ISSN 0389-4010
UDC 527.62
533.696
629.783

TECHNICAL REPORT OF NATIONAL AEROSPACE LABORATORY

TR-1194T

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March 1993

NATIONAL AEROSPACE LABORATORY

CHŌFU, TOKYO, JAPAN

A GPS Surveying Method Applied to Terminal Area Navigation Flight Experiments*

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ABSTRACT

Flight experiments have been conducted at the Sendai airport using the experimental research aircraft Dornier-228-200 (Do-228) of the National Aerospace Laboratory (NAL). The objective is to evaluate new navigation sensor technologies which will play a key role in the design of terminal area navigation systems for aerospace vehicles including HOPE (H-II Orbiting Plane). The navigation sensors tested include Microwave Landing System (MLS), Global Positioning System (GPS), Inertial Navigation System (INS), and radio altimeter. Differential GPS (DGPS) is also tested in both standalone and hybrid modes. During the flight, the Do-228 is tracked by a laser tracker to provide reference profiles of the aircraft. In these experiments, navigation accuracy is evaluated as the difference between the reference profile and navigation output from respective navigation sensor or hybrid systems in the post-flight analysis mode. This comparison is not possible without establishing a common reference navigation frame on which all navigation outputs are transformed. In this paper, a method based on GPS surveying is proposed and applied to establish such a reference frame and position coordinates of the ground-based navigation-aid facilities. Examples of application of the surveying results are presented which evaluate standalone GPS navigation accuracy of NAVCORE-1 GPS receiver for the approach／landing(A／L)and orbit flight phases.

Keywords: GPS (Global Positioning System), GPS surveying, carrier phase, flight testing, terminal area navigation

概　要

マイクロ波着陸誘導システム(MLS), 全世界測位衛星システム(GPS), など新しい進入・着陸航法系の精度評価を目的とした飛行実験を, 仙台空港において当所の実験用航空機Dornier228-200を使用して実施している。本機には, GPS受信機NAVCORE-1（C/Aコード, 1チャンネル）が搭載されている。さらに, 地上のNAVCORE-1受信機と組合せて, ディファレンシャルGPSも行える。精度評価は, レーザートラッカによる航空機の追跡データからカルマンフィルタにより標定された基準軌道と, 航法結果との直接比較により行う。ところで, GPSはWGS84 系という地心地球固定の世界測地系に関する絶対的な位置・速度情報を出力する。従って, GPS単独あるいは慣性航法装置(INS) 等との複合航法の結果を基準軌道または他の航法センサ出力と比較するためには, WGS84 系に準拠した高精度な航法基準座標系を構築する必要がある。これは, それほど簡単ではない。本論文では, この問題に対するGPS位相干渉測位を応用した手法を提案し, 実際に飛行実験データの解析に適用し, 1応用例としてNAVCORE-1による単独航法精度の評価に応用した結果を述べる。

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* Received 10 July 1992

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1. Introduction

Electronic Navigation Research Institute (ENRI), National Space Development Agency of Japan (NASDA), and National Aerospace Laboratory (NAL) have been collaborating on the flight experiments of navigation systems at the Sendai airport to obtain technical data for the design of terminal area navigation system of aerospace vehicles including HOPE (H-II Orbiting Plane)1), 2), 3) . At the Sendai airport an experimental microwave landing system (MLS) and a laser tracker for precision profile determination of an aircraft, both ENRI's facilities, are available. The Dornier-228-200 (Do-228), a flight research aircraft of NAL, is used in the flight experiments. Navigation sensor data for MLS, Global Positioning System (GPS), radio altimeter, Inertial Navigation System (INS), and so on are collected, and navigation performance for integrated navigation systems such as differential GPS (DGPS), hybrid DGPS-INS, hybrid DGPS-MLS and others, as well as navigation accuracies and fundamental characteristics for respective standalone systems, is evaluated in the post-flight analysis mode. Evaluations are made by direct comparison of navigation results from both standalone and hybrid systems with reference profiles determined by the laser tracker. For the comparison, both navigation results and the reference profiles should be expressed in a common navigation reference coordinate frame. Furthermore, we need accurate position coordinates for the ground facilities such as the MLS, the DGPS base station, the laser tracker, etc, which also should be expressed in the same reference frame.

Depending on the objectives and accuracy requirement of the flight navigation experiments, several options can be selected for the way to build up such a reference coordinate frame. However, as our ultimate goal is the flight evaluation and demonstration of the terminal area navigation operations with particular concerns on HOPE app roach/landing (A/L) navigation systems, such a reference frame and position coordinates of the ground facilities should be surveyed with the accuracy being better than or at least commensurate with the required level for the HOPE A/L navigation, which is typically of better than 1 m in absolute position.

Moreover, GPS is one of the core navigation sensors tested in the flight experiments and it produces absolute position and velocity information in the *World Geodetic System 1984* (WGS84)4) which is the Earth-Centered-Earth-Fixed (ECEF) system, so that it is clearly convenient from analysis point of view to use a common navigation reference frame established in a sense *with reference to the WGS84.*

The conventional survey techniques are not always adequate for non-professionals to determine the *geocentric positions* with high accuracy required for our objectives, while GPS could provide the easy means for such surveying. One of the basic GPS observables is carrier phase which is ambiguous range from GPS satellite to a receiver. Positioning using GPS phase data is often called GPS surveying or GPS interferometric positioning.

In this paper, a method to determine the common reference frame using GPS surveying is proposed and the results of application to the flight experiments are shown. By the method, the accurate coordinates of reference points on the ground facilities are obtained in the WGS84 system, and reference navigation coordinate frame referred to WGS84 is also established. Finally, usefulness of the coordinate frame established in that way is shown by examples taken from flight evaluation results of standalone GPS navigation accuracy of NAVCORE-1 GPS receiver.

2. Proposed Method and GPS Survey Results

Among navigation sensors tested in the experiment, only GPS outputs *absolute* position and velocity expressed in the WGS84 system, while outputs from other sensors are essentially *relative*. Furthermore, as we are concerned with flight experiments in the terminal area flight operation, it is convenient that navigation accuracy be evaluated in a Runway Coordinate System (RCS), a local frame, rather than in the ECEF system. From these reasons, we adopt the RCS referenced to the WGS84 as a fundamental navigation coordinate system for the flight experiments. The RCS is defined in such a way that, with the origin at the center point of the runway threshold (TH/30) (see Fig.1), the x-axis (along-track) is parallel to the center line of the runway passing towards to the runway threshold (TH/12), the y-axis (cross-track) is perpendicular to the x-axis in the horizontal plane at the origin, and the z-axis (vertical) completes the right handed system$^{3)}$.

As already mentioned, position coordinates for the ground facilities including DGPS antenna and laser tracker should be given in both the WGS84 and RCS for the analysis. So, in an atempt to establish the RCS and to determine position coordinates of the ground control points, we took the following approach consisting of three steps.

In the first step, one geodetic control point (named #06) in the Sendai airport was determined using GPS surveying technique. In GPS surveying, two GPS geodetic receivers, both dual frequency model Trimble 4000SST, were used. They were set up at Sendai and Tsukuba to collect phase data concurrently for the same scheduled period of time. The GPS observation was made on September 4, 1991, 10:00 – 14:00 JST. The reason why Tsukuba was selected is as follows. Several geodetic control points are available in Japan whose position coordinates have been determined at a few centimeter level in the world terrestrial frames by space geodetic technologies such as VLBI and satellite laser ranging (SLR). One of such points nearest to Sendai is that of Tsukuba which has been established and maintained by the Geographic Survey Institute (GSI) using VLBI.

