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A Preliminary Flight Evaluation of DGPS-INS Hybrid Navigation System

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A Preliminary Flight Evaluation of DGPS-INS Hybrid Navigation System*

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ABSTRACT

This paper summarizes the flight evaluation of the DGPS-INS hybrid navigation system conducted as a preliminary study for constructing a next-generation navigation system at the National Aerospace Laboratory (NAL). First, the configuration used in the flight experiments, including ground facilities and the measurement systems, is described. Secondly, the design concept for a method of estimating navigation errors using a Kalmann filter is presented. Thirdly, flight profiles employed in the experiments are defined, and the experimental results of GPS, DGPS, INS in both stand-alone and hybrid modes which correspond to each profile are shown. Also, improvement in navigation performance by introducing the DGPS-INS hybrid navigation system was experimentally verified. In conclusion, the design concept of the DGPS-INS hybrid navigation system available for future space vehicles has been successfully completed.

KEY WORD : GPS, INS, Differential GPS, Hybrid Navigation, Terminal Area Navigation, Flight Evaluation

概　要

本論文は，次世代航法システム構築のために進められている DGPS-INS 複合航法システムの飛行評価の概要を記している。地上設備，計測システムを含む飛行実験の構成を述べるとともに，カルマンフィルタを用いた航法誤差評価方法の設計概念を明らかにし，また，実験に用いる飛行プロファイルを定義し，GPS, DGPS, INS の各航法システムの単独あるいは複合モードにおける飛行実験の結果を各プロファイルに即して評価し，DGPS-INS 複合航法システムの導入によって航法性能が向上することを実験的に立証している。最後に，将来の航空宇宙機に適用可能な DGPS-INS 複合航法システムの設計概念が確立できたと結論している。

Abbreviations

A／L : Approach and Landing
DGPS : Differential GPS
DRMS : Distance RMS
ENRI : Electric Navigation Research Institute
GPS : Global Positioning System
GPSR : GPS Receiver
INS : Inertial Navigation System
LTS : Laser Tracking System
MLS : Microwave Landing Sytem
NAL : National Aerospace Laboratory
NASDA : National Space Development Agency of Japan
RA : Radio Altimeter
RCS : Runway Coordinate System
RMS : Root Mean Square
SA : Selective Availability
SD : Standard Deviation
SEP : Spherical Error Probability

* received 1 February 1995
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1. Introduction

Recently, the GPS(Global Positioning System)[1] has drawn attraction as a navigation aid for vehicles such as aircraft, space vehicles, ships, etc. Accuracy of a GPS receiver with Clear and Aquisition (C/A) code is regarded as approximately 100m (2 DRMS) due to the implementation of Selective Availability(SA)[2,3]. Such accuracy is insufficient for navigation during the approach and landing (A/L) of high-manoeuvable vehicles which are now under development or will be developed in the future in Japan. DGPS[4,5,6] is a suitable method for reducing the SA error. If receiving conditions of onboard and base station GPS receivers are identical (both receivers are operated under the same atmospheric conditions), not only SA error but also tropospheric and ionospheric delay errors can be reduced to the extent of positon error of 2~5m (SEP) for a baseline of smaller than 100 km, using a C/A code receiver. Thus, DGPS is able to achieve significantly improved accuracy over the standalone GPS within a local area. Flight evaluation of the DGPS, with a view to applying it to the advanced space vehicles in Japan[5], has been conducted at NAL using the research airplane Dornier Do-228. But DGPS, as well as GPS, has a bad tracking performance[4] for the entire satellite-to-receiver translational motion during high dynamics, including the influence of shadowing by wings in curved flights. And the high DGPS accuracy is limited by the distance between the reference base station and the user. One method of overcoming the drawbacks of the DGPS is the combination of the DGPS with an INS, the so called DGPS-INS hybrid navigation system[4] which is the mixed use of the DGPS with its long term position accuracy and the INS with its good short term dynamic stability. The hybrid navigation system should reach a sufficient accuracy for navigation, guidance and control of space vehicles in A/L phase.

Since 1989, experimental research on the DGPS-INS hybrid navigation system has been conducted with the co-operation of NASDA, ENRI, etc. using the research airplane Dornier Do-228 at NAL in order to establish an autonomous navigation technique[7]. The research for constructing the onboard hybrid navigation system is under way at present. All flight experiments were done at the Sendai International Airport where the Laser Tracking System (LTS) for reference trajectory determination is available. The aim of this research is to pave the way for development of an advanced landing navigation system with higher performance,

