd} of BeiDou satellites. From the figure, we can see that C2I and C7I have similar noise level, generally around 0.15 m, and much higher than that of C6I, which is between 0.05 and 0.1 m.

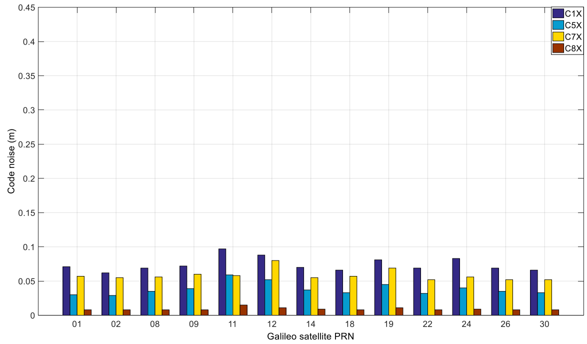

Figure 6 Galileo code noise

Figure 6 is SD_{zd} of Galileo satellites. From the figure, we can see that the noise of all of the four code measurement types is less than 0.1 m. C1X has the highest noise level, around 0.08 m. C7X is the second high, generally between 0.05 and 0.06 m. C5X is the third high, generally around 0.04 m. While C8X noise is the smallest, only around 0.01 m.

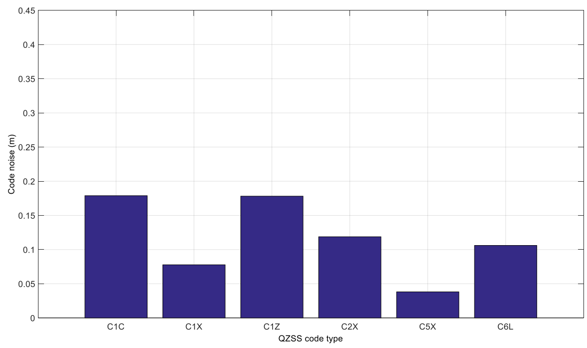

Figure 7 QZSS code noise

Figure 7 is SD_{zd} of QZSS satellite. From the figure, we can see that C1C and C1Z have the higher noise level than the others, about 0.18 m. The noise levels of C2X and C6L are similar, between 0.10 and 0.12 m. C1X noise is about 0.08 m and C5X is the smallest, only about 0.04 m.

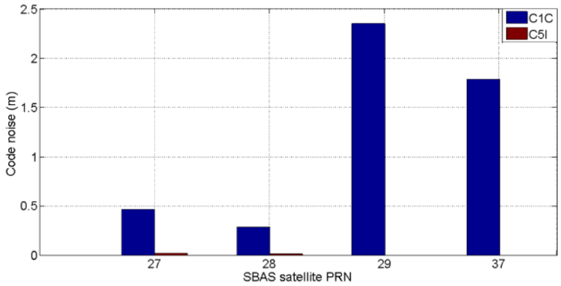

Figure 8 SBAS code noise

Figure 8 is SD_{zd} of the four observed SBAS satellites. From the figure, we can see that C1C noise of Satellites 27 and 28 are about 0.5 and 0.3 m. C5I noise of satellites 27 (GAGAN) and 28 (GAGAN) is only about 0.022 and 0.016 m, much smaller than that of C1C. While C1C noise of SBAS satellites 29 (MSAS) and 37 (MSAS) is abnormally high, about 1.8 and 2.3 m. Figure 9 and 10 show the time-series data of combination C1C-L1C of satellites 29 and 37 and we can see that the observation noise is very big.

