

A Preliminary Test of the Pseudolite-Based Inverted GPS Positioning in Kinematic Mode

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Abstract. Recently some countries have begun conducting feasibility studies and R&D projects on High Altitude Platforms Systems (HAPS). Japan has been investigating the use of an airship system that will function as a stratospheric platform (altitude of about 20km) for applications such as environmental monitoring, communications and broadcasting. In addition, if pseudolites were mounted on the airships, their GPS-like signals would be stable augmentations that would improve the accuracy, availability, and integrity of GPS-based positioning systems because the airship network would cover all of Japan. The accuracy of the pseudolite positions would be a limiting factor for such a service since the PL 'ephemeris error' is more serious than GPS due to the lower height of the airship. The carrier phase-based inverted GPS method is one of the positioning schemes that could provide the precise 'ephemeris' of the airship. Therefore, a preliminary test of the pseudolite-based inverted-GPS positioning has been conducted in both static and kinematic mode. The static test using pseudolite measurements indicated the potential for high positioning accuracy. The kinematic test suffered from serious multipath error, and therefore it was difficult to obtain high accuracy. However, the tracking performance of the pseudolite signal was highly improved compared with the previous tests, through the use of a different type of GPS receiver.

Key words: Pseudolite, Inverted GPS, Kinematic positioning, Stratospheric platform

1 INTRODUCTION

The transmitters of GPS-like signals, which are called pseudolites (PL), or "pseudo-satellites", have been extensively investigated as additional ranging sources that enhance the performance of GPS (see, e.g., Cobb, 1997). Ground-based GPS augmentation systems using pseudolites have been investigated for several applications, such as vehicle navigation in downtown urban canyons (Altmayer, 1998), positioning in deep open-cut pits and mines (Stone & Powell, 1999), attitude determination (Wang et al., 2000), precision landing of aircraft (Barltrop et al., 1996; Pervan & Parkinson, 1997), and within an integrated

GPS/INS positioning system (Wang et al, 2001). The application of airborne pseudolites was suggested by Raquet et al. (1995). However, their purpose was the positioning of mobile pseudolites installed on military aircraft (Pachter & McKay, 1998), not the augmentation of a navigation/positioning system. Recently feasibility studies and R&D projects have commenced on the use of High Altitude Platforms Systems (HAPS). Although some investigators have suggested the use of HAPS as navigation aids, it is envisaged that their main function would be providing (pseudo-range) DGPS correction data (Dovis et al., 2000), not transmitting extra ranging signals.

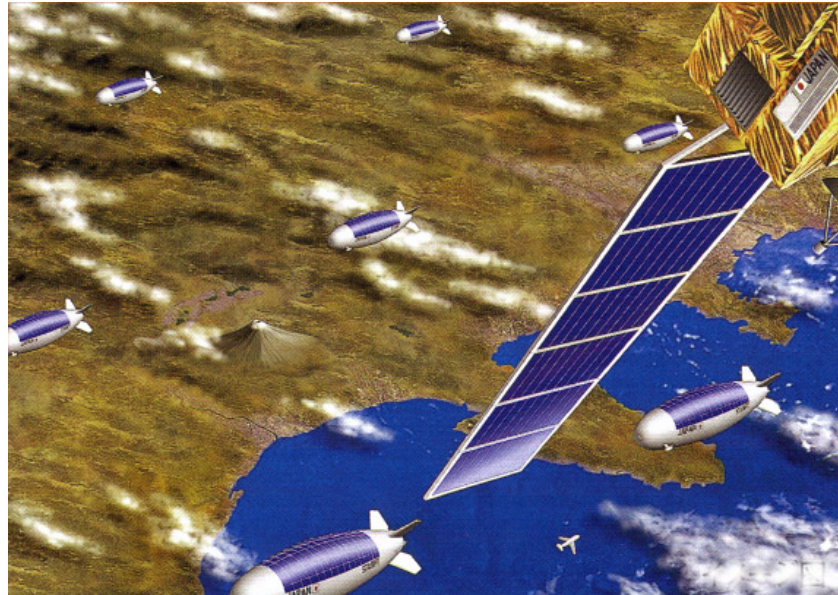


Figure 1. Conceptual image of the stratospheric airship system (Taken from <http://www.nal.go.jp>).

