Evaluation of the Pseudolite DGPS System for ALFLEX

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ABSTRACT

For a reusable space plane, GPS navigation is essential for accurate onboard navigation. Moreover, if GPS navigation with differential GPS technique performs high navigation accuracy and can be applied to the landing phase, the onboard GN&C system of the space plane is simplified and its weight is reduced. The National Aerospace Laboratory (NAL) and the National Space Development Agency of Japan (NASDA) have been studying the GPS navigation for an automatic landing. As one of the research items of the Automatic Landing Flight Experiment (ALFLEX), we designed and manufactured the pseudolite DGPS system for ALFLEX and evaluated its function and performance using real flight data. This paper outlines the Pseudolite DGPS System for ALFLEX and evaluates the results of the performance of the DGPS navigation, the carrier smoothing DGPS navigation, the IMU-DGPS integrated navigation, and the multipath effect on the pseudolite signal.

1. Introduction

In order to establish automatic landing technologies for a space plane, the Automatic Landing Flight Experiment (ALFLEX) was planned and 13 flights were carried out from July to August in 1996. As one of the research items of ALFLEX, we developed the Pseudolite DGPS System for ALFLEX [1] and evaluated its function and ability to acquire the differential GPS technique for an automatic landing. We chose the pseudolite method for the ALFLEX DGPS system because of the simplification of the onboard system and the improvement of the geometrical dilution of precision (GDOP) at landing. On the other hand, the pseudolite method had some technical problems and had many newly developed elements. Although there were some difficulties with the development of the Pseudolite DGPS System, finally the system performed with efficient accuracy at the automatic flight experiment.

This paper outlines the Pseudolite DGPS System for ALFLEX first, the results of its development second, and then shows the evaluation results of the performance of the DGPS navigation, the carrier smoothing DGPS navigation and IMU-DGPS integrated navigation. This paper also shows the evaluation results of multipath effect on the pseudolite signal and the comparison of the GDOP between the pseudolite method and the datalink method.

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2. Pseudolite DGPS System

It is necessary for the differential GPS (DGPS) to send the pseudorange correction data estimated at the ground reference station to the onboard GPS receiver and there are two principle methods of sending the correction data: the datalink method and the pseudolite method. The datalink method uses an additional datalink such as VHF to send the correction data, and the pseudolite method, which was selected for the Pseudolite DGPS System for ALFLEX, uses the pseudolite signal to send the data. The pseudolite signal is modulated in a manner similar to the modulation of the GPS signal so as to enable the onboard GPS receiver to receive the pseudolite signal, which means that a dedicated datalink system is not necessary and the onboard system is both simpler and lighter. In addition, since the pseudorange of the pseudolite signal can be used as one of the observation data for the differential GPS navigation, the geometrical dilution of precision (GDOP) at landing and the accuracy of the DGPS navigation are improved.

The Pseudolite DGPS System for ALFLEX consists of the pseudolite ground station and the onboard DGPS receiver (DGPSR). Figure 1 shows a block diagram of the Pseudolite DGPS System. The main characteristics of the pseudolite ground station are provided below and the main characteristics of the pseudolite signal are shown in Table 1.

- To avoid the radio interference problem for non-target GPS receivers, the frequency of the pseudolite signal is set to 1624.61MHz which is different from the frequency of the GPS signals, 1575.42MHz.
- To avoid the false lock for the small peak of the auto-correlation function, the M-sequence code which has no small peak is selected for the pseudo random noise code.
- To prevent the increase of the pseudorange error caused by the time delay of the pseudorange correction data, the data transmission rate of the pseudolite message is set to 250 bps, although that of the GPS message is 50 bps.

The specification of the DGPSR are shown in Table 2 and the main characteristics of the DGPSR are as follows.

- DGPSR can receive the GPS signal (1575.42 MHz) and the pseudolite signal (1624.61 MHz).
- DGPSR uses the peak search algorithm for the code search to prevent the near-far problem for the pseudolite signal.
- DGPSR synchronizes to the onboard computer of the ALFLEX vehicle.

Table 1 The characteristics of the pseudolite signal

EIRP	more than +9dB
Band Width	less than 3.78MHz
Center Frequency	1624.61MHz
Modulation	Bi-Phase Shift Keying (BPSK)
PRN Code	1. C/A Code (PRN from no.33 to no.37) 2. M-sequence Code (10 bits, feedback position(3,10))
Chip Rate of PRN Code	1.023MHz
Data Transmission Rate	50,100,200,250 bps
Polarization	Right-Hand Circular Polarization

Table 2 Specification of the DGPS receiver

Receiving Signal	GPS Signal (C/A code) Pseudolite Signal
Number of Channel	6ch (1ch is for the pseudolite signal)
Outputs	Pseudorange, Deltarange, Carrier Phase Measurements, GPS Satellite Position, etc.
Accuracy (3 σ)	Pseudorange 22.5 m Deltarange 3.3 cm
Weight	less than 7.5kg
Size	less than 230 × 200 × 230 mm
Power Consumption	less than 30 W