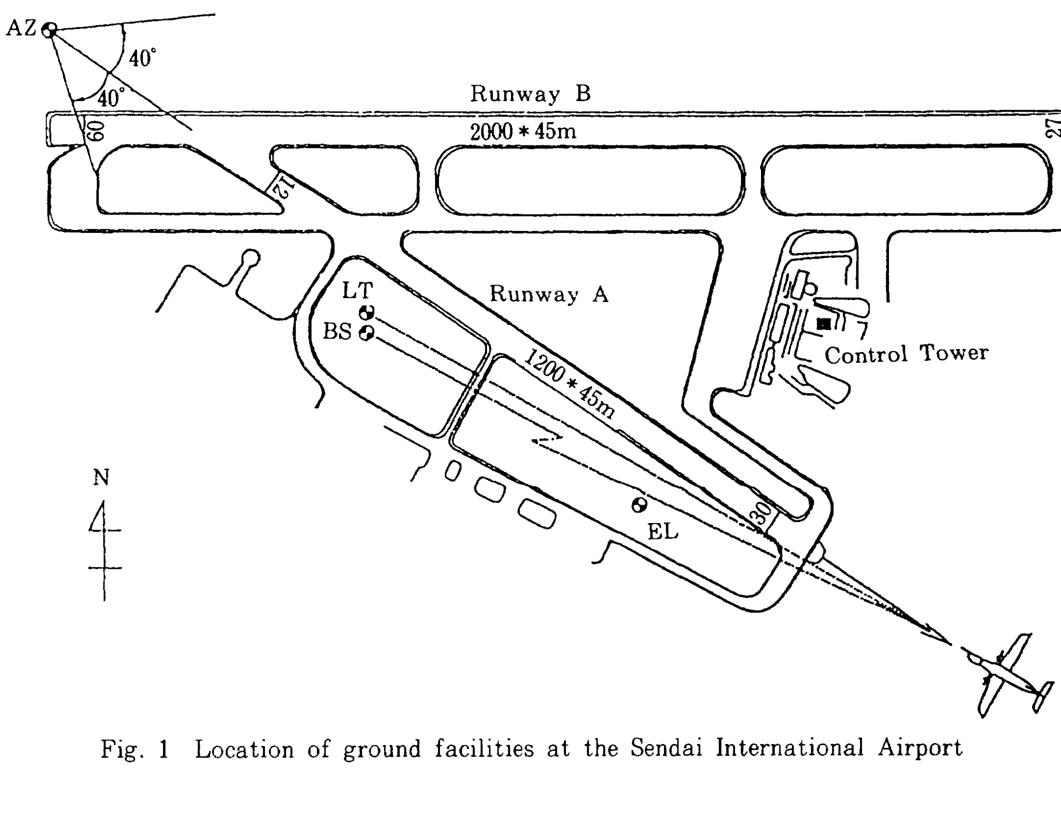

Fig. 1 Location of ground facilities at the Sendai International Airport

which will lead to improvements of the navigation performance of future space vehicles. So the research has been performed based on the viewpoint that it is very important in the process of putting the hybrid navigation system into practical use for aerospace vehicles to evaluate the outputs of the system using highly accurate reference trajectory data under real flight conditions.

2. System Concept of The Flight Experiment

2. 1 Instrumentation System

In the flight experiment for evaluating the DGPS-INS hybrid navigation system conducted at the Sendai International Airport, not only flight data of GPS receivers and INS but also those of other navigation systems such as MLS and RA were obtained at the same time. Fig. 1 shows the location of the ground facilities at the airport concerning those flight experiments. There are two runways at the Sendai International Airport. One is Runway-A (RWY-A), the length of which is 1200 m, and the other is Runway-B (RWY-B), the length of which is 2000 m. A/L experiments for evaluating the hybrid navigation system were conducted using RWY-A. Elevation and azimuth subsystems are set up at points EL and AZ, respectively. The DGPS base station is set up at point BS in Fig. 1 and voice communication is transmitted to the airplane from this point. The LTS is located at point LT in Fig. 1 and measures elevation and azimuth angles and range to the reflectors mounted on the bottom of the airplane nose. Fig. 2 shows an outline of the data acquisition. Flight data are stored in the Flight Data Acquisition System using a personal computer (J3100) along with the data from other navigation sensors. These stored data are synchronized with the LTS data using the Time Code Generator (TCG). The two TCGs shown in Fig. 2 are synchronized before departure in each flight experiment.