Japan has been investigating an airship system, as illustrated in Figure 1, that will function as a stratospheric platform (SPF) at an altitude of about 20km, for applications such as environmental monitoring, communications and broadcasting (Yokomaku, 2000). Because of the airship's station-keeping characteristics, the SPF can be considered as a signal source for a navigation/positioning service (Figure 2). If pseudolites were mounted on the airships, their GPS-like signals would be stable augmentations that would improve the accuracy, availability, and integrity of GPS-based positioning systems across all of Japan. The concept of an innovative GPS navigation/positioning system augmented by SPF-based pseudolites, referred to here as a GPS/PL system, was suggested by Tsujii et al. (2001). Some tests of PL positioning based on the 'inverted-GPS' concept were conducted in April 2001. A static test of inverted-GPS positioning, where a GPS satellite was used as a reference transmitter, showed excellent positioning accuracy. However, when operated in kinematic mode, the GPS receivers distributed on the ground

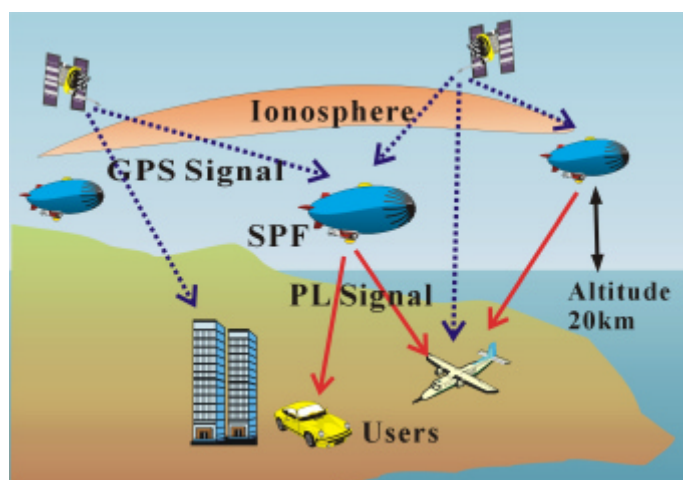


Figure 2. Navigation/positioning service using pseudolites on stratospheric platforms.

had difficulty maintaining lock on the moving pseudolite. In this paper, improved tracking performance using the different type of GPS receiver is demonstrated. Also, the effectiveness of using a helical antenna to mitigate the multipath error is discussed.

2 Inverted-GPS Positioning

The advantages of the GPS/PL system was demonstrated and the results discussed in a previous paper (Tsuji et al., 2001). Since the precise positioning of the PL antenna – to provide the ‘PL ephemeris’ – is one of the most important tasks, some schemes for estimation of the PL position were described. Although the transceiver-based method seems to be the best among the methods, the inverted-GPS experiment was conducted as a preliminary test to identify the potential problems of the proposed GPS/PL system because the required PL transceivers are currently not commercially available.

The system configuration for inverted-GPS is shown in Figure 3. The position of a PL antenna underneath a SPF can be estimated directly by the inverted-GPS method (Raquet et al., 1995), where the ranging information is obtained by a receiver on the ground. In order to perform double-differenced processing an additional transmitter, such as a GPS satellite or a ground-based PL, is required. The use of a GPS satellite would affect the positioning accuracy because ionospheric delay impacts only on GPS signal measurements (not on the PL signal). If a ground-based PL is used as a reference transmitter, this system is referred to as ‘pseudolite-based inverted-GPS’ (Dai et al., 2001) because the ranging data to the GPS satellite are not required for the computation of the position of the mobile PL. In this system, the reference transmitter should be located on a high mountain or a tower to ensure line-of-sight to all ground receivers.

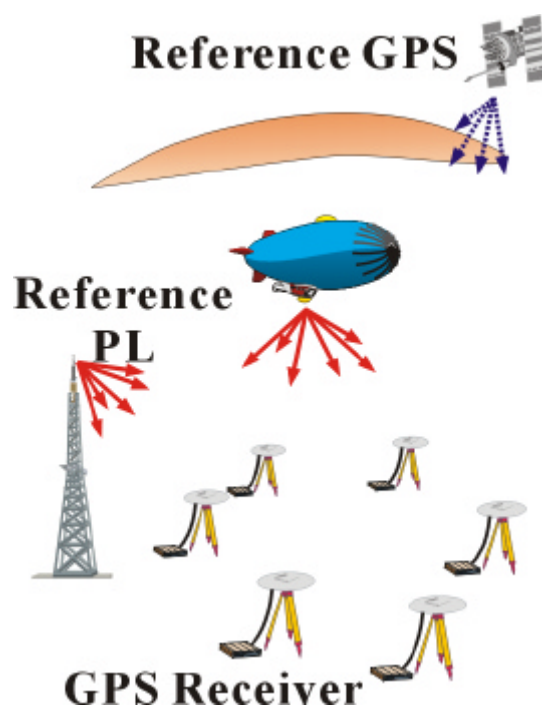


Figure 3. Inverted GPS method.