In this study, we used a point called GSI#05 in GSI at Tsukuba. The coordinate of GSI#05 was originally determined in the VLBI coordinate system, and converted into the ITRF90 (*International Earth Rotation Service (IERS) Terrestrial Reference Frame 1990*)$^{5)}$ (see Table 1). The coordinate of GSI#05 in the ITRF90 can be further transformed into the WGS84 by the following 7-parameter transformation$^{6),7)}$:

$$\begin{pmatrix} XS \\ YS \\ ZS \end{pmatrix}_{WGS\,84} = \begin{pmatrix} T1 \\ T2 \\ T3 \end{pmatrix} + \begin{pmatrix} 1+D & -R3 & R2 \\ R3 & 1+D & -R1 \\ -R2 & R1 & 1+D \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ITRF90}$$

where

$T1 = 0.071\,m$

$T2 = -0.509\,m$

$T3 = -0.166\,m$

$D = -0.0173 \times 10^{-6}$

$R1 = 0.0179''$

$R2 = -0.0005''$

$R3 = 0.0067''$

The position coordinate for Tsukuba (GSI#05) in the WGS84, after this transformation, is given in Table 1.

Phase data collected at both sites were analyzed by a baseline analysis program TRIMVEC to obtain baseline vector with its baseline length, and the coordinate of Sendai (#06), the other end of baseline, was then determined by fixing Tsukuba coordinates. The result is also summarized in Table 1. The error in the final coordinate of Sendai includes error in the values used for the 7-parameter transformation as well as error in GPS survey. The accuracy is estimated to be within one meter in absolute position and some tens centimeters in relative position. In this way the geodetic reference point at Sendai with reference to the WGS84 has been

Table 1. Baseline determination between Tsukuba(GSI＃05) and Sendai(＃06)in WGS84.

Point	*X*	*Y*	*Z*
Tsukuba (ITRF90)	-3957205.5150	3310196.2264	3737711.4236
Tsukuba (WGS84)	-3957205.492	3310195.207	3737711.471
Sendai (WGS84)	-3899060.518	3166938.421	3917349.579
baseline length	237008.8491	± 0.0057	
dx	58144.974	± 0.018	
dy	-143256.786	± 0.010	
dz	179638.108	± 0.008	

units : meters

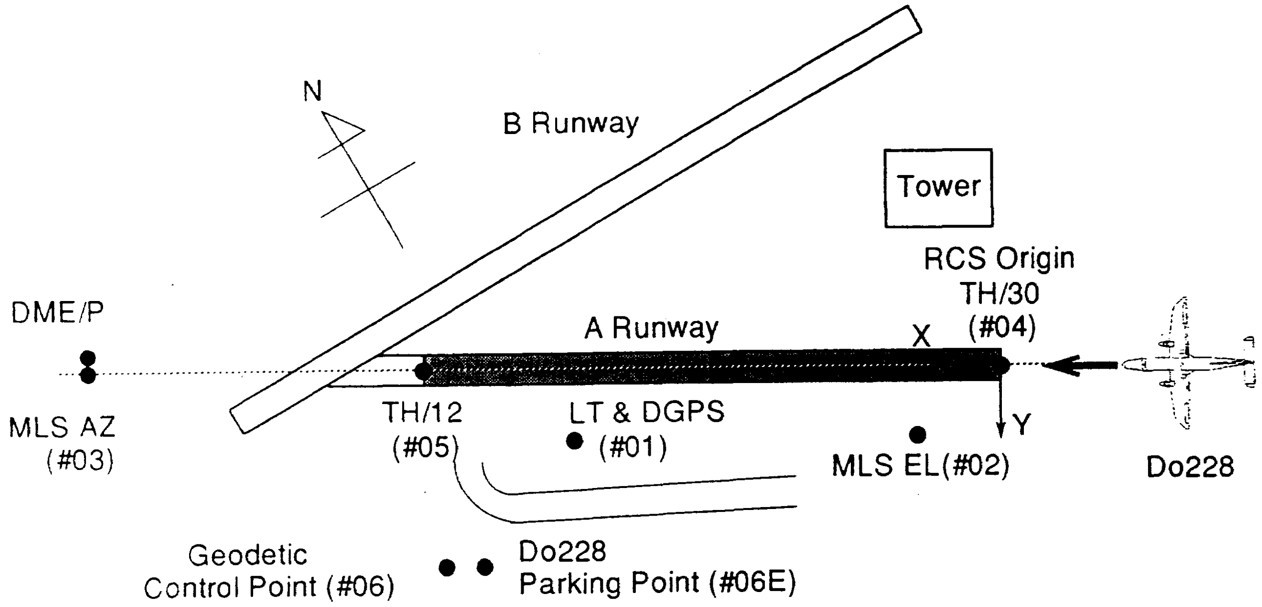

Fig. 1. Location of ground facilities and GPS survey points at the Sendai airport.

established.

In the second step, the following six control points in the Sendai airport were surveyed using dual frequency GPS geodetic receivers, Trimble 4000SST.

1) laser tracker (LT) and DGPS base station (＃01)
2) MLS EL (＃02)
3) MLS AZ and DME/P (＃03)
4) TH/30 on the runway A (＃04)
5) TH/12 on the runway A (＃05)
6) geodetic reference point (＃06)

These control points except ＃06 are built near each navigation facility in order to determine their precise positions. Note that MLS is generally composed of angular and ranging subsystems: MLS AZ (azimuth), MLS EL (elevation), and DME/P (Distance Measuring Equipment/Precise), and their antennas are located at different places as shown in Fig.1.

The GPS observation was conducted on October 3, 1991, 8:50 – 22:30 JST, in which three GPS receivers were used for time saving. Phase data were collected concurrently at each of three pairs of control points, and analyzed by TRIMVEC to obtain baseline vectors with its baseline lengths. Note again that baseline vectors have components expressed in the WGS84. Thus, starting from a geodetic control point (＃06) surveyed accurately in the WGS84, we can determine position coordinates of the remaining survey points with a comparable accuracy to the control point #06. The coordinates obtained are summarized in Table 2.

Finally, in the third step, laser theodolites were used to locate reference points for the phase centers of antennas and the optical center of the laser tracker, relative to the ground survey points obtained in the second step. Of course, we cannot put a set of retroreflector prisms directly on a phase center itself, but we can only measure a point near the phase center using theodolites. Thus, geometrical corrections to theodolite-determined points using the specifications need to be applied to obtain the true coordinates of the phase centers and the optical center. The antenna phase center of a GPS receiver in the Do-228 at the parking point is presumed to be just over the ground marker(#06E) which is one of the survey points by the theodolite. Final results for position coordinates in the WGS84 and in the RCS are summarized in Table 3. The ground DGPS system used the position coordinate (#DGPS) for its antenna phase center to generate differential corrections which are sent to the aircraft in real-time via radio link.

Table 2. GPS survey results for ground control points in the Sendai airport.

Point	X_{WGS84}	Y_{WGS84}	Z_{WGS84}
# 01	-3899109.814	3166740.617	3917460.356
# 02	-3899616.077	3166429.836	3917209.160
# 03	-3898410.293	3167105.683	3917857.582
# 04	-3899772.171	3166223.846	3917220.569
# 05	-3898835.388	3166831.549	3917659.526
# 06	-3899060.518	3166938.421	3917349.579

units : meters

In this way a reference frame and reference position coordinates have been established with respect to the WGS84. The accuracy is estimated to be within one meter at maximum for each coordinate component. On the basis of this reference coordinate system, navigation performance can be evaluated. It is stressed here that in total only two days were spent to end up the whole GPS surveying composed of the first and second steps.

