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Development of a Pseudo Quasi Zenith Satellite and Multipath Analysis Using an Airborne platform

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Abstract. Japan has been developing a new satellite based positioning system called Quasi-Zenith Satellite System (QZSS). Since improvement of positioning availability in urban area is one of the most important advantages of the QZSS, multipath mitigation is a key factor for the QZSS positioning system. Therefore, Japan Aerospace Exploration Agency (JAXA) and GNSS Inc. developed a pseudolite, which transmits the next-generation signal such as BOC(1,1), in order to evaluate the effect of multipath on the new signal. Flight experiments using a pseudo quasi-zenith satellite installed on a helicopter were conducted, and multipath mitigation by the BOC signal was demonstrated.

Keywords: QZSS, Pseudolite, BOC, Multipath, Helicopter

1 Introduction

Japan has been investigating a new satellite based positioning system, QZSS. The service area is limited to Japan and nearby countries since the QZSS consists of Quasi-Zenith satellites and geostationary satellites. The orbit of QZS is designed so that the users in Japan can observe the satellite at nearly zenith angle. Therefore, the QZSS is expected to enhance the availability of positioning in urban/mountainous area (Kishimoto et al., 2007). The signal design of QZSS is under investigations, however, a compatible signal with GALILEO and modernized GPS would be most appropriate. The purpose of this research is to develop a pseudolite which transmits the next-generation signal, such as BOC(1,1), and to demonstrate the performance of multipath mitigation since the BOC(1,1) is supposed to be less susceptible to multipath effect than BPSK(1).

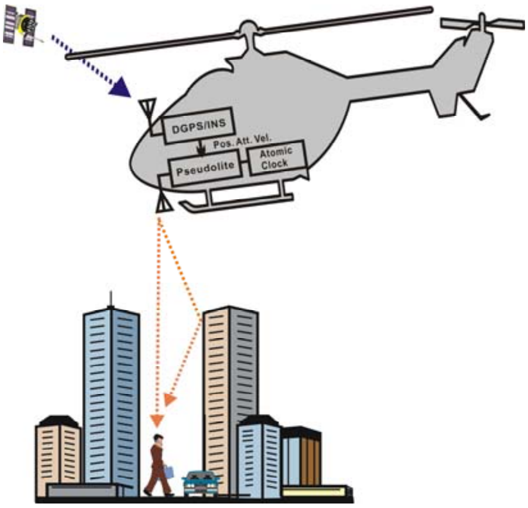

Fig. 1 Image of the Pseudo-QZS flight experiment

The aviation group of JAXA and GNSS Technologies Inc. have been conducting the research of aerial pseudolites for the future airship/UAV-based positioning system, and carried out several flight experiments using a helicopter (Petrovski et al., 2001, Tsujii et al., 2002, 2004). In this research, the helicopter hovering above the users at nearly zenith angle is considered as a Pseudo Quasi-Zenith satellite. Fig. 1 is the conceptual figure of the flight experiment using the Pseudo-QZS.

In 2004, a prototype pseudolite was developed and flight experiments were conducted (Tsujii et al., 2006).

Although the pseudolite signal was similar to GPS, the data rate was changeable up to a thousand bps. As results of experiments, the capability of data modulation up to 1000 bps, the pulsing function, and the ranging precision comparable to GPS were demonstrated. In 2005, a new pseudolite, which transmits BOC(1,1) signal as well as C/A, was developed, and some preliminary tests to verify the function of pseudolite were conducted (Tsujii et al., 2007). Then several flight tests to observe multipath effects on BOC(1,1) and BPSK(1) were conducted, and results are shown in this paper.

2 BOC/CA Pseudolite and Installation

By adding a channel which is modulated by BOC(1,1) to the existing C/A code pseudolite, which was developed in 2004, a BOC/CA two channel pseudolite was developed. Table 1 describes the signal characteristics of the pseudolite. Only modulation type and PRN number are different between two signals. Although real QZS will adopt a specially designed spreading code, C/A code is used for PL1 (BOC) channel since the purpose of this research is to verify the effect of BOC modulation in multipath environment.