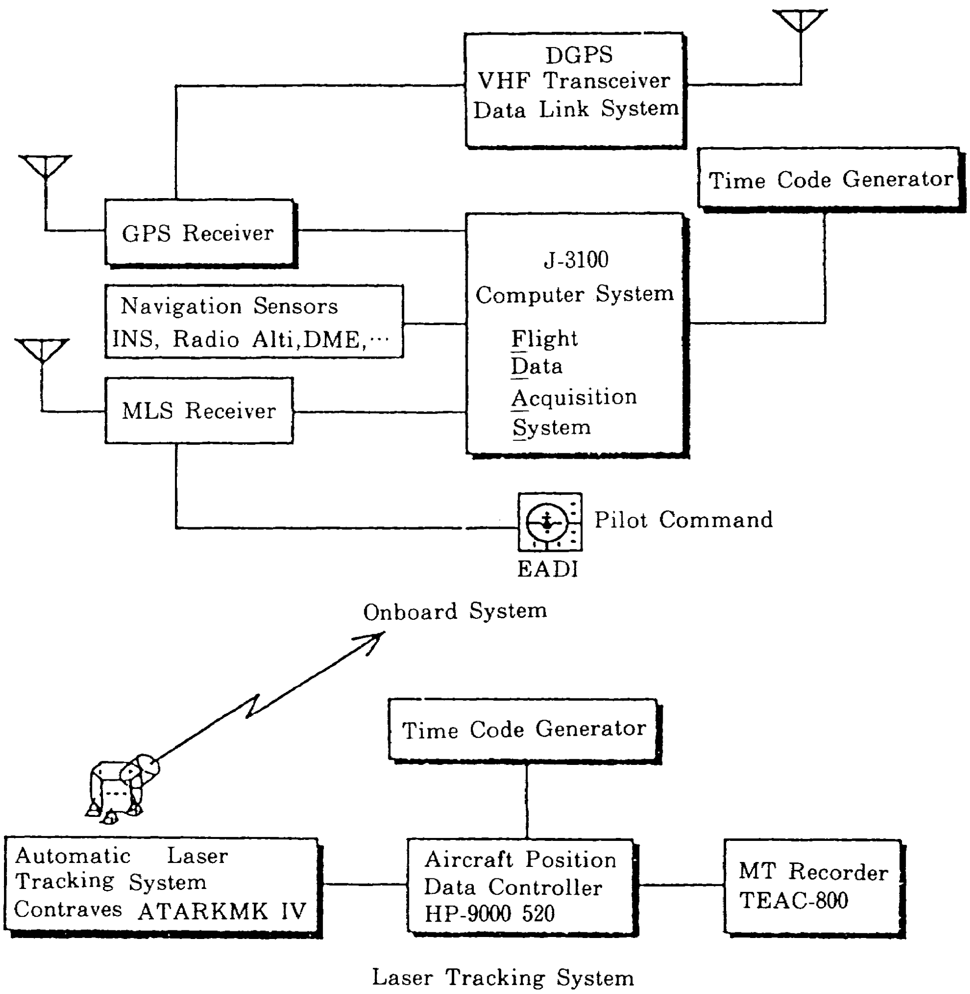

Fig. 2 Onboard and ground-based instrumentation systems

2. 2 Outline of The DGPS-INS Hybrid Navigation System

Configuration of the flight experiment[8] for the hybrid navigation system at NAL is shown in Fig. 3. The hybrid navigation system consists of the on-board and ground-based receivers (NAVCORE-1), the INS (LTN-92 or IMU made by the Toshiba Corporation) and the on-board computer (J3100SGT). The on-board GPS receiver and the INS are interfaced with the on-board computer where output data are stored. The hybrid navigation system in this study does not include an on-line data processing system;the recorded data are processed through off-line data analyses. The pseudorange and deltarange (range-rate) correction data are obtained using the output data measured by the ground-based GPS receiver (GPSR) and transmitted to the airplane by a radio transmitting system, and stored in the onboard computer. When transmitting correction data from ground-based GPSR by a ground-to-air data link, which was developed at NAL, the onboard GPSR is automatically changed to DGPS operation mode. Thus, the DGPS is formed as an on-board system connected by a data-link with a ground-based reference system operating at a known fixed location.

NAVCORE-1 on-board and ground-based receivers[8] are of C/A code single-channel type, and have a DGPS function. The receivers, sequentially acquiring and tracking each visible GPS satellite at 0.25 sec intervals, can measure three-dimensional positions and velocities using a self-contained navigation calculation system.

The INS is composed of three ring laser gyros and three force-rebalanced accelerometers, and is capable of high-rate determination of the three-dimensional positions,velocities and attitudes without the use of external information. The infomation from the INS is transmitted to the on-board computer through ARINC-429 code and is recorded for post-flight data analysis. In order to confirm the performance of the INS, the tests for evaluating the INS errors were conducted using a three-axis motion table. The values of the errors obtained from such tests were used for calibration of the outputs of the gyros and the accelerometers.

2. 3 Loop Configuration for The DGPS-INS Hybrid Navigation System

Various types of hybrid system could be designed in accordance with a degree of mixing of DGPS and INS. For example, there exist two differ-