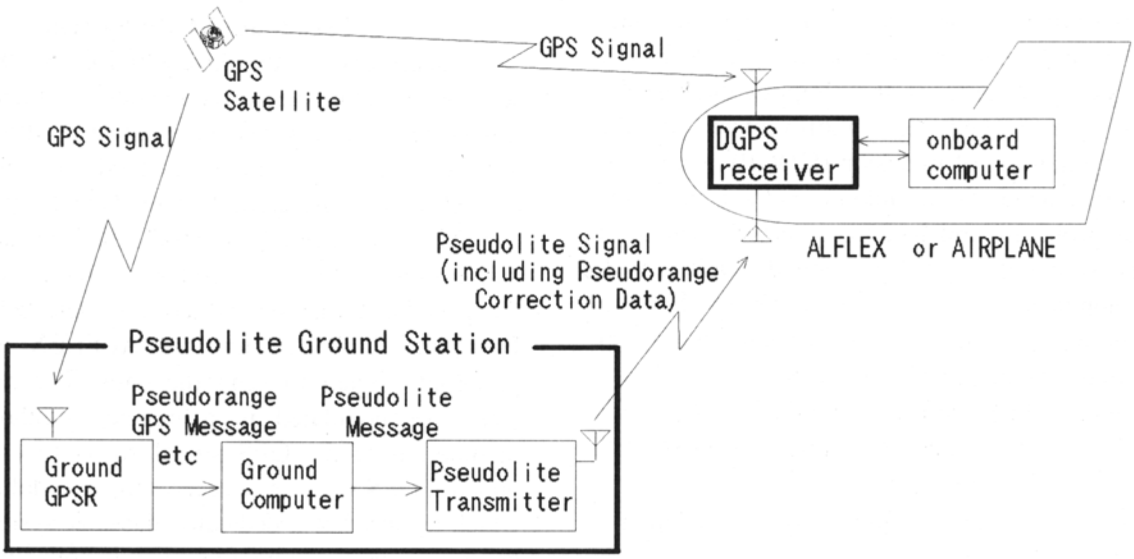

Fig.1 Pseudolite DGPS System for ALFLEX

The role of the Pseudolite DGPS System for ALFLEX is to provide observation data for the onboard IMU-DGPS integrated navigation during the hanging phase. The accuracy of the DGPS navigation at free flight was evaluated by post processing. [2]

3. Results of the Development of the System

Since the pseudolite method is an experimental technology with many newly developed elements, there were some difficulties with the development of the Pseudolite DGPS System. The main reason for our choice of the pseudolite method for the system are the simplification of the onboard system and the improvement of the GDOP at landing. For the pseudolite method, any other communication system, such as a decoder, a demodulator and so on, is not necessary. It is important for a space plane to simplify the onboard system and to lighten its weight. In addition, using the pseudolite method the GDOP is improved because the position of the pseudolite ground station is on the opposite side of the GPS satellites for a space plane in flight. Also, it is important for a space plane to improve GDOP because a space plane must use a heat-resistant antenna whose antenna gain at low elevation angles is not good.

The technical problems which were recognized at the beginning of the development are as follows: [1],[3]

- The pseudolite signal must be designed to free non-target GPS receivers from the radio interference.
- The system must be designed to avoid the near-far problem for the spectrum spread modulation.
- The system must be designed to prevent the deterioration of the navigation accuracy caused by clock synchronization error to the GPS time.
- The pseudolite signal must be designed to minimize the deterioration of the navigation accuracy caused by the time delay of the pseudorange correction data.
- The re-tracking algorithm is necessary to the attitude fluctuation of the ALFLEX vehicle.

Following ALFLEX, the following emerged as matters which should be considered when DGPS navigation is applied to the landing of a space plane.

(1) GPS Antenna Pattern

The GPS antenna which received the GPS signals was install at the top of the tip fin of the ALFLEX vehicle so as to reduce the influence of the hanging equipment which was installed above the ALFLEX vehicle and interfered with the coverage of the GPS antenna. However, at the domestic hanging experiment the antenna gain for at low elevation is much worse at the top of the tip fin than at the body of the ALFLEX vehicle. As the countermeasure of this problem, we attached the ground plane to the GPS antenna to improve its antenna gain, and then the GPS signals could be received when the elevation angle of GPS satellite was above 20 degree. In the future, the GPS antenna should be positioned based on the antenna gain when the antenna is attached to the vehicle.

(2) GDOP at the Mask Angle of 20 Degree

The mask angle of the DGPSR was set to 20 degrees for ALFLEX, for a GPS signal could not be received when the elevation angle of the GPS satellite is below 20 degree. This made the GDOP without the pseudolite signal worse and sometimes the number of visible satellites was less than four, which is the minimum required for GPS navigation. Since a space plane must use a heat-resistant antenna whose antenna gain at low elevation angles is not good, a space plane must use the multi-GPS-antenna system, the development of which is technically difficult, or must restrict the use of low elevation satellites like ALFLEX. If a space plane restricts the use of low elevation satellites, the minimum requirement of four GPS satellites may not be satisfied at all times. Therefore, the operation plan should be examined in consideration for the visible GPS satellites and the GDOP. Furthermore, it is recommended that systems which restrict the use of low elevation satellites employ the pseudolite method to improve the GDOP.