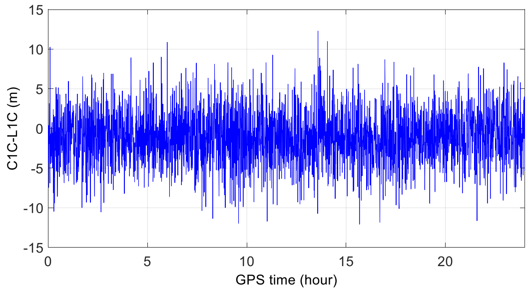

Figure 9 Noise of SBAS satellite PRN 29

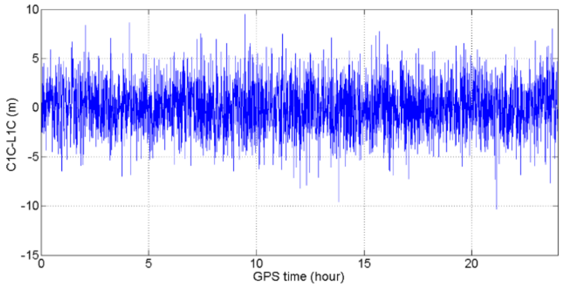

Figure 10 Noise of SBAS satellite PRN 37

From the above figures, we can see that generally, for GPS and GLONASS, the noise of Coarse/Acquisition (C/A) codes is bigger than the others and the noise of C/A code of GLONASS is obviously bigger than that of GPS. The noise of C2X of GPS and C2P of GLONASS are similar, generally between 0.1 m and 0.15 m, while the noise of C2I and C7I of BeiDou are a little bigger, around 0.15 m. The noise of C1P of GLONASS, C6I of BeiDou and C1X of Galileo are similar, generally between 0.05 m and 0.1 m. The noise of C5X of GPS and Galileo are similar, around 0.03 m. Among all code types and all GNSS systems, the noise of C8X of Galileo is the smallest, less than 0.01 m.

By comparing different GNSS systems, we can see that code noise of Galileo system is only several cm and it is the smallest among the four popularly used global GNSS systems and the code noise of GLONASS is generally higher than the others. In addition, the noise can vary greatly for different code types of each system and each system has at least one code type with noise level no more than 0.1 m.

2) noise assessment of every carrier phase type

In the last section, we find that the noise levels are different for different code type. In this section, we want to investigate whether different carrier phase types also have different noise levels. For this purpose, double-differenced carrier phase observations between stations CUT0 & CUT2 and between satellites are taken advantage of. The selection of satellite pairs to form difference considers two factors, first, as many common observations as possible and second, involving all observed satellites.

Similar to code noise assessment, the standard deviation SD_{dd} of double-differenced noise is calculated first, then the original noise level SD_{zd} is acquired according to error propagation rules:

$$SD_{zd} = SD_{dd}/2$$

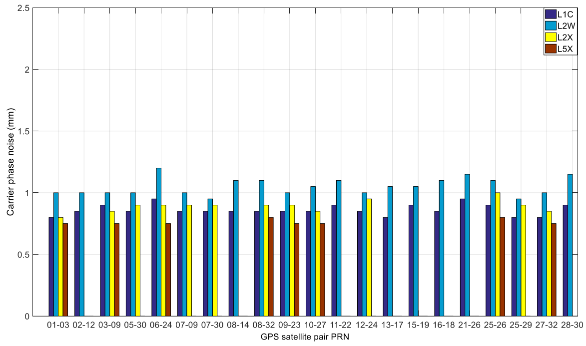

Figure 11 GPS carrier phase noise

Figure 11 shows GPS carrier phase noise SD_{zd} assessed through differencing between different satellites pairs. From the figure, we can see that L2W has the highest noise level, generally between 1 and 1.2 mm, L5X has the smallest, and generally less than 0.8 mm and L1C & L2X are similar, generally between 0.8 and 1 mm.

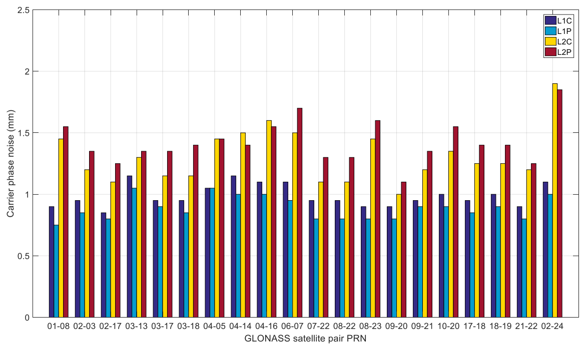

Figure 12 GLONASS carrier phase noise

Figure 12 shows GLONASS carrier phase noise. From the figure, we can see that L2C and L2P have similar noise levels, which range from 1 to 1.7 mm. While L1C and L1P have similar noise levels, which generally between 0.8 mm and 1.0 mm.