In summary, GPS surveying has proven to be a simple and powerful means to establish absolute reference frame as well as relative reference frame, both with reference to the World Geodetic System. It can be done with high precision and in a short time even by non-professionals in surveying.

Table 3. Summary of reference position coordinates of respective navigation facilities.

Point	X_{WGS84}	Y_{WGS84}	Z_{WGS84}	X_{RCS}	Y_{RCS}	Z_{RCS}
# DGPS	-3899093.022	3166758.883	3917466.530	891.244	116.979	2.198
# 06E	-3899072.167	3166938.349	3917338.112	951.444	330.288	-0.875
# LT	-3899101.349	3166748.842	3917465.385	879.238	111.786	1.601
# MLS-EL	-3899603.027	3166430.585	3917225.923	238.735	119.911	2.456
# MLS-AZ	-3898401.451	3167116.455	3917866.212	1758.540	0.068	3.757
# DME/P	-3898402.280	3167112.771	3917872.042	1758.160	-6.482	6.037

units : meters

Notes :

1. RCS	Runway coordinate system
2. LT	Laser tracker
3. MLS-EL	MLS elevation subsystem
4. MLS-AZ	MLS azimuth subsystem
5. DME/P	Distance measuring eqipment/precise

3. Examples of Application

As an application of GPS surveying results described in the previous section, analysis results of standalone GPS navigation data taken in the second flight experiment at the Sendai airport in January 1991 are presented[8), 9)]. GPS receiver tested is Rockwell International/Collins NAVCORE-1 which is a sequential, L1 C/A code, 1 channel receiver. It should be noted that *selective availability* (SA)[10)] was off during the flight experiment period. SA is a term used to describe the intentional degradation of the C/A code by the DoD for national security reasons, and it will be accomplished through manipulations of both navigation message orbit data and satellite clock frequency

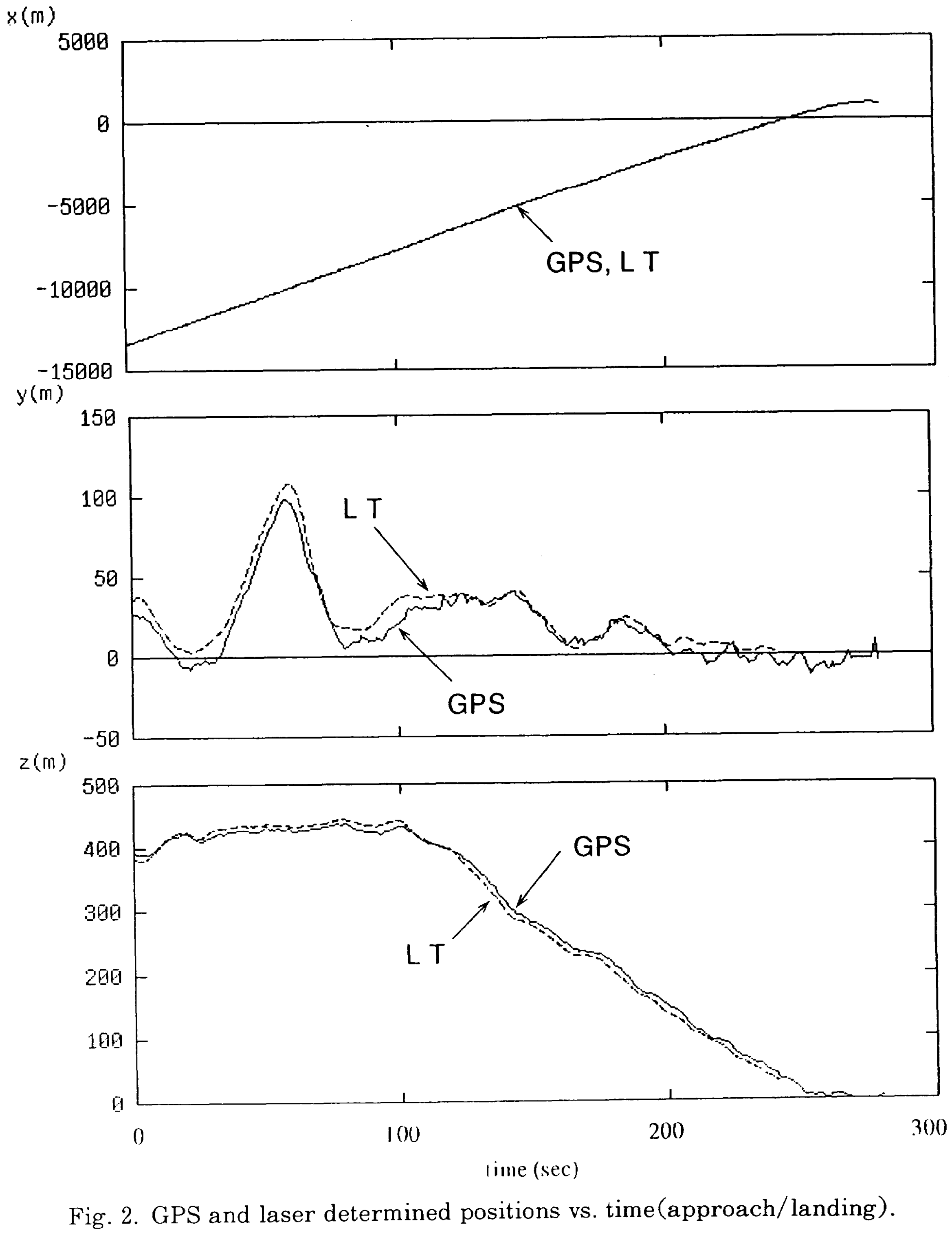

Fig. 2. GPS and laser determined positions vs. time(approach/landing).

dithering. With SA turned-on, the estimated user position will deteriorate to the extent of an error of 100 m, two distance root-mean-square (2 drms).

It is not always an easy task to accurately evaluate navigation accuracy for vehicles in aerospace, because their accurate 3-dimentional reference trajectories are difficult to obtain in general. In this study, evaluations were performed by direct comparison with laser determined profiles. Laser tracker ranges to the retroreflectors mounted at the bottom of the aircraft nose, and measures range, azimuth and elevation at a rate of 60 Hz. Accuracy in laser range is about 30 cm (rms), and accuracy in azimuth and elevation is 0.006 degrees (rms). Laser data are time-tagged on the basis of TCG