(3)Multipath of the Pseudolite Signal

We did not recognize the influence of the multipath of the pseudolite signal just before the ALFLEX experiment. When we tried to estimate the pseudolite pseudorange correction (PLC) at the apron parking point of Woomera Airfield, the bias of the pseudolite pseudorange was changed on each estimation. This fluctuation was caused by the interaction of the direct signal and the reflection signal which reflected at the Hanger. This is described in detail in chapter 5.1. When designing future pseudolite ground stations, we must design the system to minimize the influence of the multipath of the pseudolite signal and must select the position of the pseudolite ground station in consideration of the multipath.

4. Evaluation Results of DGPS Navigation

The requirement for the DGPS system on ALFLEX is as follows. The requirement of the DGPS navigation was set on the condition that the observation noise of the pseudorange is 22.5m (3σ) and that the GDOP is 3. The requirement of the IMU-DGPS integrated navigation is one of the system requirements of the ALFLEX, and the requirement is determined from the covariance analysis based on the error model of the IMU and the DGPSR.

(1) Requirements of DGPS Navigation

Requirement:

Position error (RSS) is less than 70m (3σ)

Condition:

- Selective availability (SA) is ON
- GDOP is less than 3
- The distance from the pseudolite ground station is less than 3km

(2) Requirements of IMU-DGPS Integrated Navigation

Requirement:

Position errors on each axis are less than 25m (3σ) at ALFLEX release point

Condition:

- Selective availability (SA) is ON
- GDOP is less than 3

4.1 DGPS Navigation on the Ground

First, we installed both the pseudolite ground station and the onboard DGPS receiver at the place where its position is measured precisely, and evaluated the accuracy of the DGPS navigation in the static state. Figure 2 shows the position error of the DGPS navigation calculated with pseudoranges and deltaranges. In this figure, a runway coordinate is used, the x-axis is along the runway, the y-axis is across it, and the z-axis is opposite to the altitude. In Fig. 2, the effect of the selective availability (SA), a feature which is unique to GPS navigation, is almost eliminated. Table 3 shows the statistical results of the DGPS navigation corresponded to Fig. 2. Though there is a little bias at the z-axis, other errors are the random error which is about 5m. This random error is caused by the observation error of the pseudoranges. The DGPSR for ALFLEX outputs carrier phase, which does not use onboard navigation of the ALFLEX, so that it can be used for the post processing of the advanced GPS navigation. So, we applied the carrier smoothing technique to the DGPS navigation. This technique uses the carrier phase to smooth the noise of the pseudorange. The results of the carrier smoothing DGPS navigation are shown in Fig. 3 and Table 4. The noise error seen in Fig. 2 is nearly eliminated and accuracy of a few meters is obtained. Looking at z position error in Fig. 2 carefully, there is small wave whose period and behavior resemble that of the SA. We suppose that this small wave of the position error is caused by the time delay of the pseudorange correction data.

Table 3 DGPS navigation error

	X position	Y position	Z position
mean	0.25 m	0.69 m	-2.22 m
std.	3.32 m	4.08m	5.38 m

Table 4 Carrier Smoothing DGPS navigation error

	X position	Y position	Z position
mean	0.27 m	0.66 m	-1.71 m
std.	1.39 m	1.29 m	2.02 m

4.2 DGPS Navigation during Free Flight

The first flight of the automatic flight experiment was successfully carried out on July 6, 1996. The position errors of the DGPS navigation, which are estimated by comparing with laser tracker data, are shown in Figs.4 and 5. Figure 4 shows the error of the DGPS navigation using pseudoranges and deltaranges, and Fig. 5 shows the error of the carrier smoothing DGPS navigation. The results are almost the same as the DGPS navigation on the ground, the bias errors are almost eliminated and the random errors are nearly eliminated by using the carrier smoothing technique. At the period from 524540 sec to 524550 sec, z-axis position error, which is opposite to the altitude error, is increasing. At this period, the ALFLEX vehicle did the nose down just after the release of the ALFLEX vehicle. Since the pitch angle of the ALFLEX vehicle went to –60 degrees, the pseudolite signal once interrupted and resumed receiving the pseudolite signal 8 seconds later by the re-tracking algorithm.

