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A NEW POSITIONING/NAVIGATION SYSTEM BASED ON PSEUDOLITES INSTALLED ON HIGH ALTITUDE PLATFORMS SYSTEMS (HAPS)

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Abstract

Japan Aerospace Exploration Agency (JAXA) has proposed a new positioning/navigation service using pseudolites installed on the High Altitude Platforms Systems (HAPS), such as the stratospheric airship (SPF), and the high-altitude unmanned aerial vehicle (UAV). If pseudolites (PLs) were mounted on the SPFs/UAVs, their GPS-like signals would be stable augmentations that would improve the accuracy, availability, and integrity of GPS-based positioning systems. In order to establish the fundamental technologies for such a service, the augmentation tests using a GPS pseudolite installed on a helicopter were conducted. These were the first flight tests using a station-keeping vehicle as a signal transmitting source in Japan. The position of the pseudolite antenna underneath the helicopter, which is analogous to the GPS 'precise ephemeris', was successfully determined with a few centimeters accuracy by the inverted GPS method. Also, the results demonstrate the efficacy of integrating the pseudolite signal with GPS.

1 Introduction

The transmitters of GPS-like signals, which are called pseudolites (PL), or "pseudo-satellites", have been widely investigated as additional ranging sources to enhance the performance of GPS [1]. Ground-based GPS augmentation systems using pseudolites have been investigated for several applications such as vehicle navigation in downtown urban canyons [2], positioning in deep open-cut pits and mines [3], attitude determination [4], precision landing of aircraft [5,6], and integrated positioning system with GPS/INS [7]. The application of airborne pseudolites was suggested by Raquet et al. [8]. However, their purpose was the positioning of mobile pseudolites installed on military aircraft [9], not the augmentation of a navigation/positioning system.

Recently, some countries have begun conducting feasibility studies and R&D projects on High Altitude Platforms Systems (HAPS). The concept of 'Stratolite', Stratospheric Pseudo-Satellite, for augmentation of Galileo has been shown by Dovis et al. [10], where the use of the high altitude airplane was assumed. On the other hand, Japan has been investigating an airship system that will function as a stratospheric platform (SPF) at an altitude of about 20km for applications such as environmental monitoring, communications and broadcasting [11].

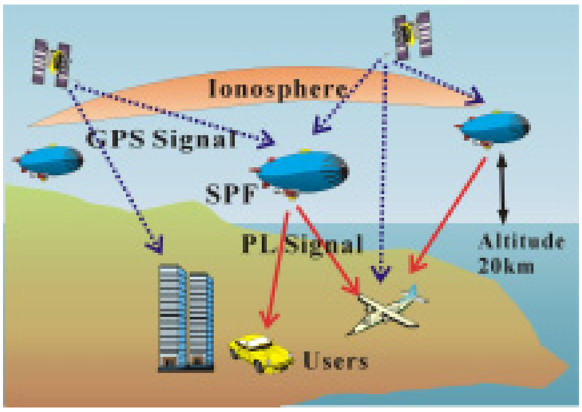

Fig. 1. Navigation/positioning service using pseudolites on stratospheric platforms.

Because of the airship's station-keeping characteristics, the SPF can be considered as a signal source for a navigation/positioning service (Fig. 1). 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.

An Example of the SPF constellation is shown in Fig. 2. A rather dense distribution of nine platforms above the Tokyo metropolitan area is assumed. The height of the platforms is about 20km and separation is about 0.5 degrees (about 55km) in latitude and longitude. The GDOP (Geometrical Dilution of Precision) variation at Chofu City, Tokyo (indicated as × in Fig. 2) is shown in Fig. 3.

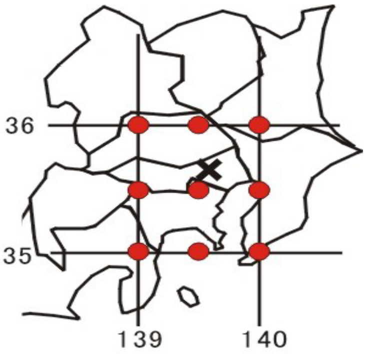

Fig. 2: Example of SPF constellation

(● : SPF, × : user)

The elevation mask angles are set at 10 degrees in the top figure, and 20 degrees in the bottom figure (Note that the scales are different). The GDOP varies greatly in the case of GPS (blue thin line) yet is very stable if the GPS is augmented by stratosphere-based pseudolites (blue bold line). This tendency is distinguished in the case of mask angle of 20 degrees. The GDOP of GPS/GLONASS integrated systems was also computed, and is shown in Fig. 3 (red line). However, since only seven GLONASS satellites are operating (as of May 2001), the GPS/PL system is undoubtedly superior to the GPS/GLONASS system.