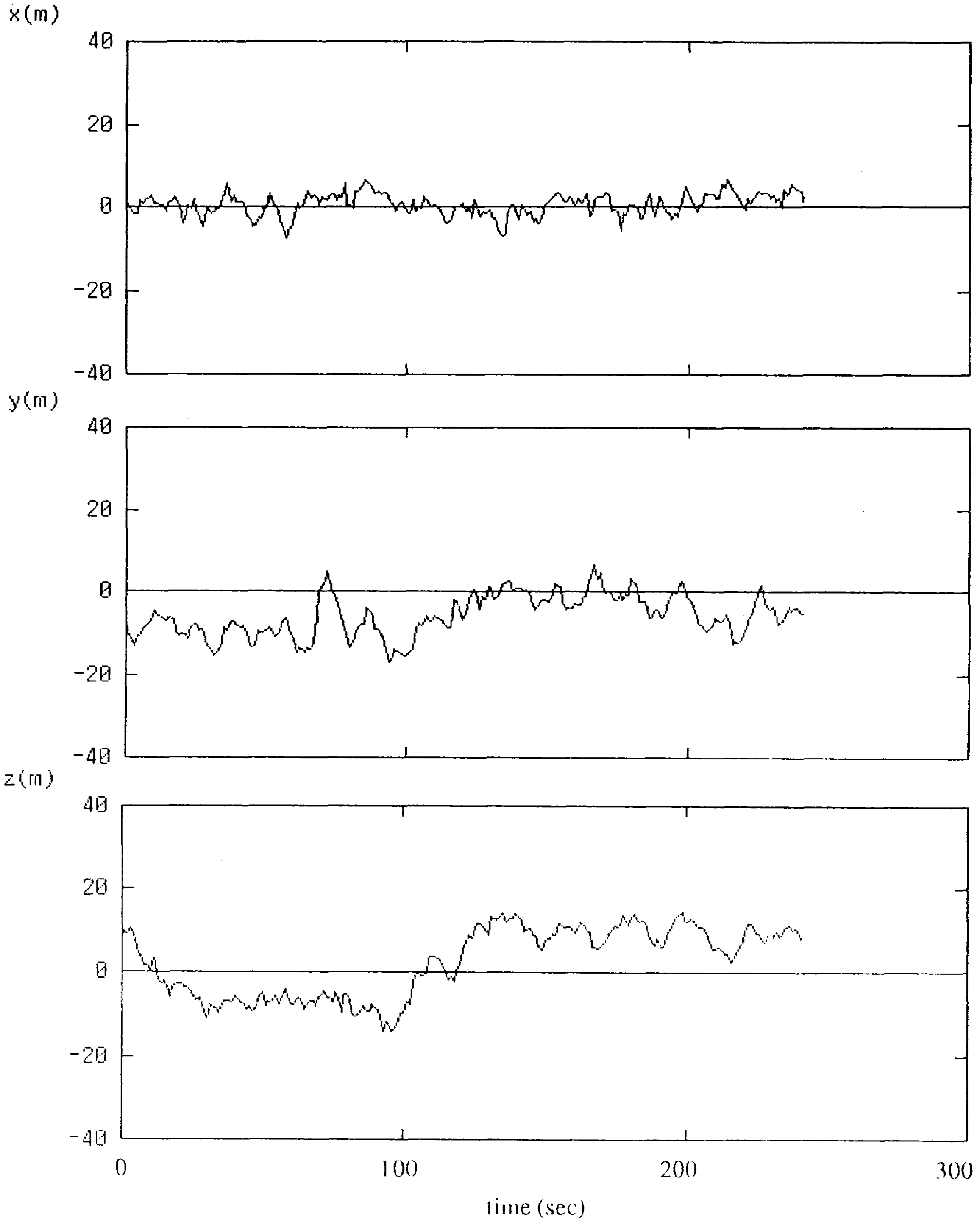

Fig. 3. Differences between GPS and laser determined positions(approach/landing).

(Time Code Generator) controlled by a rubidium atomic oscillator. The extended Kalman filter[11] was applied to sequentially process laser tracker data for the determination of the reference position and velocity of the *laser retroreflector location* of the aircraft in the laser coordinate system. This process was done off-line.

The reference profiles of the retroreflectors were then converted into the RCS, and further transformed into those of the location of the GPS antenna phase center, by assuming the aircraft at a level-flight and applying offset correction[12]. All navigation sensor data collected onboard the aircraft are also time-tagged using an onbord TCG which is presumed to be synchronized with ground TCG time. This synchronization is

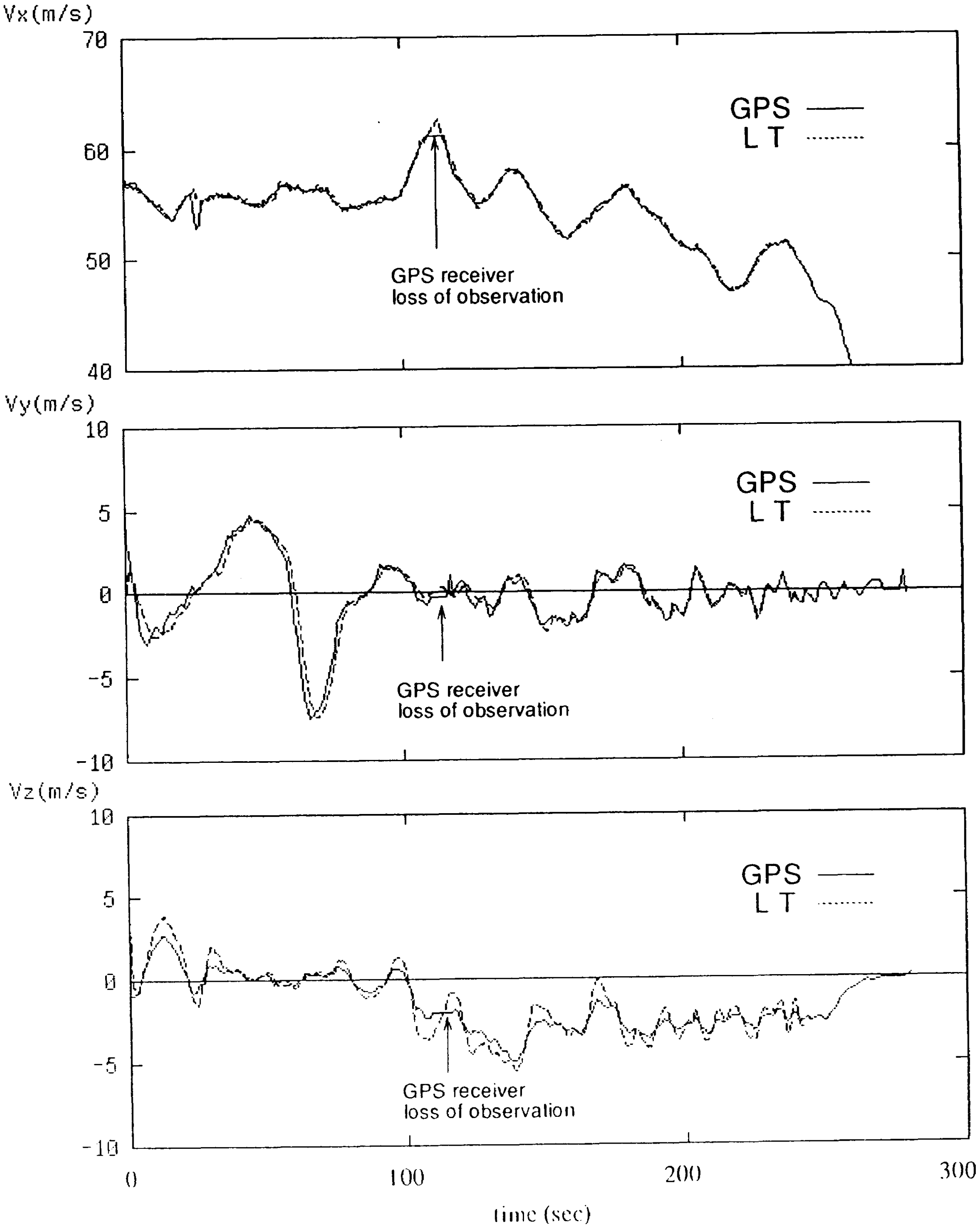

Fig. 4. GPS and laser determined velocities vs. time(approach/landing).

performed by time comparison between TCGs at each start time of the flight experiments. Analysis indicates synchronization error is within a few milli-seconds at the end of the flights of about one hour or so. NAVCORE-1 outputs navigation solution at every 1 second of GPS time, and GPS time was related to TCG time later in the post-flight analysis.