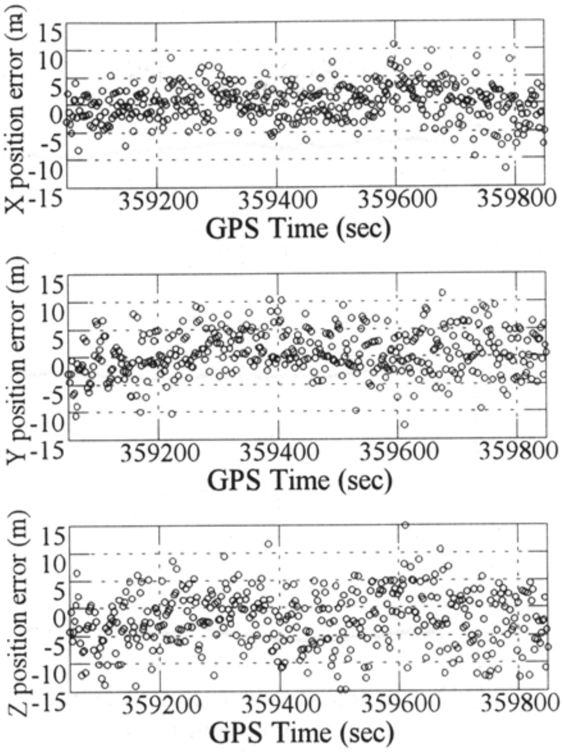

Fig.2 DGPS Navigation on the Ground

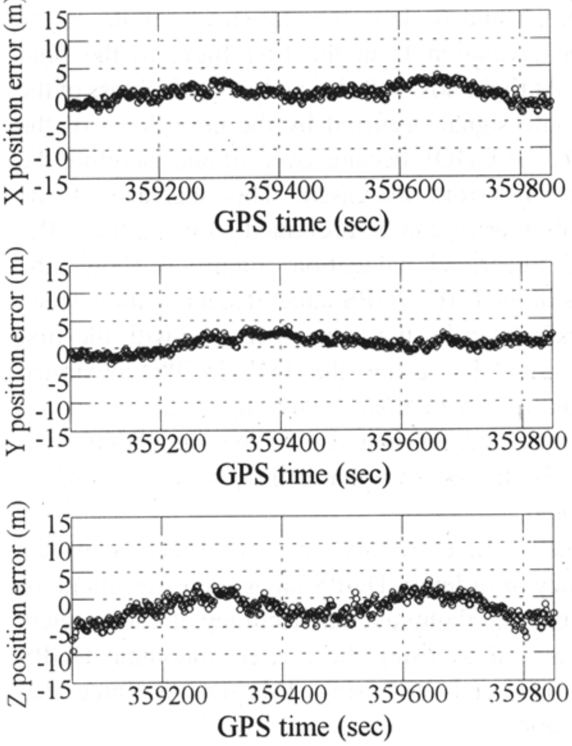

Fig.3 Carrier Smoothing DGPS Navigation on the Ground

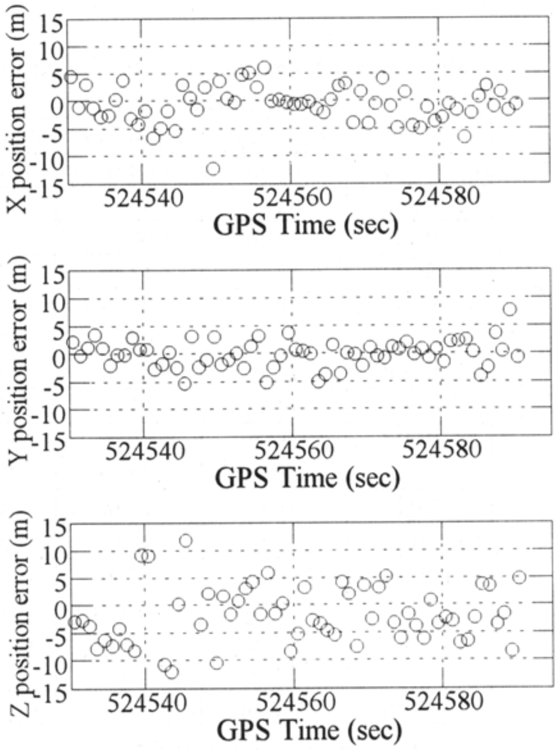

Fig.4 DGPS Navigation during Free Flight

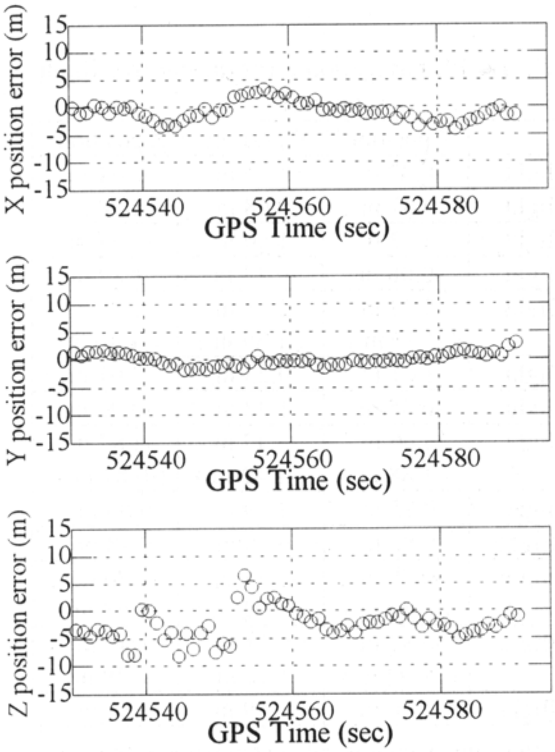

Fig.5 Carrier Smoothing DGPS Navigation during Free Flight

Tables 5 and 6 show the statistical results of the DGPS navigation from the first flight to the final flight. At flight nos. 5, 8, 11, and12, the lockloss of the pseudolite signal occurred by the nose down of the vehicle, the GDOP became over 10 and therefore the navigation errors increased. This increase of the navigation error can be prevented by using the IMU-DGPS integrated navigation. Figure 6 shows the results of the IMU-DGPS integrated navigation which was calculated by the post processing with the first flight data. By using the IMU-DGPS integrated navigation, the random errors shown in Fig. 4 are eliminated and the increase of the navigation error caused by the interruption of the pseudolite signal is prevented.