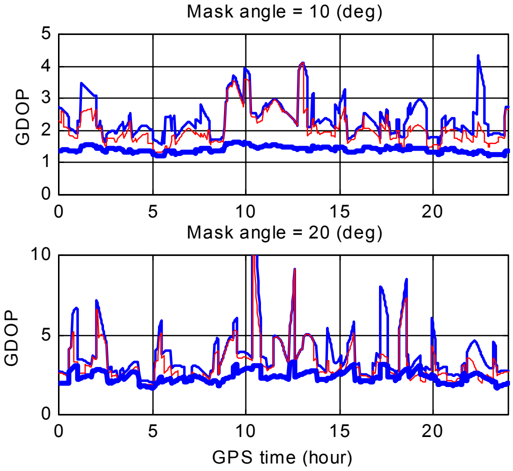

Fig. 3: GDOP variation (Blue bold: GPS/PL, Red: GPS/GLONASS, Blue: GPS)

The concept of an innovative GPS navigation/positioning system augmented by SPF-based pseudolites, which is referred to as GPS/PL system hereafter, was introduced by Tsujii et al. [12]. Also, a series of PL positioning experiments based on the 'inverted-GPS' concept were conducted on the ground [12,13,14], because the precision of the PL position ('PL ephemeris') would be a limiting factor for such a service. The results demonstrated the positioning accuracy of a few centimeters in both static and kinematic mode. Then a series of flight experiments using pseudolites installed on helicopter/aircraft was conducted in order to evaluate the capability of generating the PL precise ephemeris in flight. In this paper, the results of the flight experiments are presented, and the efficacy of integrating the pseudolite signal with GPS is demonstrated.

2 Inverted GPS Positioning

The advantages of the GPS/PL system were discussed and the result of a feasibility study was presented in an earlier paper [12]. Since the precise positioning of the PL antenna to provide the 'PL ephemeris' is one of the most important challenges, some schemes for estimating the PL position were described. Although the transceiver-based method seems to be the best, the inverted-GPS experiment was conducted as a preliminary test to identify potential problems of the proposed GPS/PL system, because an off-the-shelf transceiver is currently not available. Recently, a new positioning device, 'Locata & Locatalite', based on the transceiver concept has been developed [15]. The use of new technology for proposed GPS/PL system will be considered in the future experiment.

The system configuration of the inverted-GPS is shown in Fig. 4. The position of a PL antenna underneath a SPF can be estimated directly by the inverted-GPS method [8], where the ranging information is obtained by a receiver on the ground.

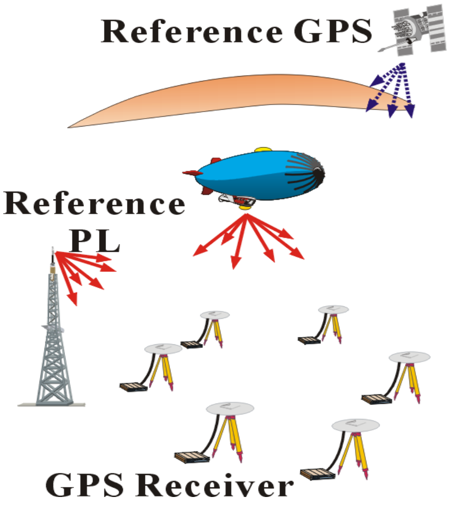

Fig. 4. Inverted GPS method.

In order to perform the double-differenced processing for the inverted-GPS approach an additional transmitter, such as a GPS satellite or ground-based PL, is required. The use of a GPS satellite would affect the positioning accuracy because ionospheric delay exists only in the GPS signal (not in the PL signal). If a ground-based PL is used as a reference transmitter, this system is referred to as 'pseudolite-based inverted GPS' or 'inverted pseudolite' because the satellite ranging data are not required to obtain the position of the rover PL. In this system, the reference transmitter should be located on a high mountain or a tower to ensure line-of-sight from all ground receivers.