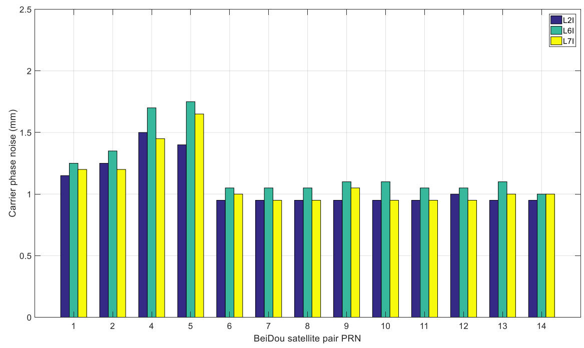

Figure 13 BeiDou carrier phase noise

Figure 13 shows BeiDou carrier phase noise by differencing between satellite with PRN 3 and the others. From the figure, we can see that though L7I noise level is slightly higher than the other two, the noise levels of L2I, L6I and L7I are generally similar, all around 1 mm, except for those of GEO satellites.

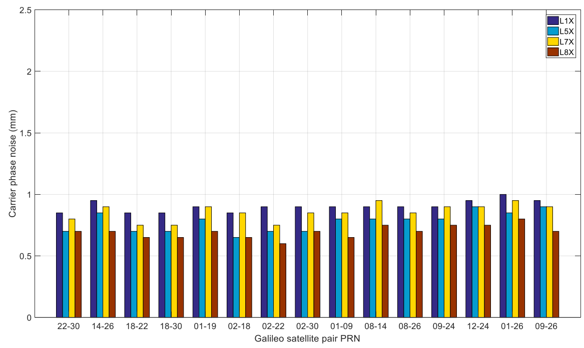

Figure 14 Galileo carrier phase noise

Figure 14 shows Galileo carrier phase noise. From the figure, we can see that L1X and L7X noise is similar, generally between 0.8 and 1.0 mm, slightly bigger than the others. While L8X noise is the smallest, generally between 0.6 and 0.8 mm.

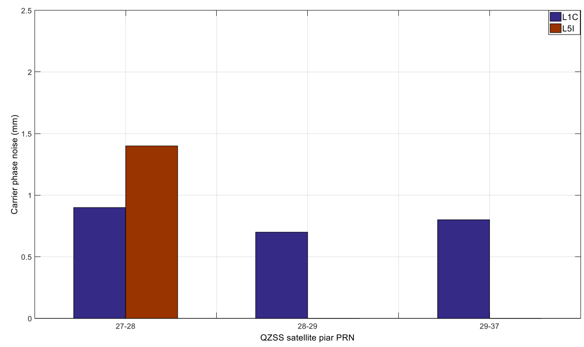

Figure 15 SBAS carrier phase noise

Figure 15 shows SBAS carrier phase noise by differencing between satellites 27-28, 28-29 and 29-37. From the figure, we can see that L1C noise is around 0.8 mm. L5I noise is much higher, about 1.4 mm.

As only one QZSS satellite is observed, its carrier phase measurement type noise is not assessed in this section. From Figures 11 to 14, we can see that generally there is no obvious difference among these four global GNSS systems. Galileo carrier phase noise is only slightly smaller than the others and all of its carrier phase noise is smaller than 1 mm. GLONASS carrier phase noise is slightly bigger and two of the measurement types has noise around 1.2 mm. In each system, generally, there is no obvious difference among all its carrier phase types, especially for BeiDou, but there is one type which has the smallest noise, such as L5X in GPS, L1P in GLONASS, L2I in BeiDou and L8X in Galileo.

3) Carrier phase noise assessment of every satellite

Some GNSS systems has different types of satellites, for example geostationary Earth orbit (GEO) satellite, inclined geosynchronous orbit (IGSO) satellite and medium Earth orbit (MEO) satellite of BeiDou, and different types of satellites may have different carrier phase noise level. And even same type of satellites, as they may have different model, such as IIR and IIF of GPS, so they may also have different carrier phase noise level. Hence, the noise level of all observed satellite is assessed through differencing between different carrier phase types and compared between them. The noise is assessed by forming geometry-free combinations between two carrier phase types. Similar to previous sections, SD of the combination noise, SD_{com} is calculated first, then the SD of the original carrier phase, SD_{zd}, is calculated according to the following error propagation rules:

$$SD_{zd} = SD_{com}/2$$

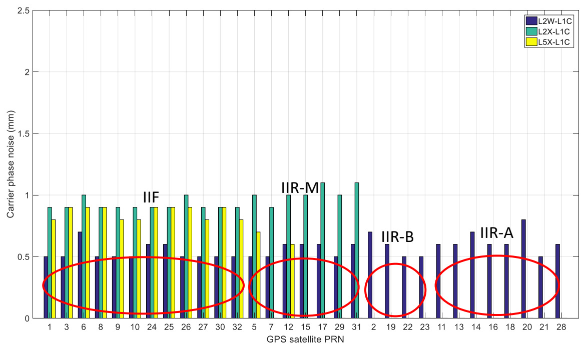

Figure 16 GPS satellite carrier phase noise

Figure 16 shows carrier phase noise of every observed GPS satellite. The twelve ones are IIF satellite, including PRN 1, 3, 6, 8, 9, 10, 24, 25, 26, 27, 30, and 32. Following them are IIR-M, including PRN 5, 7, 12, 15, 17, 29 and 31. Then, PRN 2, 19, 22 and 23 are IIR-B. The last eight ones, PRN 11, 13, 14, 16, 18, 20, 21 and 28, are IIR-A. By comparing the noise of L2W-L1C, we can see that the noise of most of IIF satellites are around 0.5 mm, generally smaller than the other satellites. But for code noise, we cannot see the obvious difference among different GPS satellite types from Figure 3.

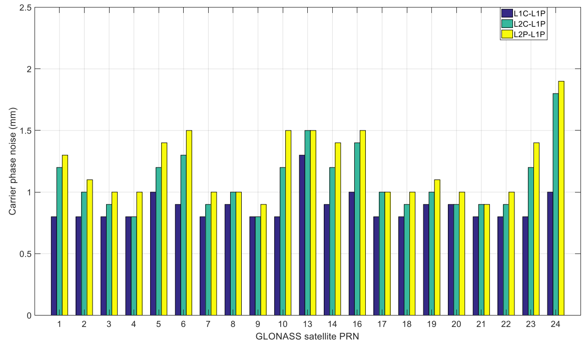

Figure 17 GLONASS satellite carrier phase noise

Figure 17 shows carrier phase noise of every observed GLONASS satellite. All the observed GLONASS satellites are GLONASS_M except that PRN 9 is GLONASS_K1. From the figure, we can see that the noise of L1C-L1P is generally similar and most of them are between 0.8 and 1.0 mm, but the noise of L2C-L1P and L2P-L1P varies greatly.

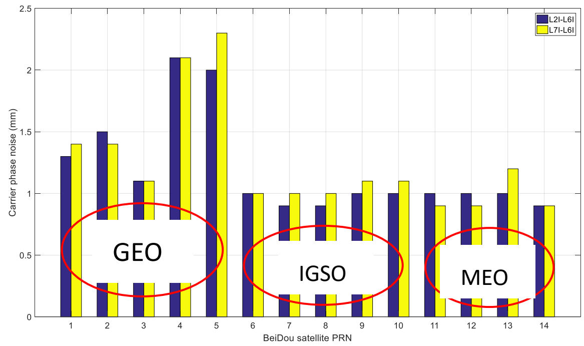

Figure 18 BeiDou satellite carrier phase noise

Figure 18 shows carrier phase noise of every observed BeiDou satellite assessed by differencing L6I and the other types. From Figure 18, we can see that the noise of IGSO and MEO is very similar, generally around 1 mm, but the noise of GEO varies greatly. Table 2 gives the average elevation angle of each GEO. We can see that the noise of GEO is clearly related to elevation angle and the higher the elevation angle, the smaller the noise. PRN 3 has the highest elevation angle and its noise is the smallest among GEO. PRN 4 and 5 have lower elevation angle and their noise is bigger. But for code noise, the difference of GEO, IGSO and MEO is not so obvious from Figure 5.

Table 2 Average elevation angle of GEO

PRN	1	2	3	4	5
average elevation	44.5	39.6	52.3	30.0	19.3

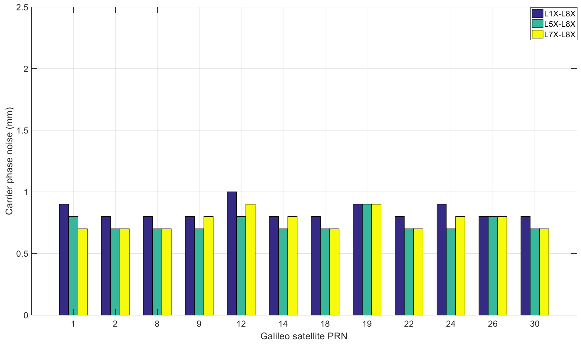

Figure 19 Galileo satellite carrier phase noise

Figure 19 shows carrier phase noise of every observed Galileo satellite assessed by differencing L8X and the other types. From Figure 19, we can see that most noise are between 0.7 and 0.8 mm. Most of the observed satellites are Galileo-2, except that PRN 12 and 19 are Galileo-1, which have slightly bigger noise than the others.