(1) **A/L flight case**

Fig. 2 shows GPS and laser determined positions (in the RCS)vs. *TCG time* for the A/L flight case at a flight path angle of 3 degrees. Here, *position and velocity of the aircraft stand for those of the location of the GPS antenna phase center.* Fig. 3 shows the three-axis position differences between GPS and laser determined trajectory, both shown

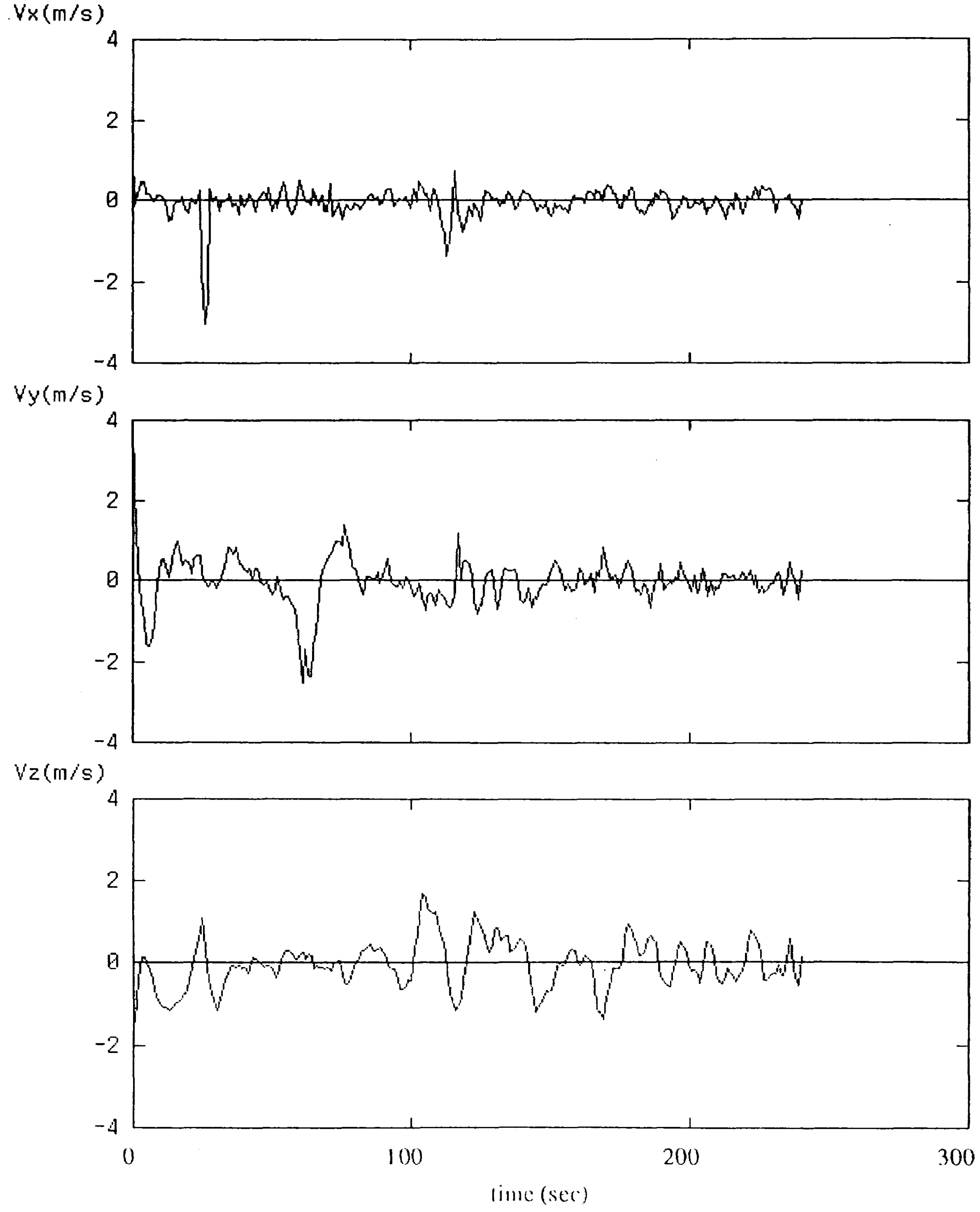

Fig. 5. Differences between GPS and laser determined velocities (approach/landing).

in the RCS. Figs. 4 and 5 show the corresponding results in velocity in the RCS. Table 4 summarizes statistics of differences for the A/L flight case. For the period of this case, satellites were geometrically in good positions with GDOP (Geometrical Dilution of Precision) value of 3.4. Thus, navigation accuracy was very good. The position difference is clearly within 10 meters in each axis. This level of accuracy seems to be close to the upper limit that can be expected with NAVCORE-1 receiver under the SA-off condition and with good GDOP. The rms of velocity difference is about 0.7 m/s in each axis, while the formal accuracy of the receiver is 0.5 m/s (each axis). The small departure from the formal accuracy can be considered to be the error in velocity estimate using the laser tracker data.

Table 4. Mean, standard deviation, and root-mean-square navigation error statistics for the A/L flight case.

	position (m)			velocity (m/s)		
	mean	std.	rms	mean	std.	rms
along-track	0.73	2.69	2.79	-0.05	0.39	0.39
cross-track	-5.69	5.07	7.62	0.004	0.66	0.66
vertical	2.51	8.38	8.75	-0.05	0.59	0.59

(2) **Orbit flight case**

Another example was taken from the orbit flight case whose approximate profile is given in Fig. 6. It was created using standalone GPS output and also segments of orbit to which laser tracker data were available were shown with thick curve. In the following analysis only a clock-wise portion of the orbit flight is considered. The GPS and laser determined positions are compared in Fig. 7, and the differences between these two positions are shown in Fig. 8. The corresponding velocity results are plotted in Figs. 9 and 10. Table 5 summarizes results of statistical analysis in velocity. As compared with the results in the A/L case, the difference is clearly large as a whole. The reason for this could be due to bad geometry of the satellites during orbit maneuvering of the aircraft, GDOP value being about 6. Also, large spikes in position and velocity differences show navigating of the filter in the receiver due to loss of observations. Loss of observations inevitably occurs with one channel, sequential receiver like NAVCORE-1 when receiver tries to acquire GPS message to fresh up satellite ephemeris or when re-