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

$$\nabla\Delta\Phi_{ab}^{1i} = \left|\mathbf{X}^1 - \mathbf{X}_a(t_a^1)\right| - \left|\mathbf{X}^i - \mathbf{X}_a(t_a^i)\right| - \left|\mathbf{X}^1 - \mathbf{X}_b(t_b^1)\right| + \left|\mathbf{X}^i - \mathbf{X}_b(t_b^i)\right| + \nabla\Delta N_{ab}^{1i} + \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \nabla\Delta d_{multi} + \nabla\Delta\varepsilon$$

$$, (i=1,2, \ldots,n) \qquad (1)$$

where $\mathbf{X}^i, \mathbf{X}_a, \mathbf{X}_b$ denote the position vectors of the i-th receiver on the ground, which are static, the airborne transmitter, and the base transmitter respectively. The t_a^i, t_b^i represent the signal transmitting time to the i-th receiver from the airborne/base transmitters, referred to each of the transmitter clocks. With GPS positioning, the signal reception time for all the observed satellites is the same. However, in the case of inverted-GPS, the signal transmitting 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 (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 $(=1m/\sec\times 1m\sec)$. Since the distance difference between the PL and the receivers is less than 150km, in the example of the proposed Japanese configuration of SPFs [12], the PL position change is less than 0.5mm $(=1m/\sec\times 150km/\mathit{speed\ of\ light})$. This effect would have to be investigated further if the station-keeping performance of SPFs were found to be worse. The non-simultaneous transmitting time causes another ranging error because the stability of PL clock is generally lower than that of the GPS atomic clocks. Since the clock drift of the PL used in the flight experiment was about 3x10^{-8} sec/sec, the ranging error would be

$1mm$ $(=3\times10^{-8}\times10^{-3}\times3\times10^{8})$. The calibration of clock drift error would be easy if both reference and user receivers tracked the GPS satellites, because the time difference of signal reception can be estimated. The ionospheric delay term can be neglected if the reference PL is used instead of a GPS satellite, or if GPS transceivers were used.

For the flight test configuration, described below, the ionospheric delay terms were neglected because of the close proximity of the receivers. Also, the effect of non-simultaneous transmitting time can be neglected due to the close proximity of the PL and receivers, and the slow motion of the helicopter. However, the tropospheric delay term for the PL in flight were considered since the height of the helicopter was about 100m, which may cause a few centimeters error in single differenced measurements. The measurement equation can be simplified as:

$$\begin{aligned}\nabla\Delta\Phi_{ab}^{1i} = {} & |\mathbf{X}^1-\mathbf{X}_a(t)|-|\mathbf{X}^i-\mathbf{X}_a(t)|-|\mathbf{X}^1-\mathbf{X}_b(t_b^1)|+|\mathbf{X}^i-\mathbf{X}_b(t_b^i)| \\ & +\nabla\Delta N_{ab}^{1i}+\nabla\Delta d_{multi}+\Delta d_{trop}+\nabla\Delta\varepsilon \\ & , (i=1,2,\ldots,n) \qquad (2)\end{aligned}$$

where t is the signal transmitting time from the PL, referred 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 base transmitter. If a GPS satellite is used as the base, the ephemeris error can be neglected because the receivers and the rover PL are close to each other relative to their distance from the satellite [8].

All data processing was performed in off-line mode using a modified version of the KINGS software developed at JAXA [16].

3 Flight Test Using a Helicopter

3.1 Flight Test Configuration

A miniature configuration of the GPS/PL system using a helicopter was established as shown in Fig. 5. The flight experiments were conducted on 23 June 2003 at Taiki Multi-Purpose Aerospace Park at Hokkaido, Japan.

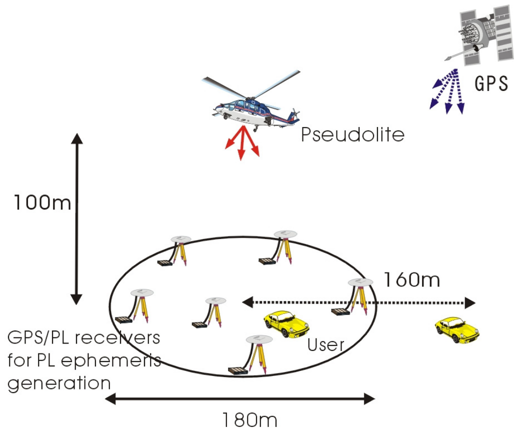

Fig. 5. Miniature configuration of the GPS/PL system using a helicopter.