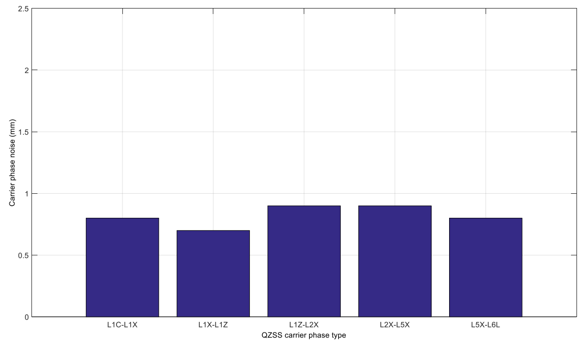

Figure 20 QZSS satellite carrier phase noise

As there is only one observed QZSS satellite, so its noise is assessed in this section. Figure 20 shows the noise assessed by differencing two carrier phase types. From Figure 20, we can see that the noise based on these five combinations is very similar and about 0.8 mm. By comparing to Figure 19, we can find that the noise of QZSS satellite is similar to that of Galileo.

Though past research (Zhang et al., 2017 and Zhang et al., 2018) revealed that differential phase biases (DPB) may have a short-term temporal variations with changes of ambient temperature, from the size of the above noise assessment results, we can see that the results are obviously not affected.

4) Noise assessment with different receiver type

In this section, based on zero baseline CUBB-CUBJ of JAVAD receiver, noise of GPS and GLONASS observations are assessed and compared to that of TRIMBLE receiver. As few satellites of BeiDou and Galileo are observed on station CUBJ, so noise of these two systems are not assessed.

Figure 21 is the assessed GPS code noise of JAVAD receiver. Similar to TRIMBLE case in Figure 3, C5X noise is also the smallest and no more than 5 cm. Noise of the other types is much bigger and is around 0.15 m. Compared to Figure 3, we can see that the noise of C1C, C2W and C5X by JAVAD are generally similar to or slightly worse than by TRIMBLE.

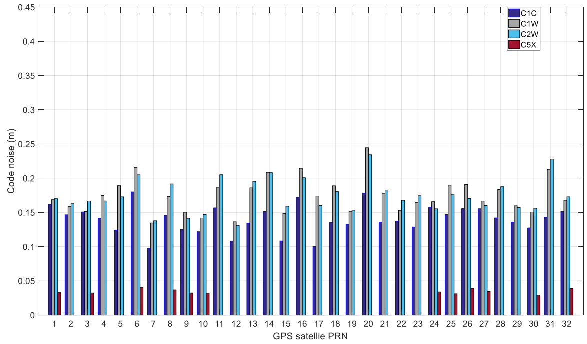

Figure 21 GPS code noise by JAVAD receiver

Figure 22 is the assessed GLONASS code noise. Compared to Figure 4, we can see that the noise of C1C and C1P by JAVAD are obviously better than by TRIMBLE. With JAVAD the noise of C1C is generally less or slightly more than 0.15 m except for PRN 5, 13, 14, 16, 20 and 24, while with TRIMBLE, the noise is generally more than 0.2 m except for PRN 9 and 12. With JAVAD the noise of C1P is generally around 0.05 m, while with TRIMBLE, the noise is generally more than 0.05 m. However the noise of C2P by JAVAD is obviously worse than by TRIMBLE. By JAVAD, the noise of many satellites is around or more than 0.15m, while there is no satellite with noise more than 0.15 m by TRIMBLE, and generally they are less than 0.10 m.