Table 1. BOC/CA Pseudolite signal characteristics

Channel	PL1 (BOC)	PL2 (CA)
Center Frequency (MHz)	1575.42	1575.42
Modulation Type	BOC(1,1)	BPSK(1)
Chip Rate (Mcps)	1.023	1.023
Message Rate (bps)	50-1000	50-1000
Code Type	L1 C/A	L1 C/A
PRN	35	33
Code Length (ms)	1	1

All functions of the existing pseudolite, such as the pulsing, high data rate modulation, etc., were equipped. Both BOC(1,1) and C/A were generated based on the same rubidium clock and combined before transmitting. Fig. 3 shows the concept of pseudolite/receiver system. Since the BOC and C/A signal propagate in the same path, the multipath error dependent on the spreading code is expected to be seen.

In order to use the pseudolite measurements for positioning, the position of the pseudolite antenna underneath the helicopter has to be known. Therefore, a DGPS/INS is installed and the position/attitude information of the helicopter is used to compute the pseudolite antenna position (pseudolite ephemeris). Although the navigation message is based on the ICD-GPS-200C, the sub-frame number 6 is used and preamble is modified for the pseudolite. Also, the TOW length is enlarged to 23 bits in order to prevent the TOW count overflow when the data is encoded at 1000bps. Six bits of Word 1 are used as TOW in addition to the 17 bits in Word 2 as shown in Fig. 3. Word 3-10 are the user data which stores the position, velocity of the pseudolite antenna, clock error, and so on.

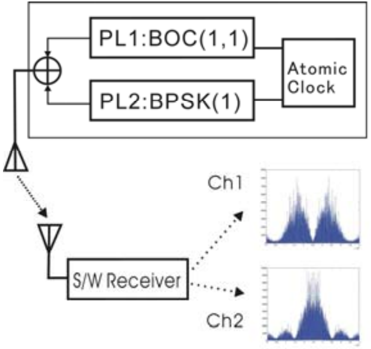

Fig. 2 Two channel pseudolite and S/W receiver

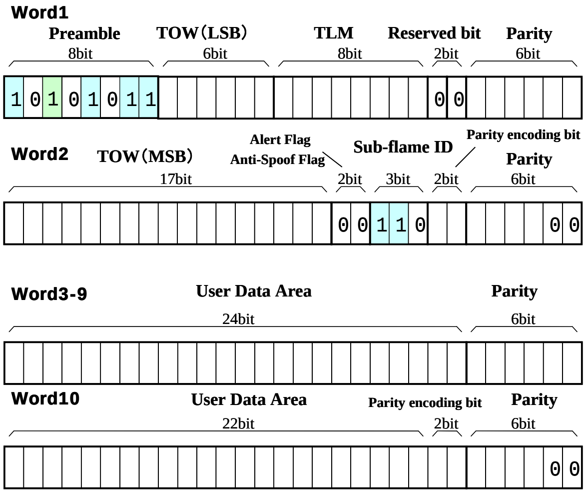

Fig.3 Pseudolite Navigation Message Format

The pseudolite was installed in a cabin of the JAXA's experimental helicopter MuPAL-e (Mitsubishi MH-2000A) as shown in Fig. 4. The pseudolite antenna underneath the helicopter is shown in Fig. 5. A DGPS/INS, which is one of standard equipments of MuPAL-e, was also installed and the position, velocity, atttitude data as well as 1pps/time-tag were sent to the pseudolite. Then pseudolite ephemeris was computed and encoded as navigation message, and sent to ground user. Before conducting the flight experiments, electromagnetic interference tests were carried out and it was demonstrated that the pseudolite signal did not affect the GPS receiver and other equipments of the MuPAL-e.