Six single-frequency GPS/PL receivers (Furuno PL-10) were placed on the ground in the airfield for providing the precise ephemeris of the PL underneath the helicopter. The locations of the GPS/PL receivers in the local coordinate system are shown in Fig. 6 where the origin of the coordinate system is the location of the central receiver. The x-axis is along the runway while the y-axis is in the horizontal plane and the z-axis is upward.

The Furuno PL-10 receiver has sixteen channels, of which five channels are programmed to track the PL signal (PRN33-37). The Spirent GSS 4100 pseudolite was installed on the helicopter (Mitsubishi MH-2000A) as shown in Fig. 7. The PRN number 33 was assigned to this PL. A low noise amplifier was used to amplify the PL signal by 20dB.

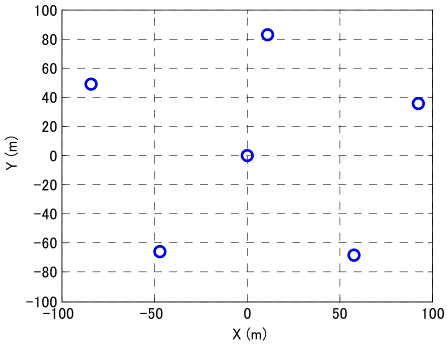

Fig. 6. Location of static GPS/PL receivers in local coordinate system.

A PL antenna was mounted underneath the body of the helicopter as shown in Fig. 8. The data from six GPS/PL receivers were recorded at 5Hz rate by two laptop computers which were connected to a LAN. In order to mitigate the multipath error for generating the precise ephemeris, the Ashtech choke-ring antennas were used for six static receivers. Another PL-10 receiver was used as a rover receiver which emulated a user of GPS/PL system. An Ashtech Geodetic IV antenna with grand plane was used for the rover receiver.

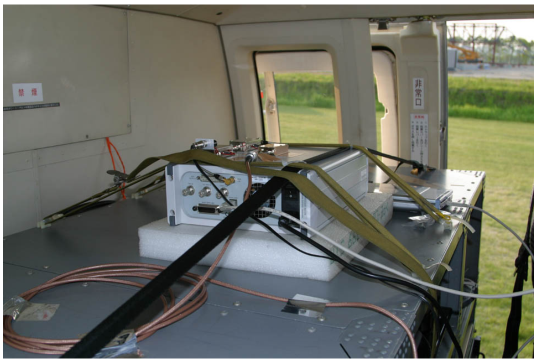

Fig. 7. Spirent GSS 4100 pseudolite in MH2000A.

Fig. 8. Pseudolite antenna underneath the MH2000A.

3.2 Generation of the Precise Ephemeris

The MH2000A helicopter hovered above the static receivers during the experiment. The flight trajectory is shown in Fig. 9, while the height profile is shown in Fig. 10. The helicopter stayed within the area of a few tens of meters. The position of the PL antenna which moved as shown in Fig. 9 & 10 was determined by the inverted GPS method in post-flight mode. The positions of the six antennas of the PL-10 receivers were surveyed by GPS beforehand.

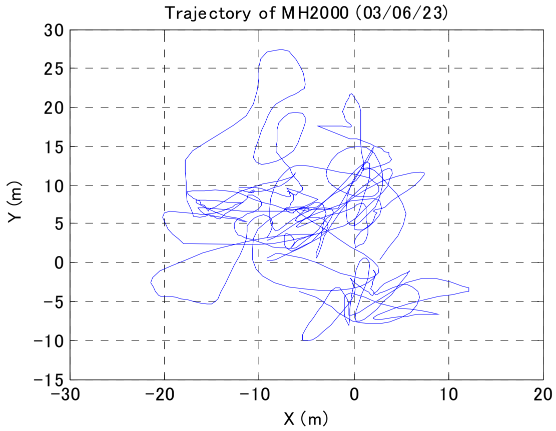

Fig. 9. Trajectory of the helicopter.