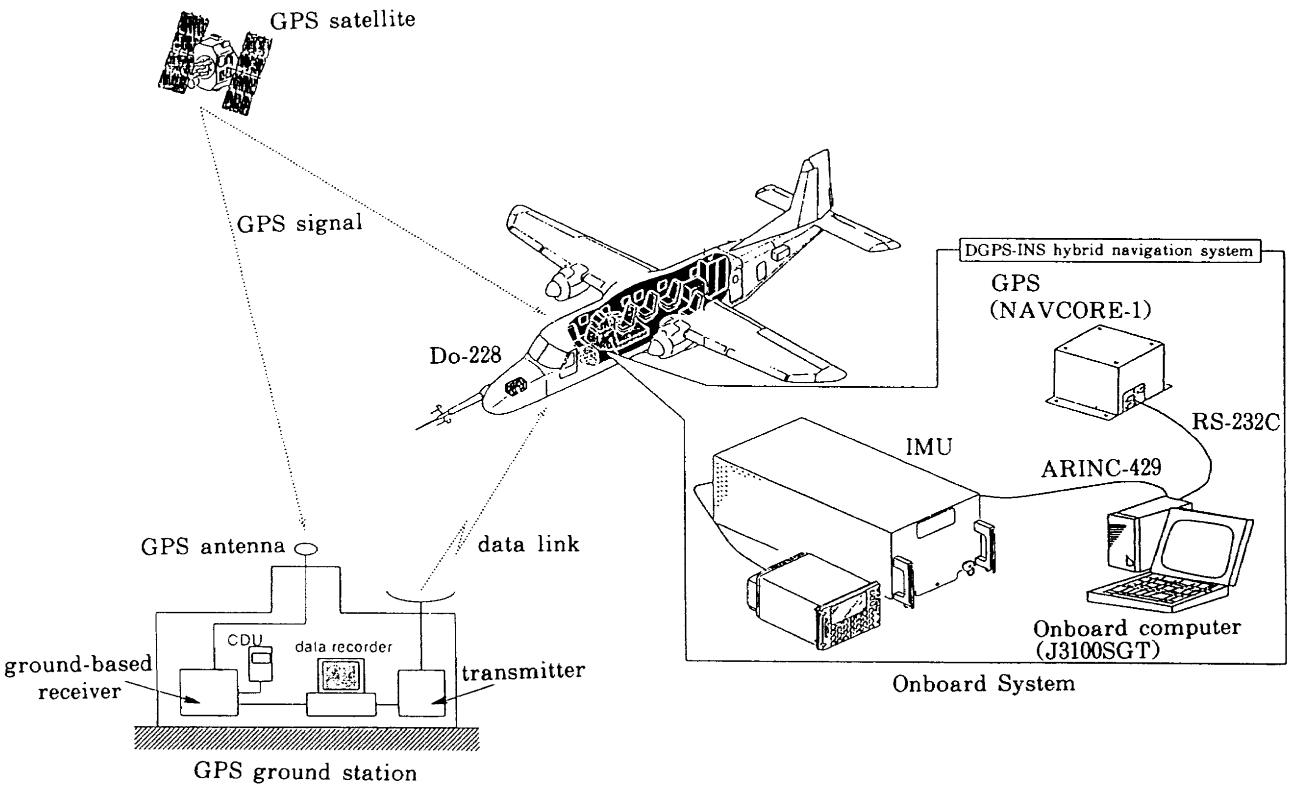

Fig. 3 Configuration for flight experiment of DGPS−INS hybrid navigation system

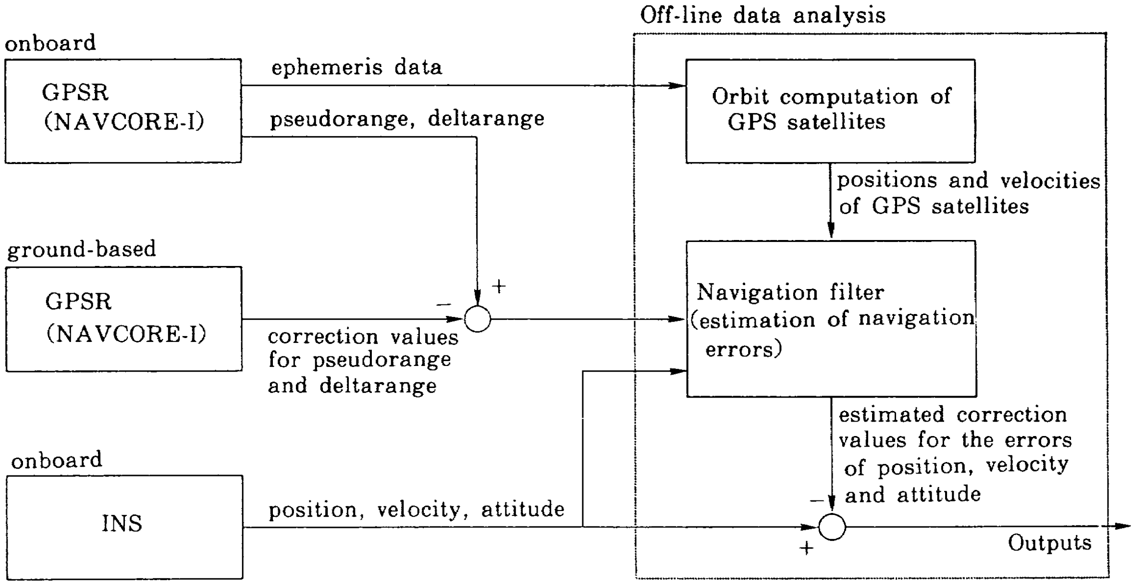

Fig. 4 Open loop DGPS-INS hybrid navigation system

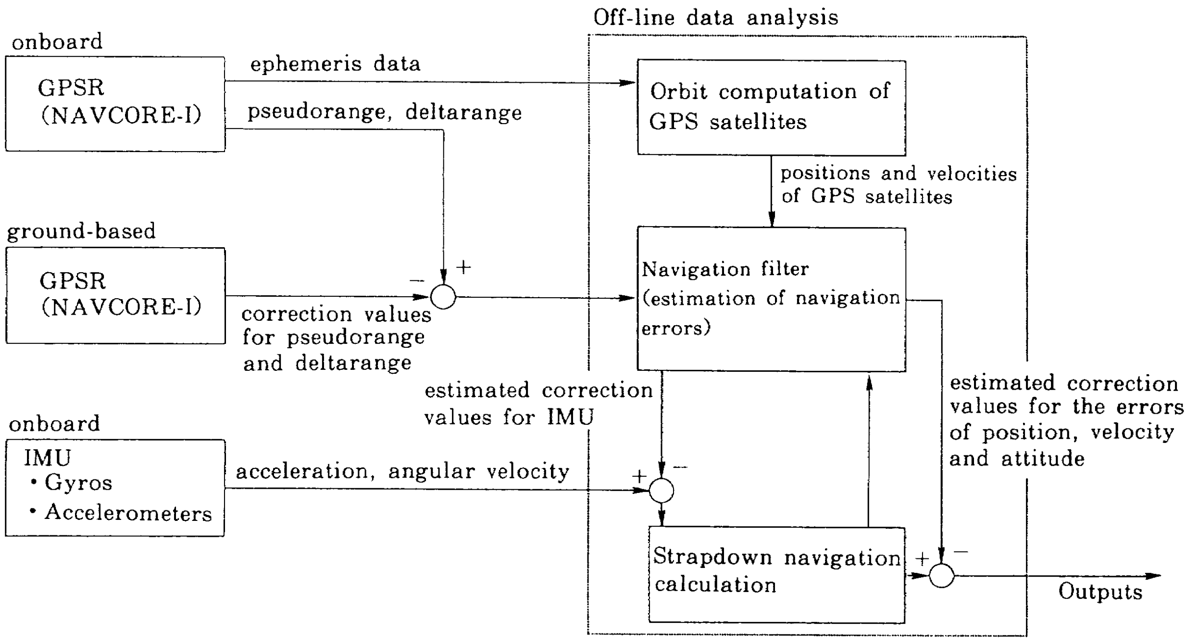

Fig. 5 Closed loop DGPS-INS hybrid navigation system

ent methods[4, 8]. The flows of the signals in a DGPS-INS hybrid navigation system are shown in Figs. 4 and 5. The configuration of DGPS-INS hybrid navigation system in Fig. 4 is called an 'open loop system' in which the outputs from the INS are updated using the correction signals obtained from the difference between output values of the DGPS and the INS without estimating the sensor errors in the INS. State variables estimated in the navigation filter are three-dimensional position and velocity errors and the bias and drift errors of the clock of the GPSR. The eight-state navigation estimation system is formed using a Kalman filter. The open loop DGPS-INS hybrid navigation system can be easily formed using the ready-made INS and GPSR, and is able to attain the positions and velocities even if either the INS or the GPSR fails. However, the navigation accuracy grows worse and worse for long-time navigation or high manoeuvring flight because the reference point of the INS gradually deviates from zero as time passes. It is very difficult to maintain the linearity of the error model because the sensors are not operating near a reference point of zero. The configuration of the DGPS-INS hybrid navigation system in Fig. 5 is called a 'closed loop system' in which the sensor errors of the IMU are estimated by a navigation filter and the estimated correction values are used for strapdown navigation calculation. The reference point of the strapdown navigation calculation is usually kept near zero through the feedback of the estimated sensor errors. Three-dimensional gyro errors, accelerometer errors and attitude errors, in addition to eight variables for the open loop system, are estimated in the navigation filter of the closed loop system. Thus, the number of state variables is 17. The sensor errors are kept low. The linearity of the error model is stable over a long period and the navigation accuracy is maintained high even if there exsits model mismatch of the errors. The outputs of the sensors (gyros and accelerometers) are necessary for the configuration of the closed loop system, and an IMU is used instead of an INS as the inertial sensor system. The IMU made by the Toshiba Corporation was used in this study.