Through these results, we confirmed that the accuracy of ordinary DGPS navigation was about 10 m during free flight and that accuracy of a few meters was realized by using the carrier smoothing DGPS navigation and by using IMU-DGPS integrated navigation.

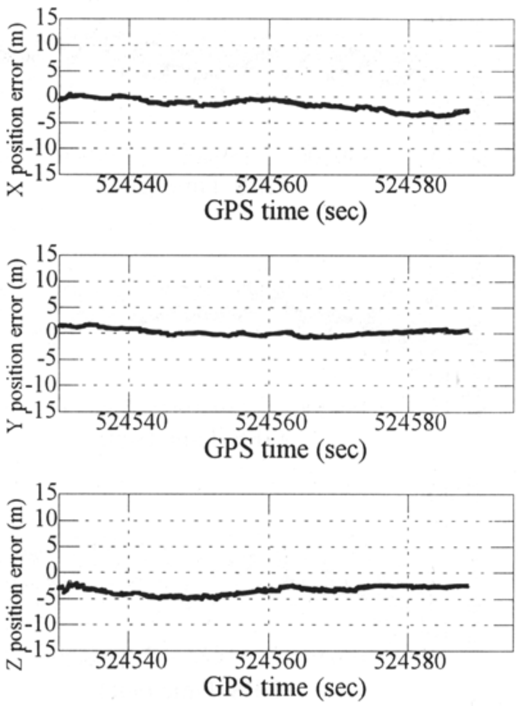

Fig. 6 IMU-DGPS integrated navigation during free flight

Table.5 DGPS navigation error during free flight (mean)

	X position	Y position	Z position
#1 flight	-0.87 m	0.16 m	-2.64 m
#2 flight	0.67 m	0.68 m	-1.98 m
#3 flight	0.32 m	1.60 m	-2.34 m
#4 flight	-0.08 m	-0.13 m	1.29 m
#5 flight	5.33 m (-0.33 m)	2.15 m (1.39 m)	1.32 m (-1.46 m)
#6 flight	1.61 m	0.23 m	-3.01 m
#7 flight	-0.35 m	1.32 m	-0.96 m
#8 flight	6.90 m (1.88 m)	-3.47 m (-1.42 m)	2.87 m (-0.81 m)
#9 flight	0.95 m	-1.79 m	0.50 m
#10 flight	0.86 m	0.05 m	0.18 m
#11 flight	-0.79 m (0.50 m)	-0.31 m (-0.91 m)	-1.70 m (-0.68 m)
#12 flight	-0.82 m (-1.92 m)	0.58 m 1.12 m	-1.40 m (-2.29 m)
#13 flight	-1.66 m	-0.39 m	0.87 m

( ) is the value which is calculated without the data whose GDOP is over 10.

Table.6 DGPS navigation error during free flight (standard deviation)

	X position	Y position	Z position
#1 flight	3.65 m	2.69 m	6.11 m
#2 flight	4.01 m	3.47 m	4.92 m
#3 flight	6.73 m	4.00 m	6.95 m
#4 flight	6.27 m	2.42 m	7.75 m
#5 flight	22.06 m (8.33 m)	3.95 m (3.64 m)	14.03 m (5.04 m)
#6 flight	6.11 m	4.29 m	5.55 m
#7 flight	7.41 m	6.01 m	7.41 m
#8 flight	19.97 m (6.86 m)	8.84 m (3.25 m)	15.42 m (5.84 m)
#9 flight	6.37 m	4.18 m	6.12 m
#10 flight	6.23 m	4.20 m	5.53 m
#11 flight	11.67 m (5.80 m)	6.57 m (4.19 m)	12.08 m (8.86 m)
#12 flight	15.85 m (7.61 m)	8.65 m (5.88 m)	13.30 m (7.59 m)
#13 flight	3.82 m	4.32 m	6.24 m

( ) is the value which is calculated without the data whose GDOP is over 10.

5. Evaluation of the Pseudolite DGPS System

The Pseudolite DGPS System for ALFLEX was evaluated and the evaluation results of the multipath effect on the pseudolite signal and the comparison of the GDOP between the pseudolite method and the datalink method are discussed.

5.1 Multipath Effect on the Pseudolite Signal

Before the operation of the Pseudolite DGPS System for ALFLEX, it is necessary for this system to estimate the pseudolite pseudorange bias which is used as the correction data for the pseudolite pseudorange during operation. The pseudolite pseudorange between the two points whose positions are precisely decided is measured and the pseudolite pseudorange bias is estimated by comparing the measured range and the true range. As for the ALFLEX, we measured the pseudolite pseudorange at the apron parking point of Woomera Airfield during the preparation of the ground support equipment and estimated the bias, and then we recognized that the pseudolite pseudorange bias was changed on each estimation. It was presumed that this fluctuation was caused by the interaction of the direct signal and the reflection signal, that is the multipath. As the countermeasure of this problem, we changed the position of the pseudolite ground station so as to avoid the influence of the multipath. The pseudolite ground station was set up originally at the position which is shown in Fig. 7 as "Pseudolite ground station (before Multipath countermeasure)" and was moved to the position which is shown as "Pseudolite ground station (before Multipath countermeasure)". After this countermeasure, we measured the pseudolite pseudorange which was sent from the position shown as "Pseudolite Ground Station (after Multipath Countermeasure)" and was received at the runway origin point.