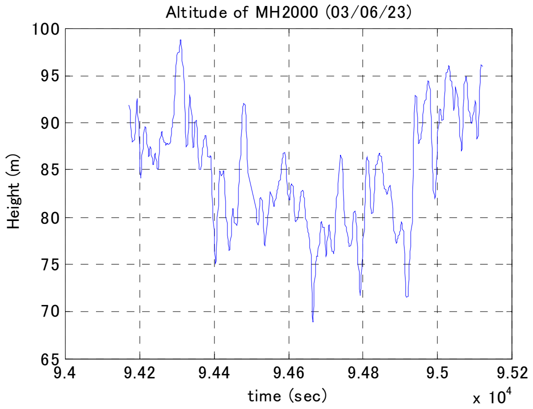

Fig. 10. Height profile of the helicopter.

Fig. 11 shows the residuals of the double differenced L1 carrier phase measurements. The GPS satellite (PRN 24), which was the highest satellite during the experiment, was used as the reference transmitter, while the central receiver on the ground was used as the reference receiver. The root mean square (RMS) of DD residuals were from 2.3 to 7.0 mm, and the DOP for Inverted GPS positioning was around three. Therefore, the accuracy of the PL ephemeris is approximately 6 cm (3σ). The precise ephemeris generated here was used for the rover positioning in later analyses.

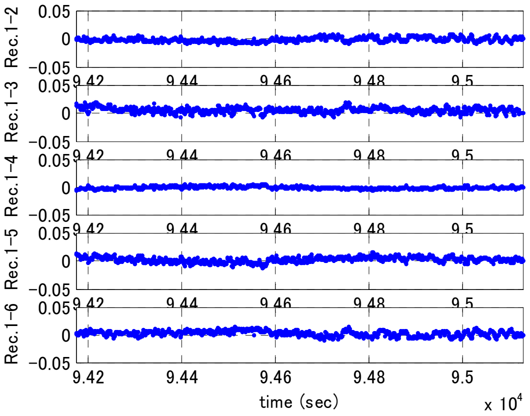

Fig. 11. DD residuals of the L1 carrier phase (in meters) in the inverted GPS positioning.

3.3 Standalone Positioning of the Rover Receiver

Now, the PL signal is able to be integrated for the positioning of the rover receiver (Fig. 12).The rover was moved along the runway (X-axis direction). The trajectory of the rover receiver computed by the usual kinematic GPS method is shown in Fig. 13. Although there were some data gaps, these seem to be the error of data transfer from receiver to PC, not the error of GPS/PL tracking. Fig. 14 shows the elevation angles of GPS/PL observed from the rover receiver. Since the height of the helicopter was less than 100 m, the elevation angle of PL changed drastically corresponding to the motion of the rover.

Fig. 12. The rover which consists of the GPS/PL receiver, antenna, PC, and battery.

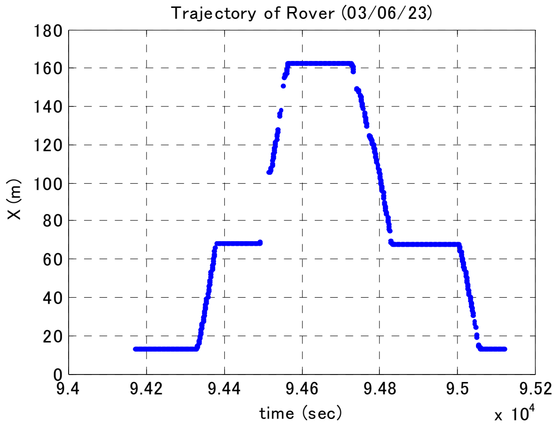

Fig. 13. The trajectory of the rover in X coordinates.

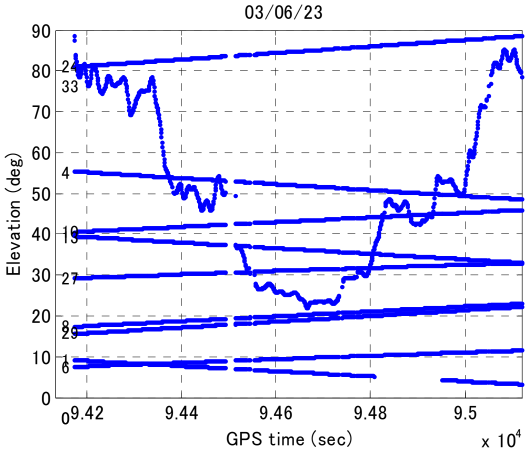

Fig. 14. Elevation angles of GPS/PL observed from the rover

The standalone positioning augmented by PL on the helicopter was carried out. The Klobuchar's ionospheric model using the broadcast message was used for GPS pseudorange correction. No ionospheric correction was needed for PL signal since the helicopter was well below the ionosphere. Saastamoinen's tropospheric model was adopted for the correction of both GPS and PL signals. The clock bias of the PL was estimated using the GPS pseudorange measured by the base receiver at the origin as

$$b^{PL} = -(PR^{PL}_{base} - \rho^{PL}_{base} - b_{base} - b_{trop} - b_{ion} - b_{sag}) \qquad (3).$$