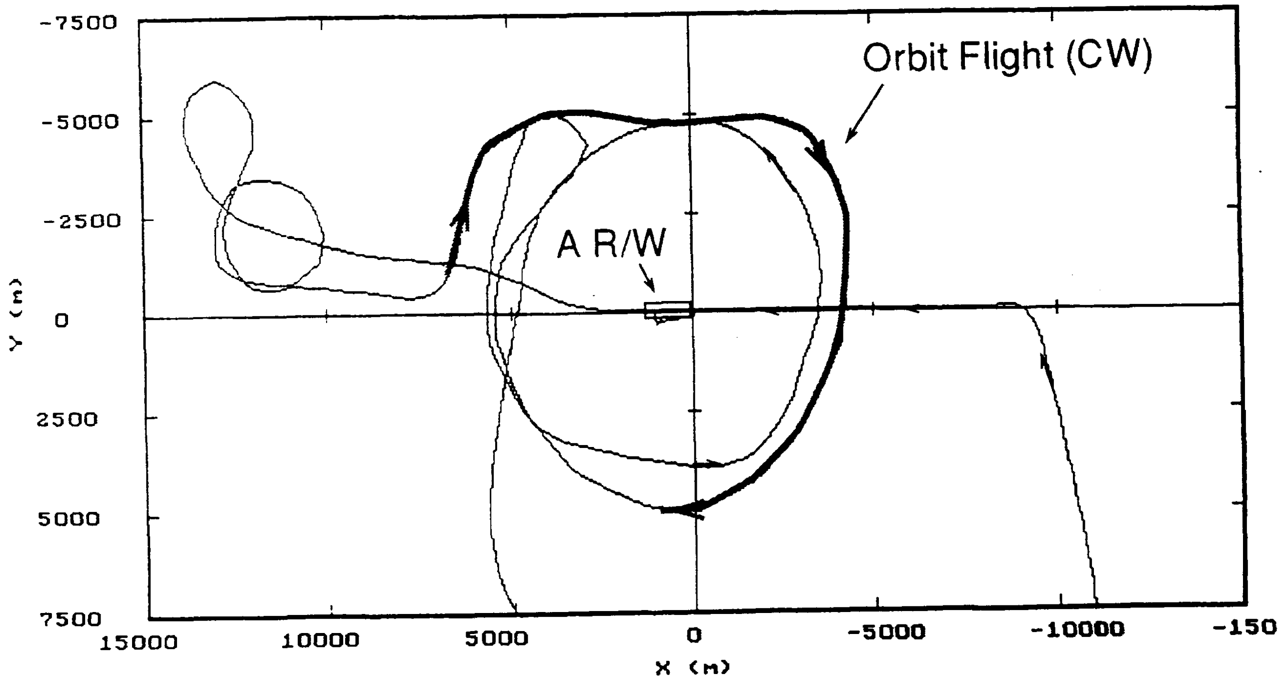

Fig. 6. Ground profile of the orbit flight case as determined by standalone GPS.

ceiver tries to lock to new satellite for improved geometry.

During the period of no observations, the filter forwards its state by simply integrating dynamics assumed in itself. This phenomenon is clearly seen in Fig. 9 in which velocity components were constrained to be constant during data gaps. Navigation filter in NAVCORE-1 is an 8-state sequential extended Kalman filter consisting of 3 position components (r), 3 velocity components (υ), clock bias (b) and clock drift (n), and assuming simple dynamics of velocity deadrekoning type as follows:

$$\dot{\gamma} = \upsilon, \quad \dot{\upsilon} = \xi, \quad \dot{b} = n, \quad \dot{n} = -\frac{1}{T}n + \eta$$

where T is a correlation time, ξ and η are process noises, although no design values for

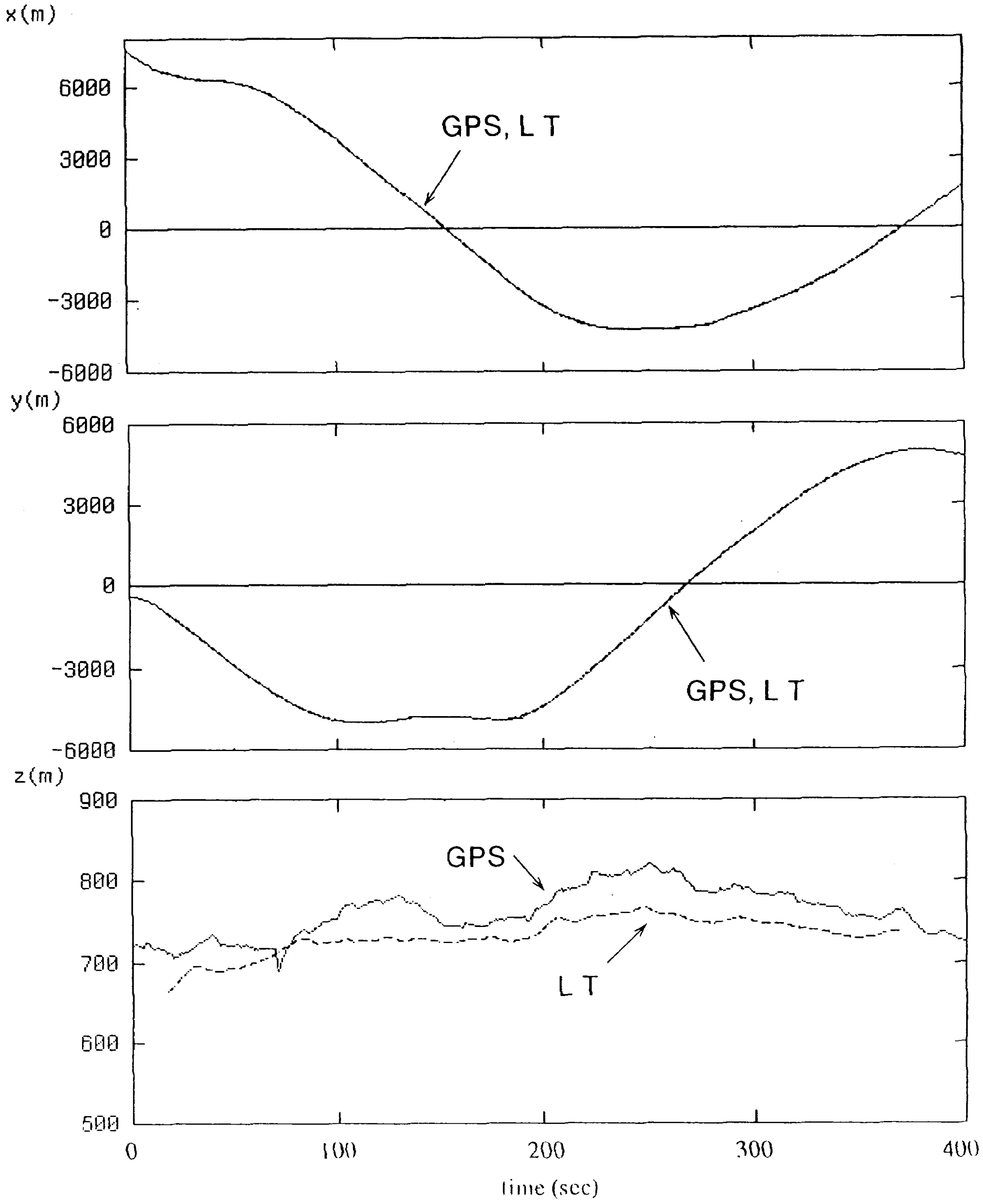

Fig. 7. Comparison of GPS and laser determined position(orbit).

T and process noise statistics have been released. Therefore, with the receiver being under loss of observations while the aircraft is turning (velocity changes rapidly), velocity error increases and thus position error increases. The loss of observations also existed at the A/L flight case, but effect on positional error has not been magnified because of straight line approach (approximately constant velocity).

There are at least three methods to improve navigation error which is typical with one chnnel sequential receivers: the first is to use higher order dynamics in the filter; the second is to use two channel receiver (one channel is devoted to observation only); the third and the best is to use multi-channel receiver (at least 4-5 channels). For most