Figure 8 shows the influence of the multipath. The PLC, which is equivalent to the pseudolite pseudorange bias, fluctuates in the range of 10 m to 20 m according to the antenna position in the range of – 100 cm to 100 cm. This is a definite feature of the multipath effect. Figure 9 shows the PLC which was estimated after the multipath countermeasure. The PLC did not fluctuate for the moving of the antenna position.

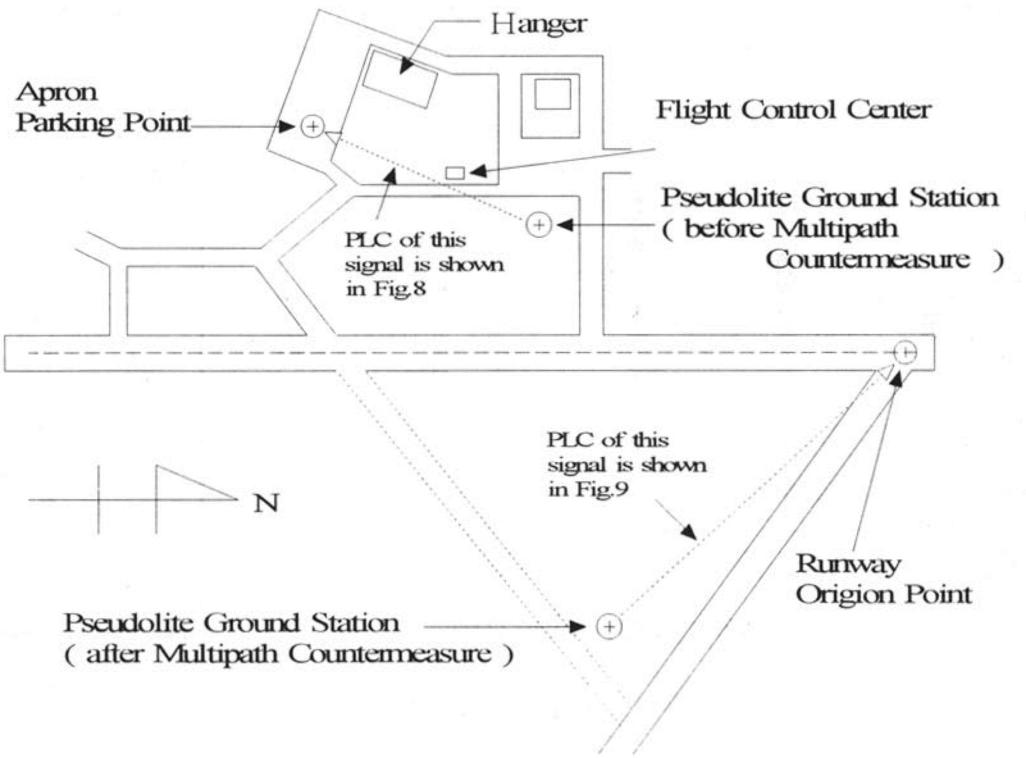

Fig. 7 Position of the Pseudolite Ground Station at Woomera Airfield

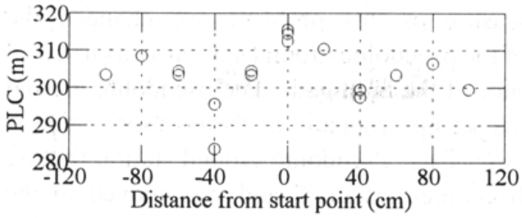

Fig.8 Multipath (before multipath countermeasure)

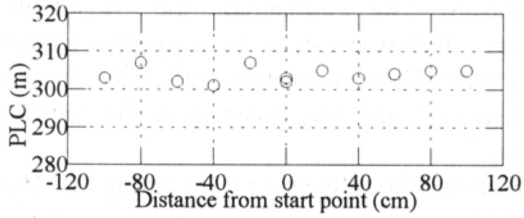

Fig.9 Multipath (after multipath countermeasure)

We explained the mechanism of the occurrence of this phenomenon. When the multipath of the pseudolite signal is occur, the received signal is the composition of the direct signal and the multipath signal. Equation (1) shows the composite signal, the first term of the right-hand side shows the direct signal and the second term shows the multipath signal. For the simplification, the term of the navigation message is omitted from Equation (1).

$$S(t) = A \cdot P(t) \cdot \sin(\omega_0 \cdot t) - \alpha \cdot A \cdot P(t-\delta) \cdot \sin(\omega_0 \cdot t - \theta_m) \quad \cdots\cdots(1)$$

where : A : Amplitude of Direct Signal
P(t) : PRN Code (either +1 or −1)
ω_0 : Carrier Frequency plus Doppler Shift
α : Relative Multipath Amplitude
δ : Relative Multipath Time Delay
θ_m : Relative Multipath Phase