The distance from the base receiver to the PL antenna, ρ^{PL}_{base}, can be computed by using the PL precise ephemeris and the known coordinates of the base. On the other hand, the clock bias of the base receiver contained a few meters error since the bias is estimated by the standalone positioning. Also, correction terms of tropospheric and ionospheric delay have some errors. The last term in equation (3) is the sagnac effect. The methodology to obtain more accurate PL clock bias will be investigated in the future analysis. Since the base data was used, the analyses here were not exact standalone. However, in the operational mode of GPS/PL system, the PL clock error parameters will be sent to user from the airborne PL as the broadcast ephemeris.

The results of GPS/PL positioning with mask angle 10 degrees was similar to the GPS standalone positioning, since there were enough GPS satellite. However, when the mask angle is 30 degrees, the effect of integrating PL can be seen. The number of observed satellite, GDOP, and positioning errors in the cases of GPS and GPS/PL positioning are shown in Fig. 15 and 16, respectively.

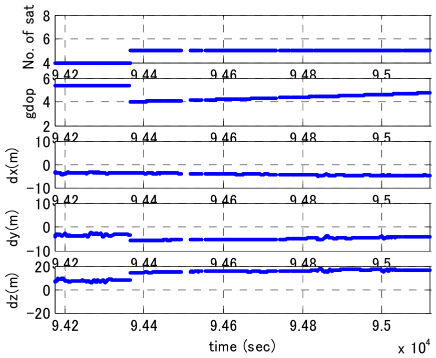

Fig. 15. Number of satellite, GDOP, and positioning errors in the cases of GPS standalone positioning.

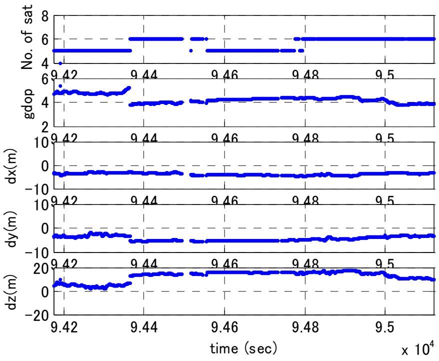

Fig. 16. Number of satellite, GDOP, and positioning errors in the cases of GPS/PL standalone positioning.

The positioning accuracy was improved if the PL signal was integrated, especially at the beginning and the end of the experiment. The positioning errors are summarized in Table 1. If the mask angle is higher, such as 40 degrees, it is clear that the GPS positioning cannot be performed all the time (see Fig. 14). On the other hand, the GPS/PL positioning is possible if the rover is not so far from the helicopter.

Table 1. Summary of the standalone positioning

RMS Error (m)	Mask = 10 degrees		Mask = 30 degrees	
	GPS	GPS/PL	GPS	GPS/PL
X	3.5	3.3	4.2	3.8
Y	2.8	2.8	4.7	4.5
Z	5.0	4.7	14.5	13.1

3.4 Relative Positioning of the Rover Receiver

The relative positioning of the rover receiver was carried out where the receiver at the origin was used as the base receiver and the highest GPS (PRN24) was used as the reference transmitter. The DD residual of pseudorange and carrier phase in the relative positioning are shown in Fig. 17 and 18, respectively. The top figure shows the residuals of the pseudolite (PRN33), while others show those of GPS satellites. The RMS of pseudolite pseudorange residuals was 32cm, which was similar to the RMS of GPS residuals (ranging from 30 to 37 cm).