2.1 Measurement Equations

The measurement equation for the carrier double-differenced observable involving the 1st and i -th receivers, and the airborne and reference transmitters for the GPS/PL system can be written as follows:

$$\nabla\Delta\Phi_{ab}^{li} = \left| \mathbf{X}^1 - \mathbf{X}_a(t_a^1) \right| - \left| \mathbf{X}^i - \mathbf{X}_a(t_a^i) \right| - \left| \mathbf{X}^1 - \mathbf{X}_b(t_b^1) \right| + \left| \mathbf{X}^i - \mathbf{X}_b(t_b^i) \right|, (i=1,2, \dots,n) \quad (1)$$

$$+ \nabla\Delta N_{ab}^{li} + \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta d_{multi} + \nabla\Delta e$$

where \mathbf{X}^i , \mathbf{X}_a , \mathbf{X}_b denote the position vectors of the i -th receiver on the ground (which is static), the airborne transmitter, and the reference transmitter respectively. The t_a^i , t_b^i represent the signal transmit times to the i -th receiver from the airborne and reference transmitters respectively, referenced to each of the transmitter clocks. In the case of GPS positioning, the signal reception time for all the observed satellites is the same. However, in the case of the

inverted-GPS method, the signal transmit time to the receivers, which is analogous with the reception time in conventional GPS, may differ depending on the clock biases of the receivers and the distances between the transmitter and the receivers. These time differences may degrade the PL positioning accuracy because the motion of a PL on a SPF is difficult to predict or monitor (in contrast to GPS satellites). The GPS receivers normally synchronize to GPS time to within 1msec. Assuming that the motion of a SPF is less than 1m/sec, the position change of a PL is less than 1mm ($= 1 \text{ m/sec} \times 1 \text{ m sec}$). Since the distance difference between the PL and the receivers is less than 150km in the example of the proposed Japanese configuration of SPFs (Tsuji et al., 2001), the PL position change is less than 0.5mm ($= 1 \text{ m/sec} \times 150\text{km}/\text{speed of light}$). This effect would have to be investigated further if the station-keeping performance of SPFs were found to be worse. The ionospheric delay term can be neglected if a reference PL is used (instead of a reference GPS satellite), or if GPS transceivers were used.

For the test configuration described below, both the ionospheric and tropospheric delay terms were neglected because of the short distances between receivers. Also, the effect of non-simultaneous transmitting times can be neglected due to the close proximity of the PL and receivers, and the slow motion of the mobile PL. The measurement equation can be simplified to:

$$\nabla\Delta\Phi_{ab}^{li} = |\mathbf{X}^1 - \mathbf{X}_a(t)| - |\mathbf{X}^i - \mathbf{X}_a(t)| - |\mathbf{X}^1 - \mathbf{X}_b(t_b^1)| + |\mathbf{X}^i - \mathbf{X}_b(t_b^i)| + \nabla\Delta N_{ab}^{li} + \nabla\Delta d_{multi} + \nabla\Delta \mathbf{e}, \quad (i=1,2,\dots,n) \quad (2)$$

where t is the signal transmit time from the PL, referenced to the PL clock. The position of the receivers \mathbf{X}^i , and the base transmitter \mathbf{X}_b , are precisely determined before the test if a PL is used as the reference transmitter. If a GPS satellite is used as the reference, the ephemeris error can be neglected because the receivers and the mobile PL are close to each other, relative to their distance from the satellite (Raquet et al., 1995).

All data processing were performed using a modified version of the KINGS software developed at NAL (Tsuji et al., 1998).

2.2 Configuration of the Inverted-GPS

A small-scale test configuration of the GPS/PL system was constructed as shown in Figures 4 and 5. An inverted-GPS experiment, in both static and kinematic modes, was conducted on 11 December 2001. Six CMC (Canadian Marconi Corp.) single-frequency



Figure 4. Test configuration of the GPS/PL system at UNSW.