Outputs from the sensors used in the flight experiments are expressed in different coordinate systems. For example, GPSR outputs and INS outputs are expressed in the absolute WGS84 and the relative Earth-fixed coordinate systems[9], respectively. Moreover, an RCS is appropriate to evaluate the navigation accuracy, considering that the flight experiments are mainly concerned with the A/L flight phase. Navigation outputs and LTS determined reference profiles should be expressed in a common navigation reference coordinate system because flight evaluation is made by direct comparison of the navigation outputs with the reference profiles, so an attempt to determine position coordinate of the ground reference point was done in our study and used for the post-flight data analysis. Details of the coordinate systems related to the flight experiments are fully described in reference 9.

3. Algorithm for The Navigation Filter

The DGPS-INS hybrid navigation system is integrated by a Kalmann filter algorithm to update the information about the state vector and its covariance matrix. Navigation errors are adopted as state variables for Kalmann filter estimation in this study. Each element $X_i (i=1\sim9)$ of state variable vector $\boldsymbol{X}$ is defined as a variation of each navigation output. X_1, X_2 and X_3 are the position errors, and X_4, X_5 and X_6 are the velocity errors. X_7, X_8, and X_9 are the attitude errors. Each element X_i $(i=10\sim17)$ of state variable vector $\boldsymbol{X}$ is defined as the errors of the sensor outputs. X_{10}, X_{11} and X_{12} are the gyro bias errors. X_{13}, X_{14} and X_{15} are the accelerometer bias errors. X_{16} and X_{17} are clock bias and clock drift of the GPSR, respectively. Estimation of each state variable $X_i (i=1\sim17)$ is conducted in the navigation filter (see Figs. 4 and 5). Update of the outputs of the navigation calculation and the sensors is conducted using the estimated state variable $\overline{X}_i (i=1\sim17)$. The system equation for a seventeen-state model in Kalmann filter estimation is defined as follows:

$$\dot{\boldsymbol{X}}=\boldsymbol{F}\cdot\boldsymbol{X}+\boldsymbol{u} \tag{1}$$

$$\boldsymbol{X}=[X_1,\ X_2,\ X_3,\ \cdots\cdots,\ X_{17}]^T \tag{2}$$

Here, $\boldsymbol{X}$ is a 17-dimensional vector and $\boldsymbol{F}$ is a 17 by 17 matrix whose elements $f_{ij} (i,\ j=1\sim17)$ are obtained from the navigational parameters of an airplane, outputs of the gyros and the accelerometers and the terrestrial constants. $\boldsymbol{u}$ is a system noise vector with a 17 by 17 covariance matrix $\boldsymbol{Q}$. Considering that positions and velocities of the airplane are updated using the outputs from the DGPS as the reference, measurement data (Y_1, Y_2 for Kalmann filtering are used in the following form:

$$Y_1=\tilde{\rho}_{\mathrm{INS}}-\tilde{\rho}_{\mathrm{GPS}} \tag{3}$$

$$Y_2=\tilde{\dot{\rho}}_{\mathrm{INS}}-\tilde{\dot{\rho}}_{\mathrm{GPS}} \tag{4}$$