Fig. 4 JAXA's experimental helicopter MuPAL-e and pseudolite installed in the cabin

Fig. 5 Pseudolite antenna underneath the helicopter

3 Ground tests and results

Prior to the flight tests, several ground tests were conducted at Taiki airfield in Hokkaido, Japan. Test area is shown in Fig. 6. The right building was a hangar of airship, which was 30 meters high, and was used as a signal reflector. The pseudolite antenna was mounted on the roof of the left building, which was 11 meters high, and the signal was transmitted toward the hangar. The signal was received by a rover, which was moved between two buildings and a fixed receiver shown in Fig. 6. The fixed receiver was installed at the area which seemed to be less susceptible to the reflected signal.

Since generic GPS receivers were not able to track the signal of the high data rate pseudolite, NordNav R-30 software receivers were used in the experiment. The software of R-30 receiver was customized to track the pseudolite signal modulated by BOC/CA and high data rate navigation message. There were two sets of receiver systems, which belong to the base and rover station, respectively. The GPS/Pseudolite signal received at the antenna is split to the software receiver and the Ashtech ZXtream receiver. The ZXtream receiver records GPS L1/L2 measurements for reference. The GPS/Pseudolite IF signals digitized by the R-30 receiver were recorded by a PC. The sampling frequency was 13MHz, and the intermediate frequency was 3.07 MHz.

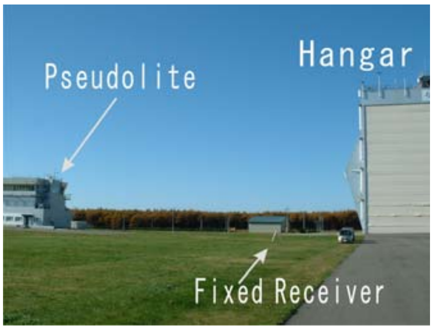

Fig. 6 Ground test configulation

In the off-line analysis, the recorded IF data were replayed by the NordNav receiver, and the pseudorange and carrier phase measurements were obtained. Correlators with 0.63 chip spacing were used to track both BOC and C/A signals.

In order to evaluate multipath effect on pseudorange, the difference between pseudorange and carrier phase (CMC, Code minus Carrier) was computed. Common errors such as pseudolite/receiver clock error and tropospheric error cancels and multipath error and measurement noise remains in CMC. Although the CMC of GPS signal suffers from ionospheric delay, the CMC of pseudolite is not affected by ionospheric delay since pseudolite signal does not propagate in ionosphere. Therefore, multipath error in pseudolite can be evaluated correctly.

Two series of 'Stop & Go' tests were conducted. In the first test, which was denoted as SG1, the rover moved perpendicular to the hangar and stopped for a minute at each of eight points. In the second case, SG2, the rover moved parallel to the hangar and stopped at seven points. Fig. 7 shows trajectory of the rover in both cases, while Fig. 8 shows north and east coordinates of the rover in SG1.

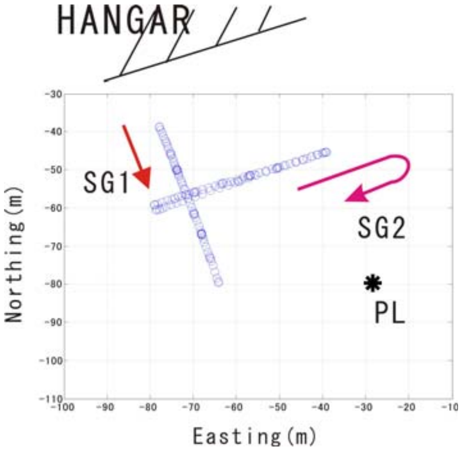

Fig. 7 Trajectory of rover in two test cases (SG1 and SG2)

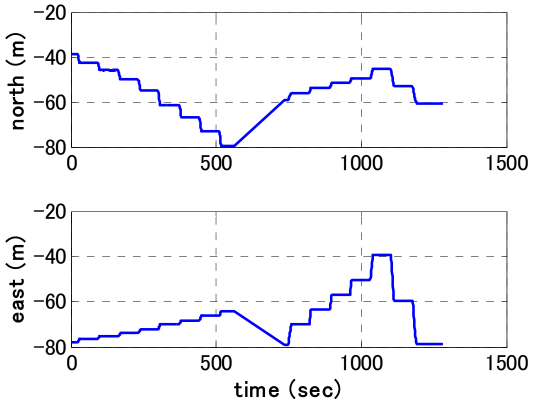

Fig. 8 Coordinates of rover (SG1)