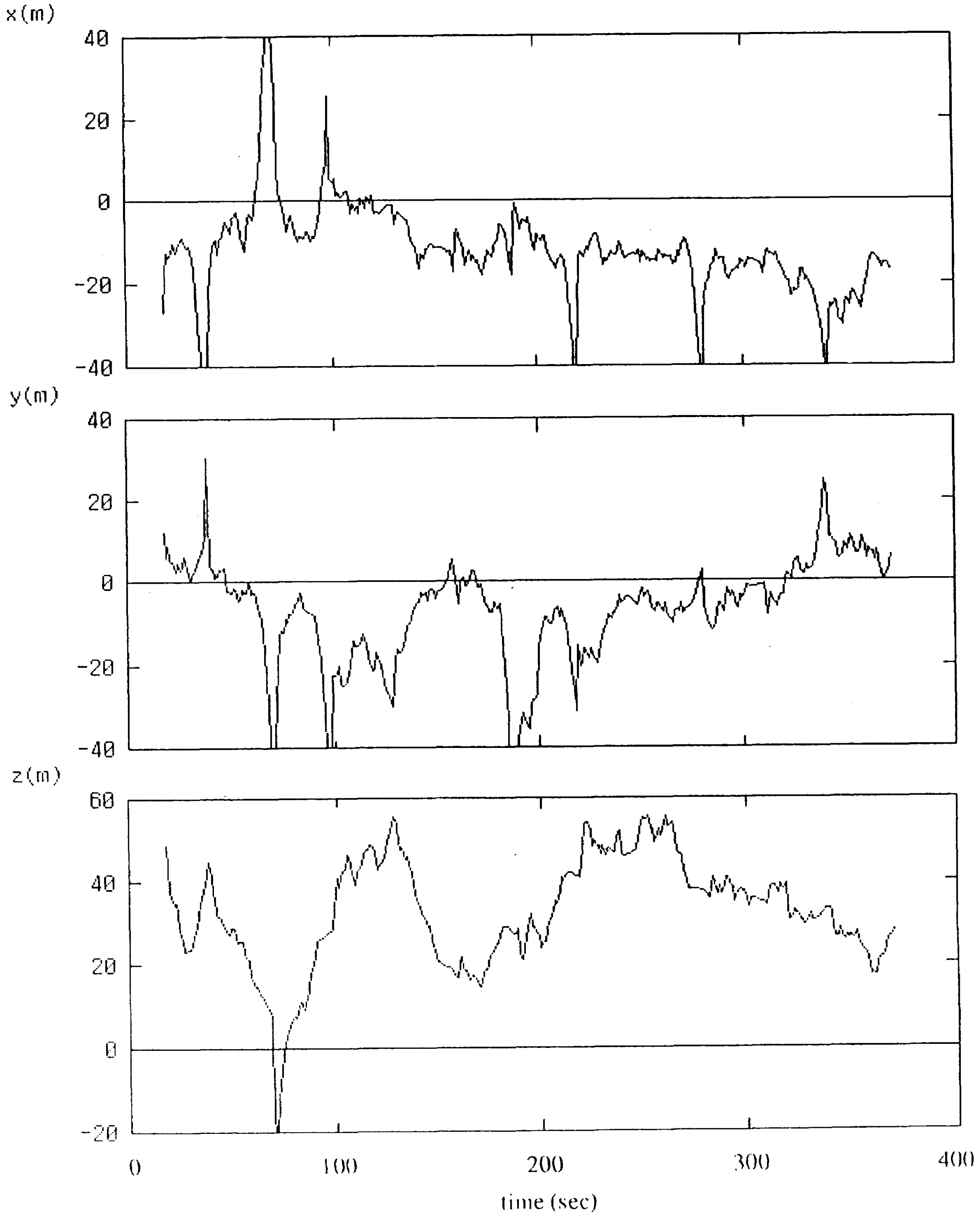

Fig. 8. Differences between GPS and laser determined position(orbit).

flight cases, navigation errors of some tens of meters or so are allowable, but there are some flight cases such as automatic landing flight operation with DGPS-INS which require more stringent accuracy, probably less than one meter in position. For such DGPS operations, only a multi-channel receiver would be an appropriate system.

The issue associated with the number of channels with GPS receivers is further worth noting. In the flight experiments, navigation accuracy of DGPS has also been tested, but the final results have not been available yet. What is of specific interest here is that we often encountered such cases that four satellites selected by onboard receiver and by DGPS base station unmatched, though they were of the same brand (NAVCORE-1). It is

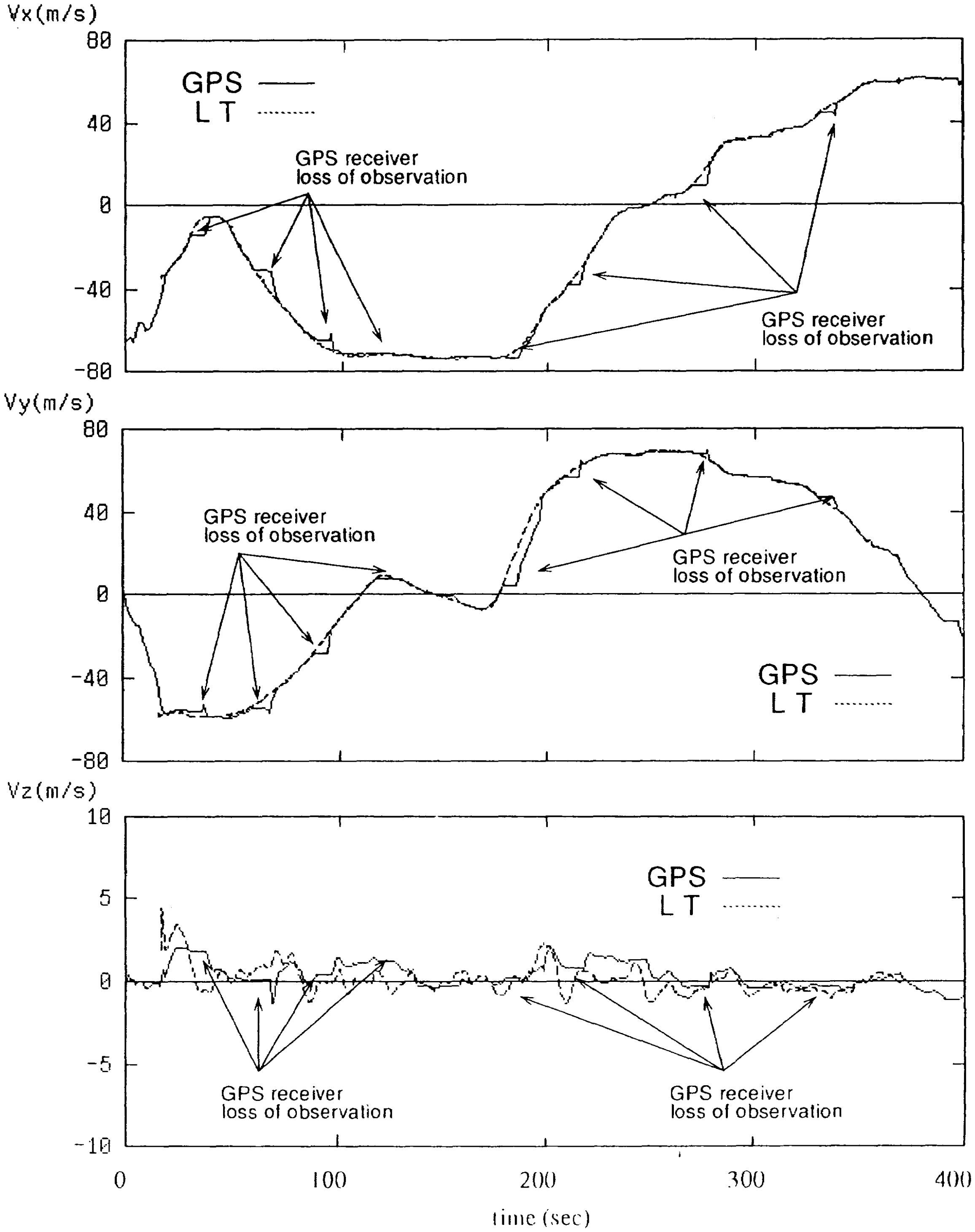

Fig. 9. Comparison of GPS and laser determined velocity(orbit).

not strange that the satellite combination becomes different when the aircraft is flying apart from the base station and/or when aircraft is banking. But in our case aircraft was not so apart from the airport, within at most 30 km. Different combination of four satellites was observed to occur even at the extreme case that two antennas of receivers were aligned close each other. This unmatch makes DGPS operation with NAVCORE-1 difficult, because differential correction data to be sent to users via radio upload link are created only for the selected 4 satellites with NAVCORE-1 receiver. At present no thorough explanation for the cause of different combination is available, but difference in the age of orbit message used by each receiver for satellite ephemeris computation