Here, $\tilde{\rho}_{\mathrm{INS}}$ and $\tilde{\dot{\rho}}_{\mathrm{INS}}$ are the relative range and the relative range-rate of the airplane to the GPS satellite, respectively, which are obtained from the INS outputs(see Figs. 4 and 5). $\tilde{\rho}_{\mathrm{GPS}}$ and $\tilde{\dot{\rho}}_{\mathrm{GPS}}$ are the pseudorange and the deltarange, respectively, measured by the onboard GPSR. Considering that the measurement data are modelled in the form of equations (3) and (4), measurement equation assumed in Kalmann filtering is defined as follows:

$$\boldsymbol{Y}=[Y_1\ \ Y_2]^T=\boldsymbol{G}\cdot\boldsymbol{X}+\boldsymbol{v}$$

$$=\begin{bmatrix}\rho_{\mathrm{INS}}-(\rho_{\mathrm{GPS}}+X_{16})+v_1\\ \dot{\rho}_{\mathrm{INS}}-(\dot{\rho}_{\mathrm{GPS}}+X_{17})+v_2\end{bmatrix} \tag{5}$$

ρ_{INS} and $\dot{\rho}_{INS}$ are the analytic functions for $\tilde{\rho}_{INS}$ and $\tilde{\dot{\rho}}_{INS}$, respectively. ρ_{GPS} and $\dot{\rho}_{GPS}$ are the analytic functions for $\tilde{\rho}_{GPS}$ and $\tilde{\dot{\rho}}_{GPS}$, respectively. $\boldsymbol{G}$ is a 2 by 17 matrix whose elements G_{ij} ($i=1$, 2, $j=1\sim17$) are obtained from the positions and the velocities of the airplane and the GPS satellite ephemeris(as the first order approximation). $\boldsymbol{v}$ is a measurement error vector with covariance matrix $\boldsymbol{R}$. Both system equation (1) and measurement equation (5) are linearly dependent on the state variables, which are derived as the first-order variable quantities (the errors) of the navigation outputs and the sensor outputs. Equations for time update and measurement update in Kalmann filtering are derived based on the equations (1) and (5), respectively.

4. Results of The Flight Experiments

Two different flight phases, one being an orbit phase and the other being an approach phase, were introduced in the flight experiments. Here the orbit phase means the flight phase where the airplane turns along an orbit with a radius of 7408m (=4 n. m.) at an altitude of 1828.8m (=6000ft). The approach phase means the flight phase where the airplane descends at an elevation angle of 3° toward the runway from a point whose altitude is 457.2m (=1500ft). Latitude, longitude and altitude of the GPS base station at the airport were determined by GPS interferometric surveying[9]. The output data from INS, IMU and onboard GPSR were stored in the onboard computer(J3100SGT), and the post-flight data analyses were performed based on the operation modes of INS stand-alone, GPS stand-alone, DGPS stand-alone and DGPS-INS hybrid navigation.

The curves in Fig. 6 show the flight profile of the GPS measurement data projected on the X-Y plane in the RCS. The profile contains both the orbit and approach flights obtained from the measurement data of the GPS stand-alone operation