First, the data received at fixed station were analysed in order to evaluate the pseudorange noise since fixed station was located at the area which was less susceptible to the signal reflected by the hangar. Figs. 9 and 10 show the variations of CMC from their averages in SG1 and SG2, respectively. Also, the standard deviations of CMC were given in the figures. Top figure shows the CMC of BPSK(1), while bottom figure shows that of BOC(1,1). The standard deviations of BOC signal were smaller than those of BPSK in both SG1 and SG2. Some trends seen in CMC could be due to the multipath effect caused by moving rover and staff.

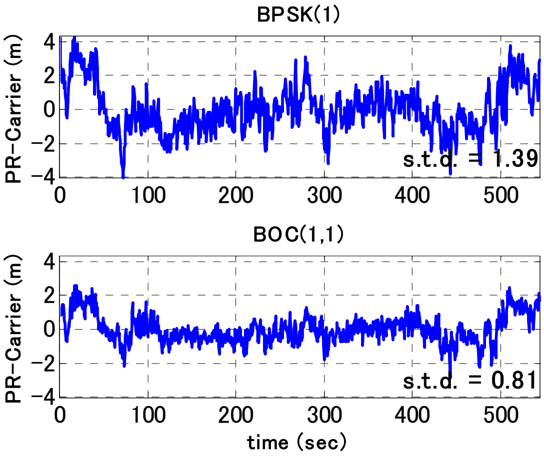

Fig. 9 CMC variation at fixed receiver (SG1)

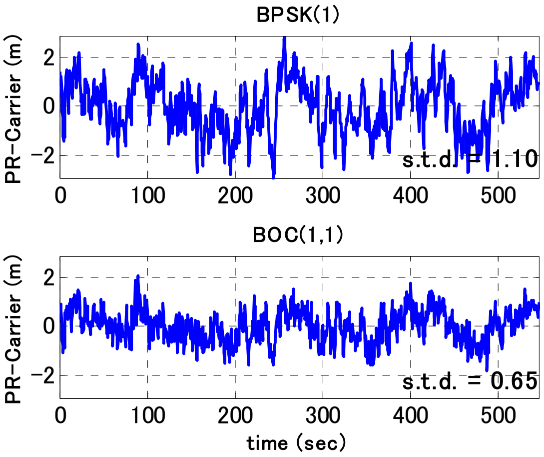

Fig. 10 CMC variation at fixed receiver (SG2)

The theoretical standard deviation of pseudorange noise is given by Eq. 1, since coherent tracking is adopted in the used software receiver.

$$\sigma_{BPSK} = cT_C\sqrt{\frac{d}{4(P_C/N_0)T}} \tag{1}$$

On the other hand, the standard deviation of BOC pseudorange is given by Eq. 2, since slope of correlation function is three times steeper than BPSK.

$$\sigma_{BOC} = cT_C\sqrt{\frac{d}{4(P_C/N_0)T}}\cdot\frac{1}{\sqrt{3}} \tag{2}$$

Chip width (T_c) is common for BOC and BPSK. Though integration time (T) and Correlator spacing (d) are changeable, equivalent values are used for both BPSK and BOC signal tracking. Signal to noise ratio was slightly different between two channels. However, the ratio of standard deviations shown in Figs. 9 and 10 were 1.71 and 1.69, which were close to the theoretical ratio ($\sqrt{3}$).

Next, the multipath effects at the rover receiver were analysed. The variation of CMC in SG1 is depicted in Fig. 11. The changes from initial value are shown in order to avoid large bias due to ambiguity. Since these values were almost constant when the rover stayed at the same location, this figure showed the variation of multipath error. Generally, multipath error was reduced by BOC modulation. Fig. 12 shows carrier to noise ratio of both channels, and strong correlation between C/N_0 and multipath error was observed.