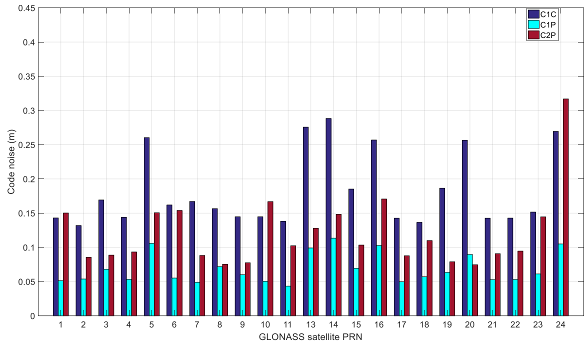

Figure 22 GLONASS code noise by JAVAD receiver

Figure 23 shows the assessed GPS carrier phase noise. Compared to Figure 11 of TRIMBLE receiver, we can see that the noise by JAVAD is obviously smaller than by TRIMBLE. The noise of L1C is generally around 0.2 mm, the noise of L5X is no more than 0.4 mm, and the noise of L2W is the largest, but it is no more than 0.8 mm. Another difference is that the noise of L1C by JAVAD is the smallest, which is much less than the others, while by TRIMBLE, the noise of L5X is the smallest.

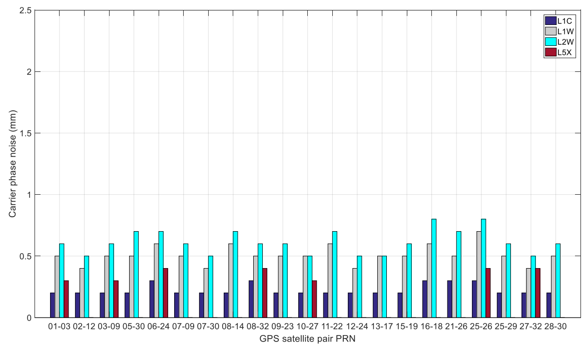

Figure 23 GPS carrier phase noise by JAVAD

Figure 24 shows the assessed GLONASS carrier phase noise. Compared to Figure 12 of TRIMBLE receiver, we can see that the noise by JAVAD is also obviously smaller than by TRIMBLE. The noise of L1C is no more than 0.3 mm, the noise of L1P is no more than 0.4 mm, and the noise of L2P is the largest, but it is no more than 0.6 mm. Another difference is that the noise of L1C by JAVAD is the smallest, which is much less than the others, while by TRIMBLE, the noise of L1P is the smallest.

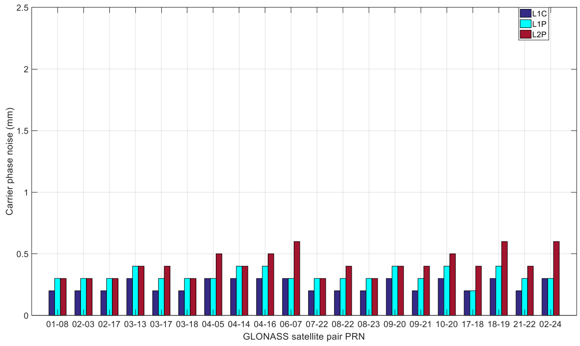

Figure 24 GLONASS carrier phase noise by JAVAD

4. Conclusions

In this research, based zero baseline data, the GNSS observation noise is assessed in details. From these numerical results, we can see that:

1) Among the six GNSS systems, the code noise of Galileo is the smallest, the noise of all observed Galileo code types are no more than 0.1 m and the noise of C8X is only around 1 cm; the GLONASS code noise is the biggest, the noise of code types C1C and C2C are around 0.25 m;

1) The noise can vary greatly for different code measurement types and there is at least one code measurement type in each system with noise smaller than 0.1 m;

2) For carrier phase, Galileo noise is slightly smaller than the other systems, the noise of all carrier phase types are smaller than 1 mm; GLONASS noise is the biggest, the noise of L2C and L2P are all bigger than 1 mm, some can reach about 1.7 mm;

3) Generally, there is no obvious difference for different carrier phase measurement types of each system, except for GLONASS, of which the noise of frequency band L2 is obviously bigger than that of L1;

4) For BeiDou, MEO and IGSO have similar carrier phase noise level, but the noise of GEO is clearly related to elevation angle, with the decrease of elevation angle, the noise will increase;

5) The carrier phase noise of different kinds of receiver may vary greatly. Numerical results show that though the code noise of JAVAD and TRIMBLE receivers are similar, the carrier phase noise of JAVAD are generally much smaller than TRIMBLE.

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