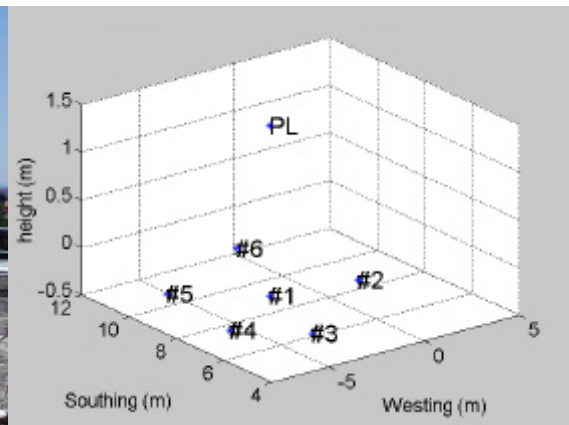


Figure 5. Coordinates of PL (PRN12) and GPS receivers.

Allstar GPS receivers were placed on the roof of the Electrical Engineering building, on the campus of The University of New South Wales. An antenna connected to an IntegriNautics IN200C PL was set on a wooden rail fixed between two pillars. The PRN number 12 was assigned to this mobile PL, and this PL is referred to as PL12 hereafter. The pseudolite was slid along the wooden rail for the kinematic test. In addition, a GPS antenna connected to a Leica System 500 receiver, was mounted on the PL antenna in order to determine the correct position of the PL antenna, and was able to slide with the PL antenna.

Although the configuration of a previous experiment (20 April 2001) was similar to this experiment, there were two important differences. First, the low-cost single-frequency receiver was used this time, instead of the rather expensive NovAtel GPS receiver. Secondly, another IntegriNautics IN200C PL was used as a reference transmitter in order to conduct the pseudolite-based inverted-GPS position test. The PRN number 32 was assigned to this reference PL, and this PL is referred to as PL32. In addition, a helical antenna was connected to the reference PL, as shown in Figure 6, since it is reported that the directional antenna can mitigate the multipath error (Kee et al., 2000). The helical antenna was approximately 61 metres away from the No. 1 receiver, and the elevation angle was 6.4° . In the previous test, the satellite with the highest elevation was used as the reference transmitter since no other PL was available.



Figure 6: Helical antenna of the reference pseudolite (PL32).

3 Results

The results of static/kinematic inverted-GPS tests are presented in this section. Two positioning modes were conducted for the static tests. The first one is referred to as the ‘mixed mode’ because a GPS satellite was used as the reference transmitter. The second mode is referred to as the ‘PL-based mode’ because a PL was used as the reference and no ranging information from GPS satellites was used.

3.1 Static Test in Mixed Mode

The PL signals may contain some multipath errors due to the many metal objects on the roof of the building. However, the multipath errors should be constant in the case of the static test mode, hence they can be calibrated in advance (Dai et al., 2001). Since the true position of the PL antenna was known, the residuals of the double-differenced (DD) carrier phase were easily estimated. The middle receiver (No.1) was chosen as the reference receiver, and a satellite (PRN21) was chosen as the reference transmitter. Unfortunately the No. 6 receiver did not record the data because of malfunction during the test. Therefore, four DD residuals computed using the data from the five receivers are shown in Figure 7. The residuals do not seem to have a constant trend, especially at around the time 187500. This is probably due to the time-varying multipath error of the reference transmitter (GPS satellite). If an additional PL were used as the reference transmitter, it is expected that the residual trend would be more constant, and the positioning solution would be improved. The constant biases were computed by averaging the residuals, and were then subtracted from the carrier phase double-differences before the positioning computations were carried out. The initial value of the PL position is

important because the mirror image of the PL with respect to the receiver constellation can also be a solution. Figure 8 shows the difference between the inverted-GPS solution and the true coordinates. The average should be zero because the biases were computed using the same data. However, it can be noted that the standard deviations (3.1 mm, 2.7 mm, and 8.6 mm in the North, East, and Height components respectively) were less than the variation of the Leica antenna computed using the normal kinematic GPS (KGPS) method (4.4 mm, 3.2 mm, and 11.3 mm).