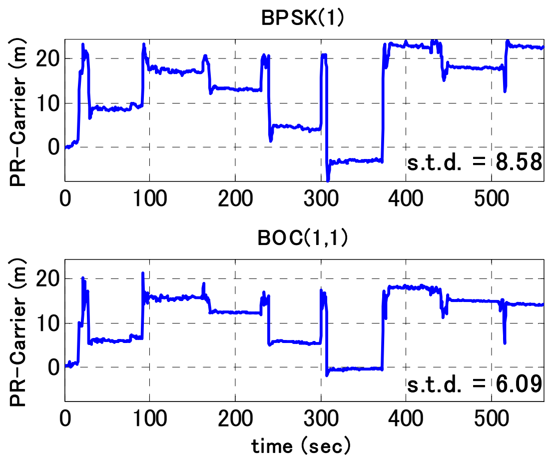

Fig. 11 CMC variation at the rover receiver (SG1)

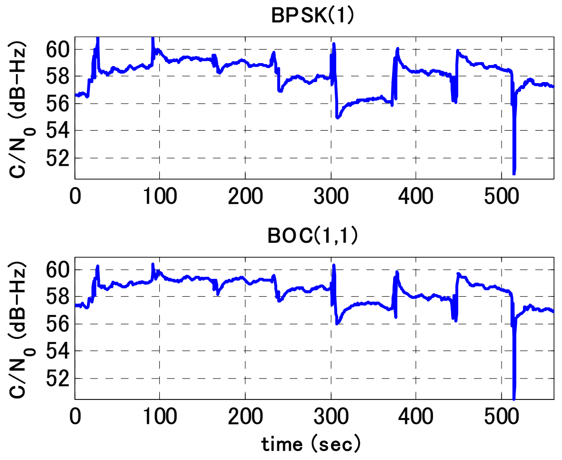

Fig. 12 C/N$_0$ variation at the fixed receiver (SG1)

The variation of CMC in SG2 is shown in Fig. 13. Similar to the case of SG1, multipath error was reduced by using BOC modulation. For example, at the second stop point, which started from time around a hundred, the multipath error was reduced from around 30 meters to 20 meters.

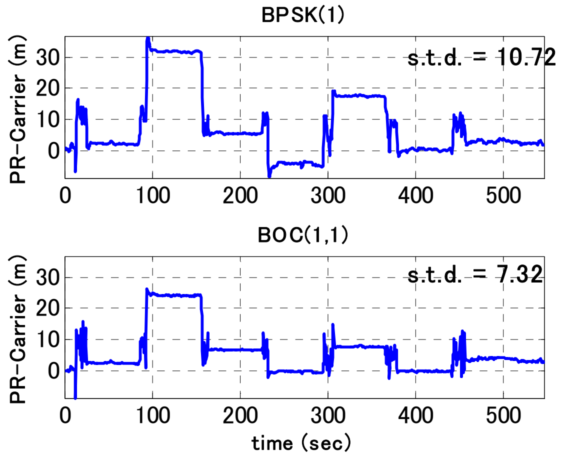

Fig. 13 CMC variation at the rover receiver (SG2)

These results were obtained by processing the IF data which were recorded by the software receiver whose bandwidth was 6 MHz. The correlator spacing was set at 0.63 (chip) in tracking settings. The theoretical multipath envelop was computed with same parameters and shown in Fig.14, where relative amplitude (α) of reflected signal to direct signal was assumed as 0.2. Since radio wave propagation process is complicated, the real values of relative amplitude and propagation delay are difficult to estimate. However, considering the locations of rover and hangar, the delay of reflected signal did not seem to exceed a hundred meters. Therefore, if the relative amplitude was around 0.2, the multipath error indicated by the dotted arrow in Fig. 14 could correspond to the multipath error at the second stop point in SG2.