Applying the code correlation processing using the delay lock loop (DLL) of the DGPSR to the signal described as the equation (1), we can get the discriminator function shown in equation (2).

$$D(\tau)=\{R^2(\tau+\tau_d)-R^2(\tau-\tau_d)\}+\alpha^2 \cdot \{R^2(\tau+\tau_d-\delta)-R^2(\tau-\tau_d-\delta)\} +2 \cdot \alpha \cdot \cos(\theta_m) \cdot \{R(\tau+\tau_d) \cdot R(\tau+\tau_d-\delta)-R(\tau-\tau_d) \cdot R(\tau-\tau_d-\delta)\} \quad \cdots\cdots(2)$$

where : R(t) : PRN Code Autocorrelation Function
τ_d : Correlator Spacing Time

If there is no multipath, the discrimination function is only the first term of the right-hand side of equation (2) and its function is symmetrical (left-hand side of Fig. 10). In this case, the tracking of the code position is correct. If there is some multipath, the figure of the discrimination function become distorted (right-hand side of Fig. 10). In this case, the tracking point, the point of $D(\tau)=0$, deviates from the correct position and

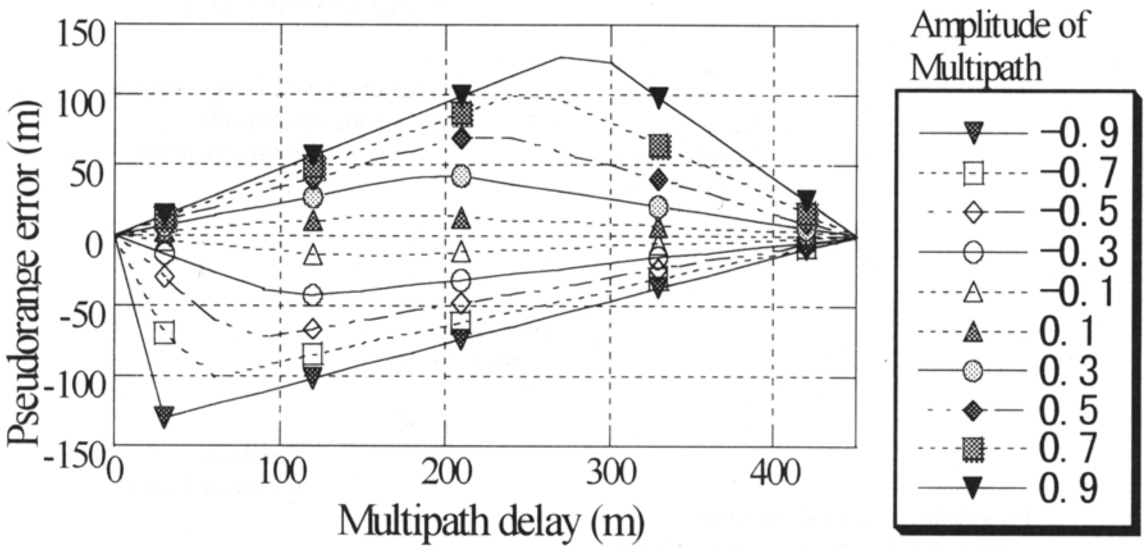

Fig. 11 Multipath Error Envelope

this deviation makes the pseudorange bias error. The magnitude of the pseudorange bias error varies according to the magnitude and the delay of the multipath signal. If we change the magnitude and the delay parametrically, the envelope of the pseudorange error becomes Fig. 11.

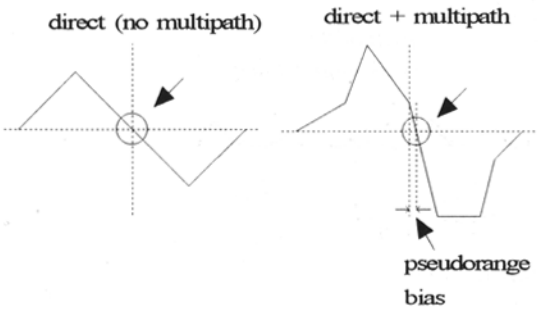

Fig.10 Discriminator Function

Next, we find the source of the multipath from the results shown in Fig. 8. In equation (2), the only parameter which is changed by the range of some 10 cm is the relative multipath phase, θ_m. Though the period of the θ_m is 19 cm, the pseudorange error fluctuates at the period of 80 cm in the Fig. 8. The condition which satisfies this relationship is that in which the multipath signal comes from the direction of ± 75 degree relative to the direction the vehicle is moving. Figure 12 shows this relationship. The only object which satisfies this condition is the Hanger. Figure 8 shows that the range of the fluctuation of the pseudolite pseudorange bias is 15 m for positive and 25 m for negative. If the relative multipath amplitude, α, is 0.3 and the relative multipath delay, δ, is 50 m, this condition is satisfied. This delay is coincident with the delay which occurs when the multipath signal reflects at the Hanger. From these results, we supposed that the multipath signal which occurred at the apron parking point was the signal reflected at the Hanger. To verify this assumption, we simulated the fluctuation of the pseudorange at the condition that the pseudolite signal reflects at the Hanger at the relative multipath amplitude of 0.3. Figure 13 shows the results of the simulation, which is almost coincident with the fluctuation in Fig. 8.