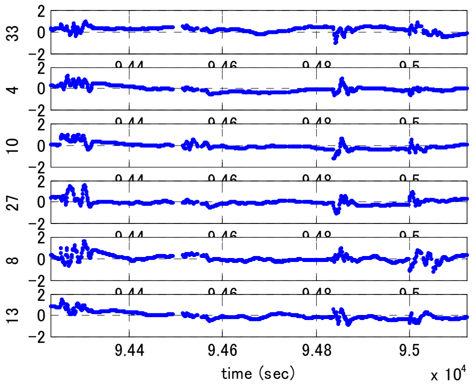

Fig. 17. DD residuals of L1 pseudorange (in meters) for PRN33 (PL), 4, 10, 27, 8, and 13.

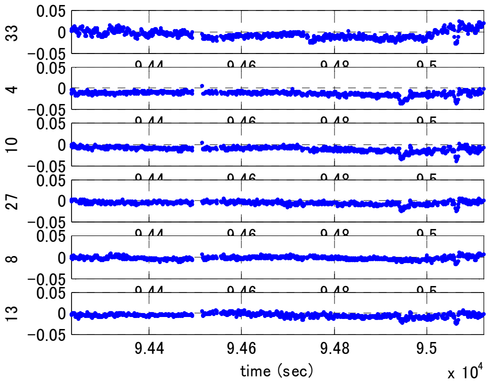

Fig. 18. DD residuals of L1 carrier phase (in meters) for PRN33 (PL), 4, 10, 27, 8, and 13.

On the other hand, the RMS of pseudolite carrier phase was 1.1 cm. This was also similar to the RMS of GPS residuals (ranging from 0.5 to 1.4 cm). These results demonstrate the equivalence of signal quality of GPS and PL.

Next, the position difference between GPS and GPS/PL relative positioning are shown in Fig. 19 (pseudorange) and Fig. 20 (carrier phase) where the mask angle was set at 10 degrees. The RMSs of position differences in x,y,z-direction were 0.26, 0.26, 0.44 (m) for pseudorange positioning, and 1.7, 1.8, 6.0 (mm) for carrier phase positioning. The impact of integrating PL signal was not significant since only one PL was added to the system. However, it is proved that the PL signal from the aerial vehicle (not-orbiting) can be used for positioning as like a satellite signal.

In the relative positioning, the positioning accuracy of GPS/PL positioning was not improved compared to GPS positioning even if the mask angle was set higher. This result is reasonable since the propagation delays cancels perfectly with such a short baseline, and therefore the effect of satellite/PL geometry is not significant. The multipath error may be the dominant error source in such a short baseline case. However, for the carrier phase positioning, the effect of integrating the PL was significant in ambiguity resolution (AR) since redundant observation was quite important for AR.

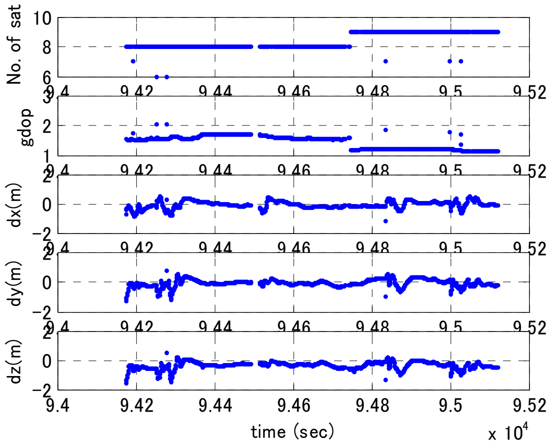

Fig. 19. Number of satellite, GDOP, and position differences between GPS and GPS/PL relative positioning (pseudorange).

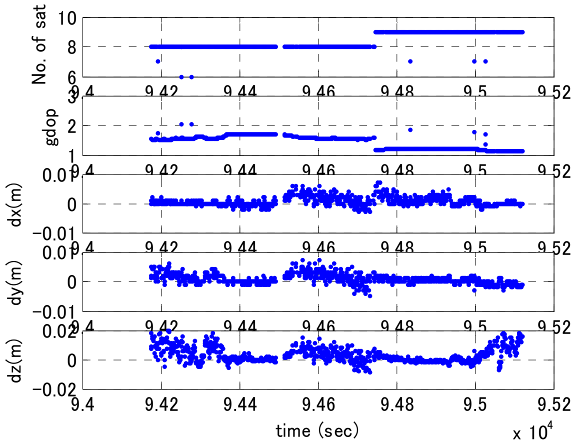

Fig. 20. Number of satellite, GDOP, and position differences between GPS and GPS/PL relative positioning (carrier phase).