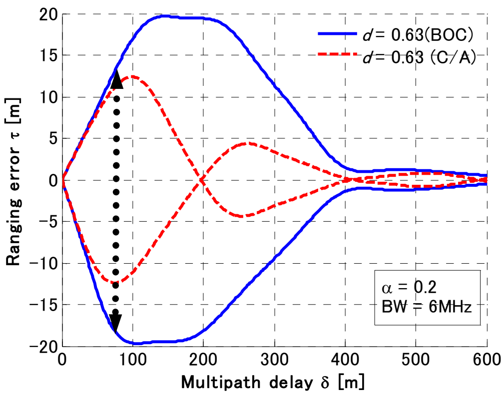

Fig. 14 Multipath envelope (BW=6MHz ,d=0.63chips)

4 Flight tests and results

The flight experiments were conducted at Taiki Airfield, Hokkaido, Japan, in 2006. The helicopter made hovering at the altitude of 1500-2000 ft above the control building as shown in Fig. 15. Base station and rover are also shown in the figure. The large hangar, which was 30 meters high, was used as a reflector and multipath measurement tests were carried out.

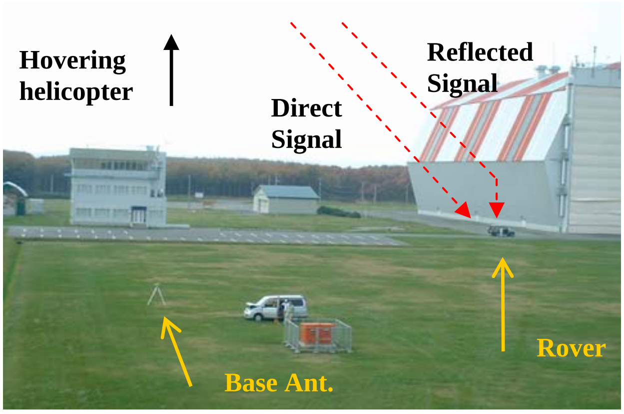

Fig. 15 Configuration of flight experiment

Before starting IF data logging, the pseudolite signal receiving status were verified by monitoring Nordnav software receiver's output. The measured pseudorange, ADR, C/N_0, etc. were shown on the screen of PC. Also, the correlation function of BOC and C/A code were seen in real time. The correlator spacing in tracking loop were 0.63 chips for both BOC and C/A channels. In multipath severe environment, we observed the deformation of correlation function as well as rapid change of C/N_0.

Results of two typical test cases are shown in this paper. Fig. 16 shows the trajectory of rover for case-1 (solid line) and case-2 (asterisk). In case-1, the rover moved in wide area between hangar and control building, while in case-2, the rover moved nearby hangar very slowly.

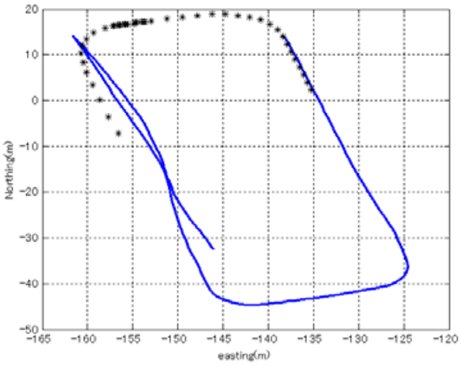

Fig. 16 Rover trajectory in Case-1 (solid line) and Case-2 (asterisk)

Fig. 17 shows the C/N_0 of BOC signal in Case-1 (top) and Case-2 (bottom). It is clearly seen that C/N_0 in Case-2 changed drastically, and therefore the multipath error is likely to change accordingly. Since the rover moved nearby the hangar in Case-2, amplitude of reflected signal seemed large.