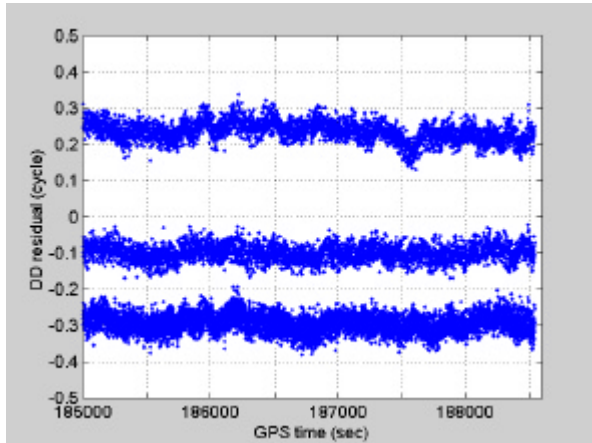


Figure 7. DD residuals of L1 carrier phase in the mixed mode static test where the transmitters are PL12 & GPS satellite (PRN21).

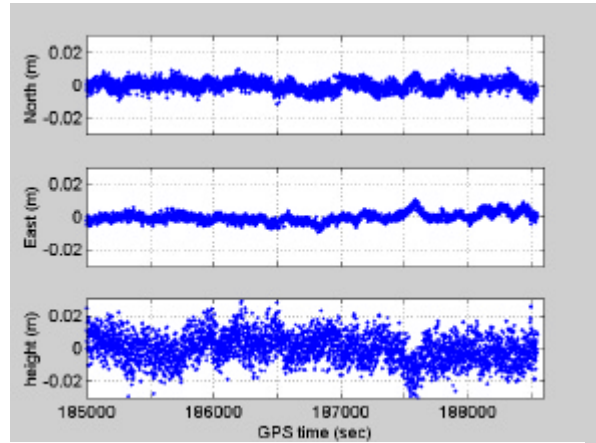


Figure 8. Positioning error of the L1 carrier inverted-GPS solution in the mixed mode static test (PL12 & PRN21).

In order to study the impact of the helical antenna on the multipath error, the DD residuals for the helical antenna were computed using the known position of the helical antenna. Satellite PRN21 was used as the reference transmitter in the same way as in the case of PL12. As shown in Figure 9, the magnitude of the DD residuals, which are supposed to be the multipath errors, are much less than in the case of the patch antenna connected to the mobile PL (PRN12). Similar results were reported by Barnes et al. (2002). These results suggest that the use of a directional antenna would be useful for local area positioning, to mitigate the severe multipath error. However, in this experiment, the position of PL32 could not be estimated accurately because of the poor GDOP.

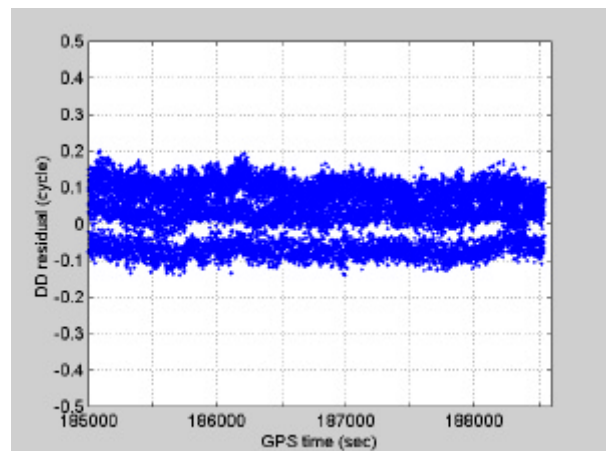


Figure 9. DD residuals of L1 carrier phase in the mixed mode static test where the transmitters are PL32 & GPS satellite (PRN21).

3.2 Static Test in PL-Based Mode

In the PL-based mode, PL32 was used as the reference transmitter, and the position of PL12 was estimated by processing the data collected by the CMC receivers. As shown in Figure 10, the DD residuals were random, as expected, compared to the mixed mode (Figure 8). In addition, the positioning accuracy was better than in the case of the mixed mode, as

indicated in Figure 11. The standard deviations are summarised in Table 1. In both modes, the RDOP, HDOP, VDOP were 3.42, 2.02, 2.22 respectively, when five GPS receivers tracked the PL signals.