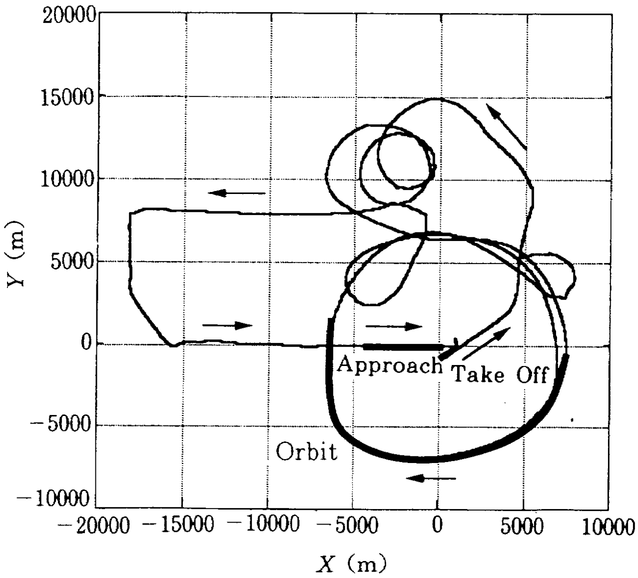

Fig. 6 A flight profile used in the experiment

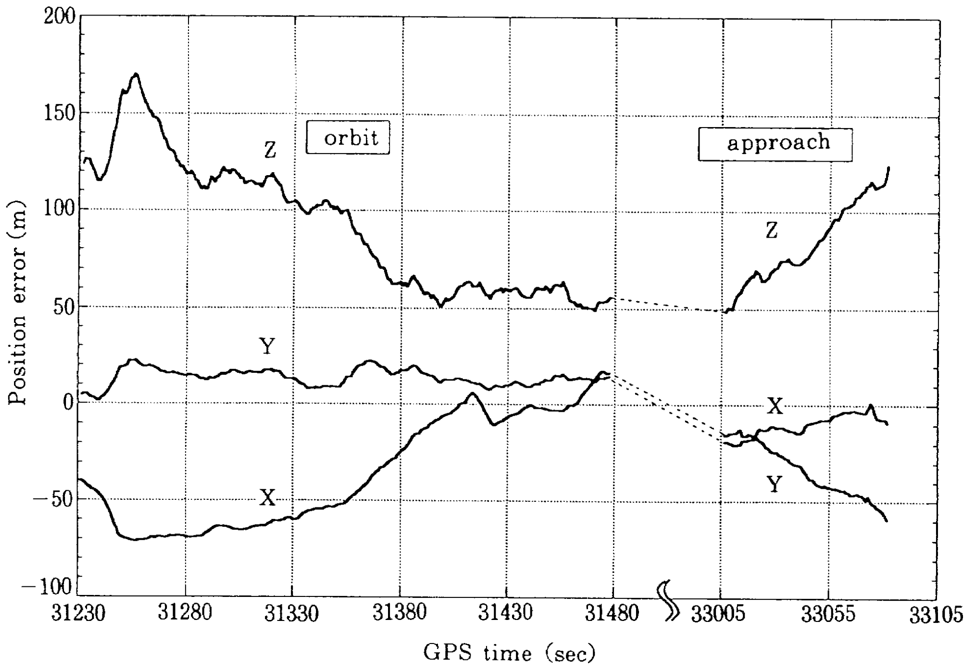

Fig. 7 Position error in the GPS stand-alone navigation

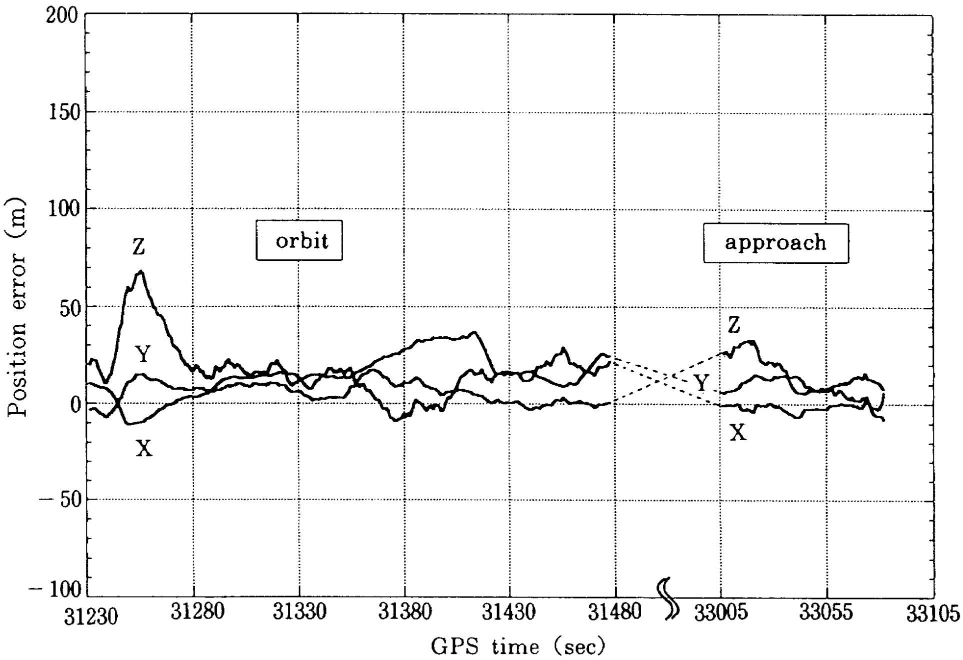

Fig. 8 Position error in the DGPS stand-alone navigation

mode. Bold solid lines show the segments of orbit to which the LTS data were available. The profile is complicated on the whole because the research airplane had to wait for permission to land on the runway. This profile was used in the GPS and the DGPS stand-alone navigation experiments. Figs. 7 and 8 show the position errors in GPS stand-alone and differential GPS operation modes, respectively. It is clear that navigation errors can be reduced a great deal by the introduction of the differential operation mode. The position and velocity at the antenna phase centre of the GPSR are measured in GPS navigation, while those in the optical centre are measured in the LTS. Thus, there exists a difference of the measurement position in GPS navigation and the LTS. Geometrical corrections for the difference between the position in the GPSR and that in the LTS have not been applied. If such a correction is adopted, the position errors in DGPS navigation would be less than the values shown in Fig. 8. As the position errors of the NAVCORE-1 GPSR are about 8 to 10 m for a baseline of less than 100 Km, the values of the position errors in Fig. 8 are considered to be equivalent to the precision of the GPSR.

The curves in Fig. 9 show the flight profile of the INS measurement data projected on the X-Y plane in the RCS. The profile contains both the orbit and approach flight phases. Bold solid lines show the segments of orbit where the LTS data were available. This profile was used in the experiments for evaluating the DGPS-INS hybrid navigation system. Figs. 10 and 11 show the estimated values of position errors in INS stand-alone and open loop DGPS-INS hybrid navigation system, respectively. It is found from these curves that the values of the INS position errors reduced up to the level of GPS errors (see Figs. 7 and 8) through the introduction of the hybrid system. It is also found that the position error reducing effect in open loop