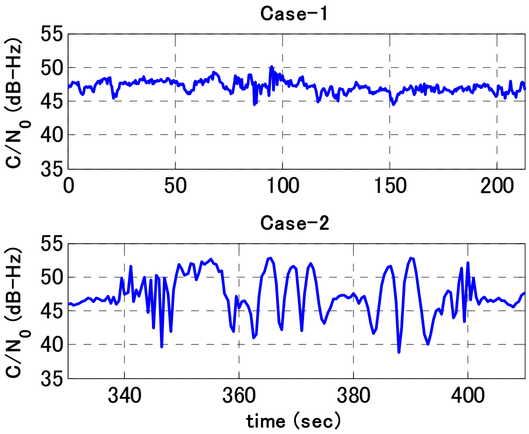

Fig. 17 Variation of C/N_0 in Case-1 (top) and Case-2 (bottom)

Differences between pseudorange and carrier phase for C/A and BOC channel in Case-1 are shown in Fig. 18. The standard deviation were 1.17 (m) for C/A channel and 1.00 (m) for BOC channel. The multipath mitigation by BOC modulation was not as much as ground tests. In the flight tests, the helicopter hovered at almost zenith above receivers, and therefore the delay of reflected signal seemed to be small. As shown in Fig. 14, when multipath delay was small, the errors of BOC and BPSK pseudorange would be similar.

In Case-2, large multipath effects were observed as shown in Fig. 19. Compared with Fig. 17, it is clear that there is a strong correlation between C/N_0 and multipath error. The standard deviation were 10.00 (m) for C/A channel and 9.44 (m) for BOC channel. Although standard deviations were similar, multipath errors at specific period differed considerably. As indicated by red arrows in Fig. 19, amplitude of multipath error was reduced from around 55 meters to 40 meters by BOC modulation.

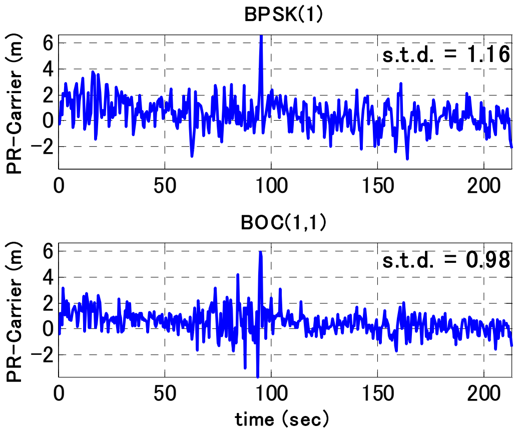

Fig. 18 Difference between pseudorange and carrier phase for C/A (top) and BOC(bottom) channel in case-1

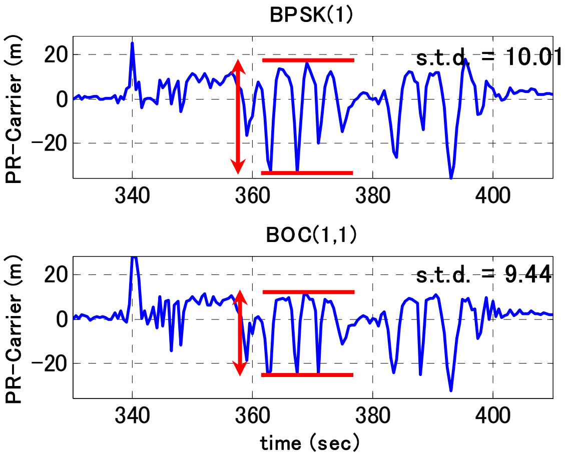

Fig. 19 Difference between pseudorange and carrier phase for C/A (top) and BOC(bottom) channel in case-2

4 Summary

JAXA and GNSS Inc. have been investigating GPS/Pseudolite applications since 2002, and the R&D

project of the Pseudo-QZS was commenced in 2004. The purpose of this project is to evaluate the next-generation GNSS signal in realistic environment using a helicopter-based pseudolite, and to develop a new positioning technology appropriate for the new signal. In succession to the high data rate pseudolite developed in 2004, a BOC/CA two channels pseudolite was developed. Ground and flight tests to measure multipath effect were conducted, and a better performance of BOC modulation on multipath mitigation was demonstrated. Also, the measured multipath error seemed to be consistent with theoretical estimation.

The established airborne pseudolite system can be used to evaluate the propagation effect of any kind of GNSS signal. Also, a new application such as GNSS augmentation is conceivable.

Acknowledgments

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