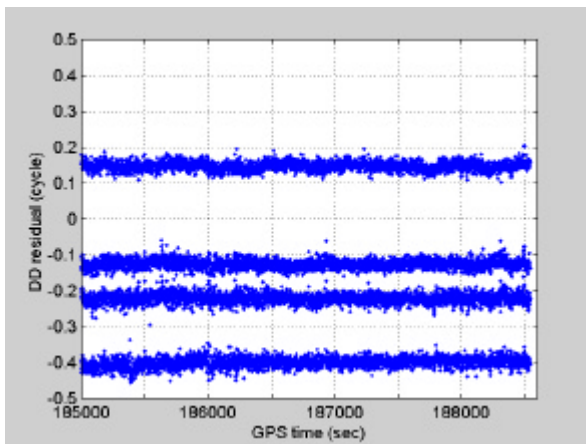


Figure 10. DD residuals of L1 carrier phase in the PL-based mode static test where the transmitters are PL12 & PL32.

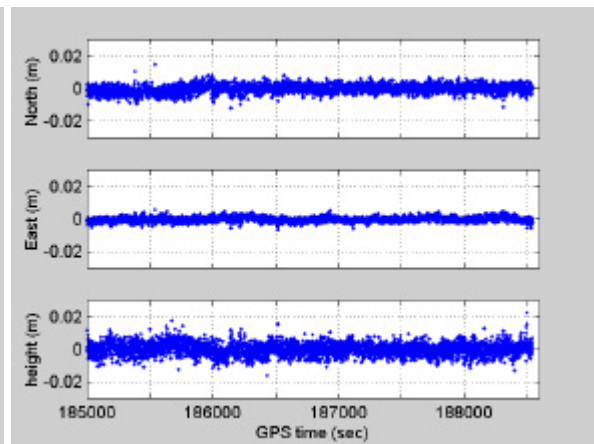


Figure 11. Positioning error of the L1 carrier inverted-GPS solution in the PL-based mode static test (PL12 & PL32).

Table 1. Positioning accuracy for the mixed/PL-based mode in the static test.

Axis	Mixed Mode (PL12 – Sat21)	PL-Based Mode (PL12 – PL32)
	s.t.d. (m)	s.t.d. (m)
North	0.0031	0.0025
East	0.0027	0.0014
Height	0.0086	0.0038

3.3 Kinematic Test

In the previous experiments on 20 April 2001, the NovAtel GPS receiver had difficulty to track the PL signal in the kinematic mode. The top plot in Figure 12 shows the trajectory of the PL in rail-coordinate, where the origin is the centre of wooden rail and the deviation from the origin is measured along the rail. The position and velocity of the PL antenna were computed by the standard KGPS method using the data obtained from the GPS antenna mounted above the PL antenna. Although the PL antenna was moved very slowly, some receivers did lose signal lock, as shown in the bottom plot of Figure 12.

In contrast, the tracking performance was indeed improved in the experiment on 11 December 2001, by replacing the NovAtel receivers by the CMC Allstar receivers. Even though the velocity of the PL was much faster than the previous test, all six receivers tracked the PL signal for almost the entire session. Table 2 summarises the performance for two different sessions. The ‘full tracking’ in the second column means that all six receivers tracked the PL signal. It is clear that the CMC receiver is superior to the NovAtel receiver in its ability to track the PL signal.

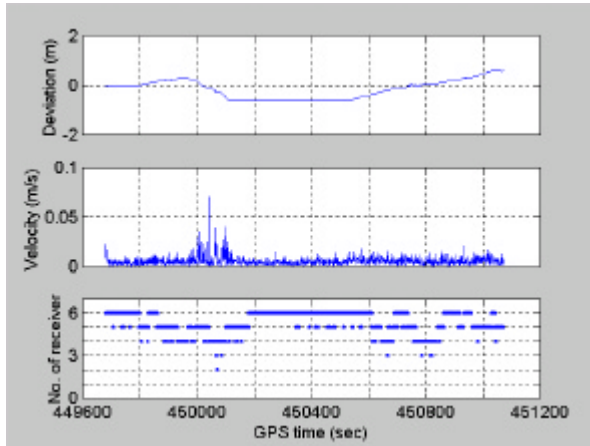


Figure 12. Motion of the PL (top & middle), and the number of NovAtel GPS receivers which tracked the PL (bottom), April 2001.