5.2 Comparison of the GDOP

The improvement of the GDOP is one of the merits of the pseudolite method. We confirmed its improvement by using the actual satellite constellation on the day

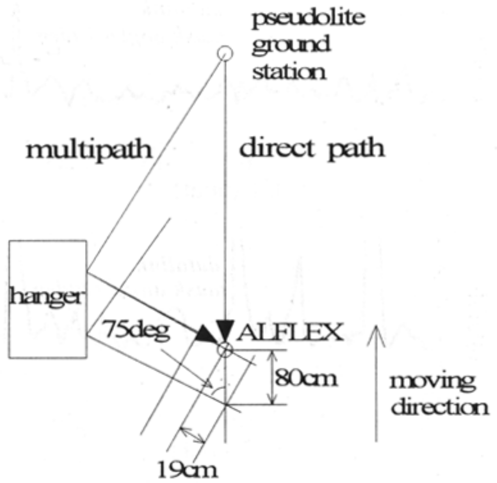

Fig.12 Multipath at parking point

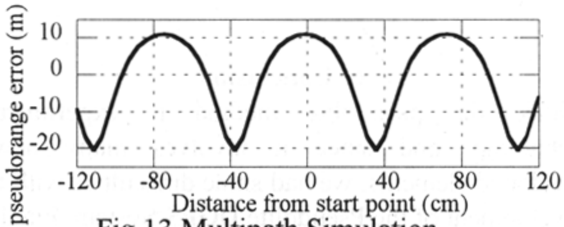

Fig.13 Multipath Simulation

when the first flight of the ALFLEX was carried out. We calculated the GDOP at the release point of the ALFLEX vehicle with the almanac data collected at the first flight and made a comparison of the GDOP between the pseudolite method and the datalink method. The upper figures of Fig. 14 shows the GDOP at the mask angle of 10 degrees and the lower figures shows the GDOP at the mask angle of 20 degrees. The left-hand figures of Fig. 14 are for the datalink method and the right-hand figures are for the pseudolite method. Figure 14 shows that there is little difference between two methods at the mask angle of 10 degrees, but at the mask angle of 20 degrees, which is used for the ALFLEX, the two methods produce fairly different results. Though the GDOP of the pseudolite method is good even at the mask angle of 20 degrees, the GDOP of the datalink method is worse at the mask angle of 20 degrees and sometimes the number of visible satellites is less than four which is the minimum required for GPS navigation. These results confirmed that the pseudolite method was useful for improving the GDOP, especially when the system restricts the use of low elevation satellites.

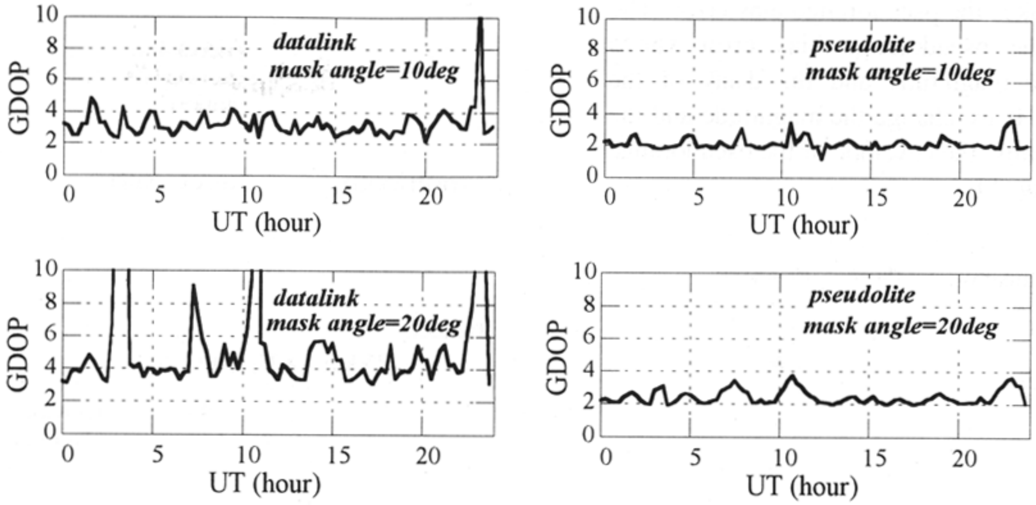

Fig.14 GDOP at Woomera Airfield (July 6,1996)

6. Conclusion

Since the pseudolite method is experimental technology and since it involves many newly developed elements, we had some difficulties with the development of the Pseudolite DGPS System. Finally, however, the system performed with efficient accuracy at the automatic flight experiment. Regarding the evaluation of the applicability of the DGPS navigation to an automatic landing, we evaluated the DGPS navigation by post processing and confirmed that the ordinary DGPS navigation produced about 10 m accuracy during free flight and that a accuracy of a few meters was realized by using carrier smoothing DGPS navigation and by using IMU-DGPS integrated navigation. Through the development of the Psuedolite DGPS System and the experiments which were carried out to evaluate the system, we developed the technique of differential GPS for landing.

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