4 Flight Test Using an Aircraft

The airborne pseudolite experiments were conducted by the Satellite Navigation and Positioning group (SNAP) of the School of Surveying and Spatial Information Systems, University of New South Wales, Australia. An aircraft of the Department of Aviation, UNSW was used. A pseudolite antenna facing downward was installed in the nose cone of the aircraft as shown in Fig. 21. In addition, a GPS antenna was installed above the pseudolite antenna in order to provide the reference position of the airborne pseudolite antenna.

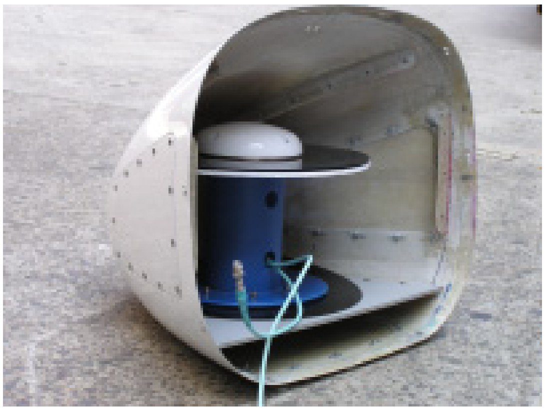

Fig. 21. GPS antenna (top) and pseudolite antenna (bottom) in the nose cone of the aircraft.

The pseudolite (assigned PRN 32) signal was transmitted from the aircraft at a height of 4500 ft over the area of Mugoa (near Blue Mountain). Six GPS/PL receivers (Novatel Millenium receivers) were set up around the Mugoa town area (approximately 4.0 - 5.0 km apart from each other as shown in Fig. 22), and the aircraft made circling above the GPS/PL receivers.

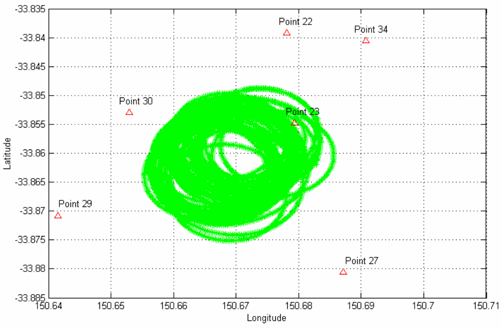

Fig. 22. Locations of the six ground GPS/PL receivers and the trajectory of the aircraft.

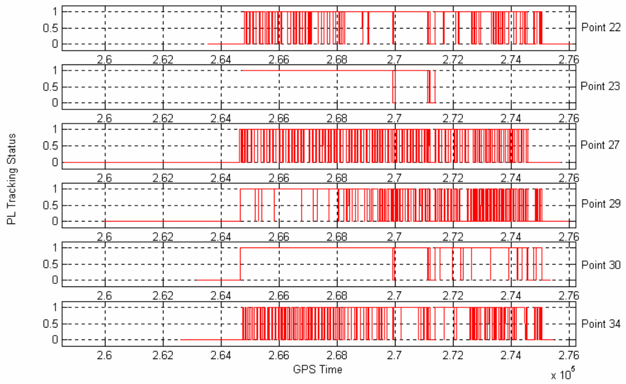

Fig. 23. Status of signal tracking by six ground GPS/PL receivers.

The pseudolite signal was tracked by the 6 receivers throughout 2.5 hours of flight trial. However, the pseudolite signal lost occasionally due to aircraft banking. The tracking status is shown in Fig. 23, in which the value one indicates tracking and the zero indicates signal loss. Unfortunately, the precise ephemeris could not be obtained due to the frequent signal loss. However, the generation of the precise ephemeris would be possible if the aircraft flied higher and the ground receivers were distributed in the wider area.

5 Summary

The GPS positioning tests augmented by a pseudolite installed on a helicopter were conducted. These were the first flight tests using a station-keeping vehicle as a signal transmitting source in Japan. The PL precise ephemeris was successfully generated with a few centimeters accuracy by the inverted GPS method. By using this ephemeris and the PL signal from the helicopter in addition to the GPS signals, the position of the ground rover was determined. As results, it is demonstrated that the quality of PL signal from the helicopter is similar to GPS signal, and the station-keeping flying PL can be used like an orbiting satellite.

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