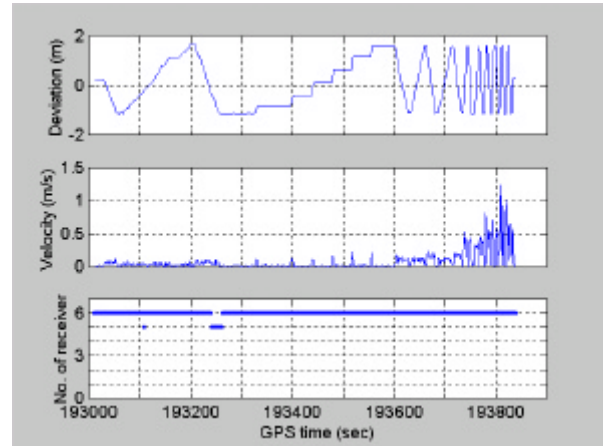


Figure 13. Motion of the PL (top & middle), and the number of NovAtel GPS receivers which tracked the PL (bottom), December 2001.

Table 2. Summary of tracking performance for two different sessions.

	Percentage of full tracking (%)	Mean number of receivers which track PL	Mean velocity of PL (m/s)	Max velocity of PL (m/s)
20 April, 2001 (NovAtel)	49.7	5.30	0.006	0.070
11 Dec., 2001 (CMC)	97.3	5.97	0.077	1.230

The residuals of the double-differenced carrier phase were computed using the true trajectory of the PL (an example is shown in Figure 14). The residuals change very quickly due to the motion of the PL. This is a reasonable result considering the characteristics of the

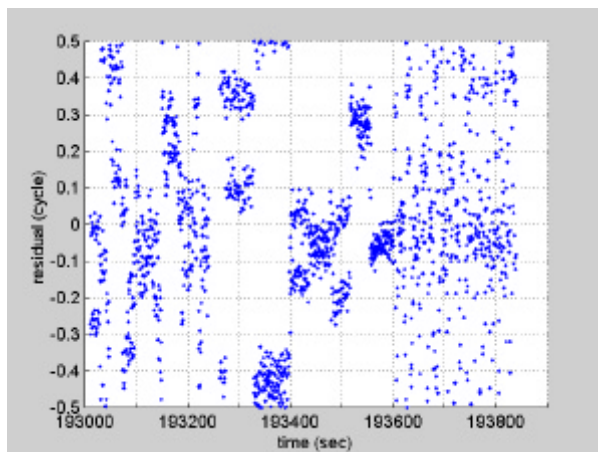


Figure 14. DD residuals of L1 carrier phase in the PL-based mode kinematic test where the transmitters are PL12 & PL32 and receivers are No. 1 & 6.

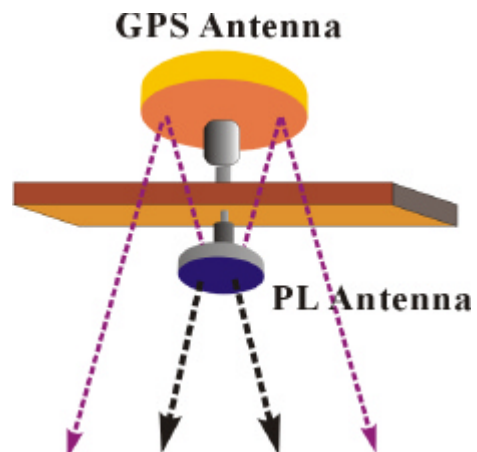


Figure 15. Direct and indirect PL signal reflected by the GPS antenna.

multipath, and because the angle between the PL antenna and the ground antenna changes drastically in such an experimental configuration. The multipath error can occur not only from the signal reflected by the ground but also from the GPS antenna, which is mounted above the PL antenna, as shown in Figure 15.

With such large residuals, ambiguity resolution would be very difficult. However, in any installed GPS/PL system the residuals should be rather constant because the angles between the ground receivers and the SPF would not change drastically, as compared to this experimental configuration. In addition, the multipath error can be mitigated by using a chokering or other multipath-suppressing antenna.

4 Concluding Remarks

The inverted-GPS positioning experiments were conducted in both 'mixed' and 'PL-based' modes. The static test in the PL-based mode showed the best positioning accuracy (standard deviations less than 4mm in each component). Also, it has been shown that the use of a directional PL antenna would be useful for local area positioning in the presence of severe multipath error.

The tracking performance in kinematic mode was indeed improved by replacing the NovAtel GPS receivers by the low-cost CMC Allstar receivers. Although this result could be due to the difference in tracking loop design, it was not possible to access the receiver firmware to verify the tracking performance. Therefore, collaborative R&D with a GPS receiver manufacturer, or the use of a receiver whose firmware could be modified by the researchers, would be necessary for future tests. A 'software GPS receiver' would be a very useful tool for the system development of such a proposed GPS/PL system.

Acknowledgments

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