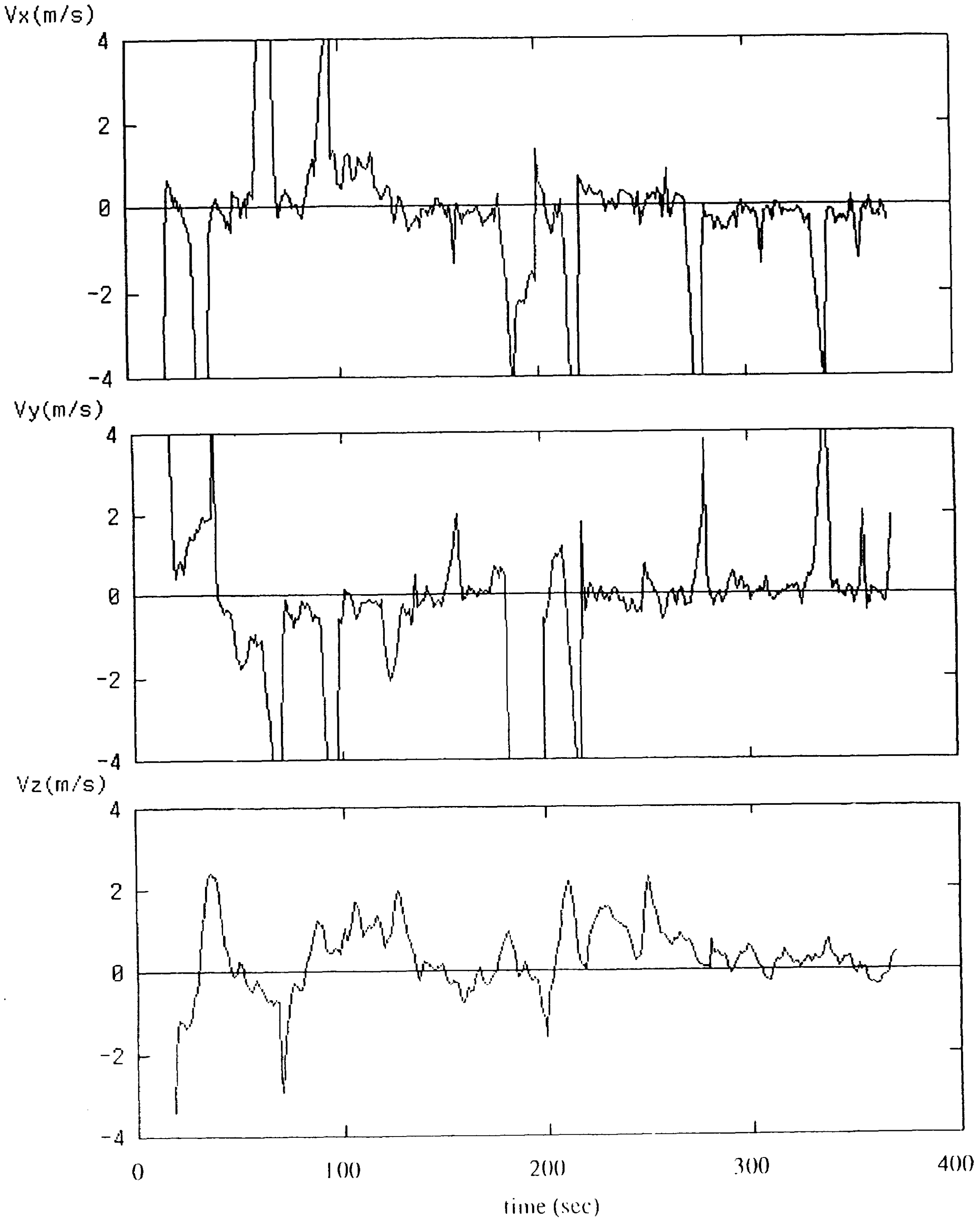

Fig. 10. Differences between GPS and laser determined velocities(orbit).

Table 5. Mean, standard deviation, and root-mean-square navigation error statistics for the orbit flight case.

	position (m)			velocity (m/s)		
	mean	std.	rms	mean	std.	rms
along-track	-11.69	13.08	17.54	-0.25	2.10	2.12
cross-track	-7.31	13.73	15.55	-0.73	2.95	3.04
vertical	32.43	13.11	34.98	0.34	0.82	0.88

will be a possible candidate. These phenomena lead us to a conclusion that multichannel receivers, at least at the base station, should be used for advanced DGPS operations.

The above examples were selected to give the impression of how the evaluation of navigation accuracy has been performed, and to show the effectiveness of our proposed approach, although the resulting navigation performance for standalone GPS with NAVCORE-1 receiver is by itself of much interest. Of course, to the accuracy level of about 10 meters, the proposed approach using GPS surveying is too accurate and costly, and the conventional survey techniques, based on the Tokyo Datum and perhaps with known transformations to the WGS84, might work well. However, it is our opinion that the conventional technique is not always adequate for general users to determine the *geocentric positions* with accuracy required for our research objectives, because the ellipsoidal height with respect to the Tokyo Datum is not directly available with high accuracy (only height over the mean-sea-level is available) and 7-parameter values for the coordinate transformation from the Tokyo Datum to the WGS84 and vice versa have not necessarily been determined accurately. On the other hand, our proposed approach overcomes these difficulties and provides consistent, easy means for surveying.

4. Conclusion

The proposed method using GPS surveying has proved to be effectively applied to the area of flight experiments to which accurate geodetic reference is prerequisite. It has the capability of establishing effective, reliable configurations not only for navigation performance analyses but also for the terminal area flight operations based on advanced navigation sensor systems. As compared with the conventional survey techniques, the proposed method is simple in nature, easy to apply even by non-professionals in surveying, much time-saving, but highly accurate.

In this paper we showed its efficiency in establishing reference frames and locating position coordinates of the reference points for the navigation-aid facilities, *both with reference to the WGS84*. The reference navigation frame and position coordinates established in that way were applied successfully to flight evaluation experiments of standalone GPS navigation accuracy by direct comparison with laser determined aircraft profiles. Thorough analysis of flight data for navigation performance of hybrid DGPS-INS and DGPS-MLS systems as well as DGPS itself is in progress, and results will be reported elsewhere. Other efforts under planning include advanced research on GPS applications to A/L flight operation using DGPS-INS and dynamic GPS in which we are sure the proposed approach using GPS surveying will play a fundamental role.

Acknowledgements. This research has been conducted as a joint research project with ENRI and NASDA in partial co-operation with Toshiba and NEC Corporations. The authors thank the colleagues for their professional contributions during the course of the flight experiments. Thanks should be extended to GSI for affording us facilities of the geodetic control point. Also, the efforts of Mr. S. Yama and Mr. M. C. Izawa of Trimble Navigation (Japan)Ltd. in GPS survey were greatly appreciated. Finally, the first author is grateful to Dr. Boucher of Institut Geographique National for discussion on relation between the IERS Terrestrial Reference Frames and WGS84.

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TECHNICAL REPORT OF NATIONAL
AEROSPACE LABORATORY
TR-1194T

航空宇宙技術研究所報告1194T号（欧文）

平成5年3月発行

発行所　航空宇宙技術研究所
東京都調布市深大寺東町7丁目44番地1
電話三鷹(0422)47-5911(大代表)〒182
印刷所　株式会社　東京プレス
東京都板橋区桜川2－27－12

Published by
NATIONAL AEROSPACE LABORATORY
7-44-1 Jindaijihigashi-Machi, Chōfu, Tokyo
JAPAN