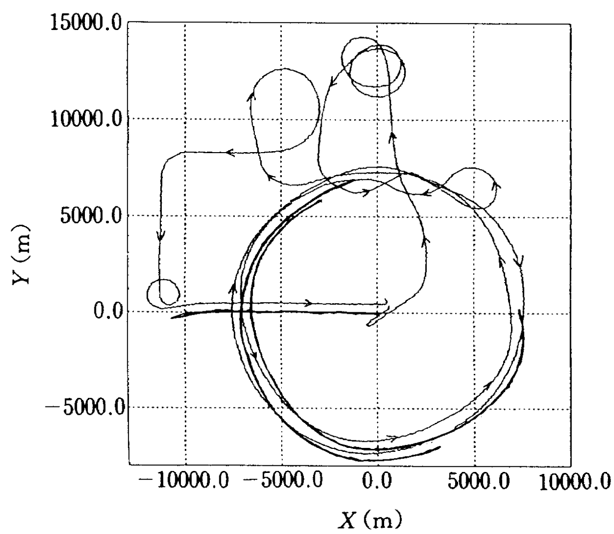

Fig. 9 A flight profile used in the experiment of DGPS−INS hybrid navigation

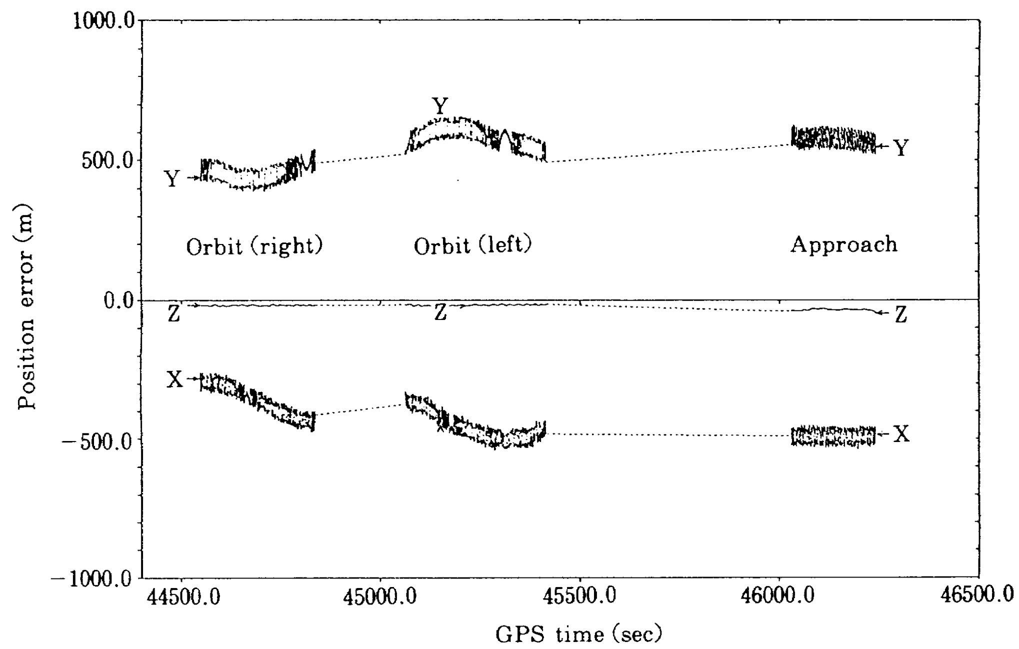

Fig. 10 Position error in the INS stand-alone navigation

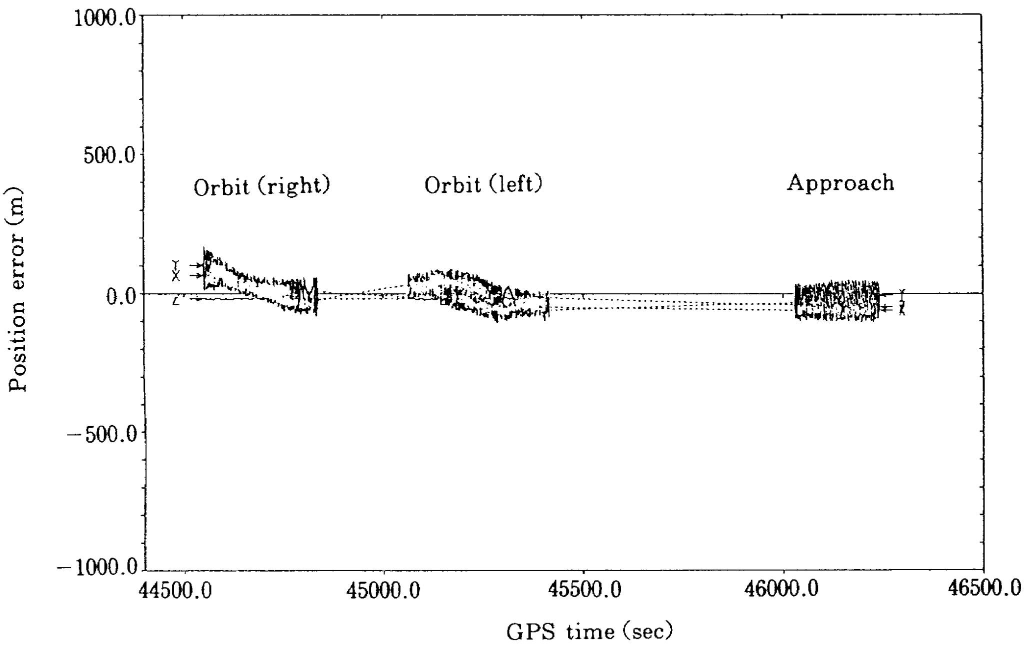

Fig. 11 Position error in the DGPS-INS hybrid navigation

DGPS-INS hybrid navigation system is of the same order as that in the GPS stand-alone navigation. Dotted lines in Figs. 10 and 11 mean that the navigation errors were not available because the data from the LTS were not collected. Navigation errors were obtained only in the intervals shown with solid curves in each phase of orbit(right turn), orbit(left turn) and approach. Velocity error reducing effect due to hybridization of the DGPS and the INS was not so remarkable, though velocity errors are not shown in this paper. The cause is considered to be that flight time is short or that the accuracy of the velocity measured by the LTS was not sufficient.

5. Conclusions

A fundamental concept concerning off-line flight data analyses of the DGPS-INS hybrid navigation system as shown in Figures 3 and 4 has been established. The design method of the navigation filter for constructing the hybrid navigation system has also been established. The results of the flight experiments show that the concept of a DGPS-INS hybrid navigation system[10] designed at NAL is applicable for the design of on-board real time system.

Additionally, research on the onboard DGPS-INS hybrid navigation system using newly developed IMU and high-precision GPS receivers (Trimble 4000 sse) is underway at NAL. Position error of such new hybrid navigation system is expected to be less than a few metres.

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