Kinematic GPS-Inertial Navigation on a Tactical Fighter

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BIOGRAPHY

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ABSTRACT

Advances in aircraft avionics and weapons accuracy have driven an increasing need for the ability to accurately measure the position, attitude and velocity of tactical aircraft to support avionics and weapon flight testing and performance validation. This paper describes an integrated sensor system for producing accurate Time-Space Positioning Information (TSPI) of an airborne fighter platform to support this requirement. The system tightly integrates an onboard GPS with a low-cost inertial measurement unit and reference-station data to create a highly accurate kinematic navigation solution for the aircraft. The system has been packaged in a small, multi-platform compatible format to allow easy integration onto a tactical platform.

INTRODUCTION

Flight testing of next generation platforms and weapons capability has historically required the use of a precisely instrumented test range. To provide a portable test capability, NAVSYS has developed a Time-Space-Positioning-Information (TSPI) system to provide accurate position, velocity and attitude information for validation and performance testing of avionics and weapon systems.

The TSPI system is an integrated sensor system consisting of various airborne and ground components, which produce data to be combined into the highly accurate results for system analysis and performance evaluation. The system tightly integrates an onboard GPS with a low-cost inertial measurement unit (IMU) and reference-station data to create a highly accurate kinematic navigation solution for the aircraft.

The system has been packaged in a small, multi-platform compatible format to allow easy integration onto almost any tactical platform. Figure 1 shows a typical installation on a F-16. The ground components are designed for simple set-up and installation to allow flight testing to be conducted at test or training sites world-wide.

In this paper, the system architecture, kinematic filtering, and GPS/Inertial Navigation System (INS)-aided design of the TSPI system is described with preliminary flight test results from a system installed on an F-16 aircraft.

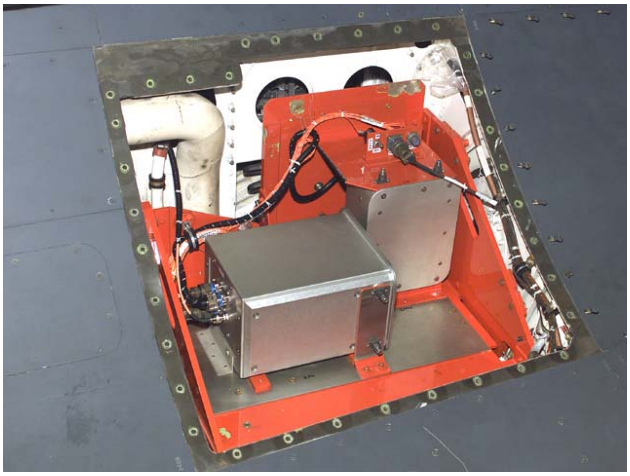

Figure 1 TSPI Installation in wing root on F-16

TSPI SYSTEM ARCHITECTURE

The three major components that comprise the TSPI system provide all the capabilities necessary for operation and result generation. The components consist of:

- Airborne Sub-System
- Ground Station Sub-System
- Master Processing Sub-System

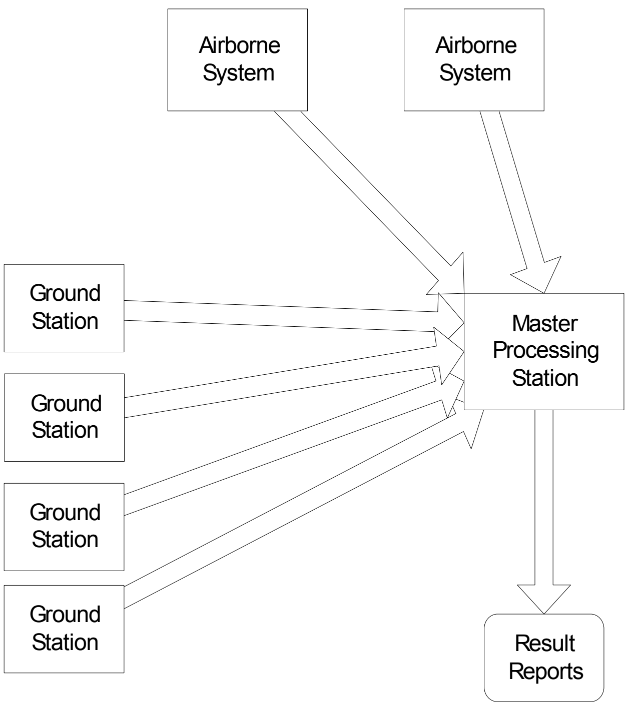

Figure 2 TSPI System Overview

AIRBORNE SUBSYSTEM

The Airborne Sub-System consists of two units, the airborne processing unit and the inertial unit, which are contained within custom containers. These containers are constructed such that they provide the form/fit match to a standard Flare bucket, but this does not preclude installation in other locations, see Figure 1. This enables the system integration into almost any platform that utilizes these units, with minor cabling interface changes to the platform. The two units house all the electronics necessary for the collection and distribution of the data required by the Master Processing Station.

Figure 3 TSPI Airborne Processing Unit

The airborne processing unit consists of:

- PC104 plus CPU
- Various interface capabilities
- GPS Receiver
- DC-DC converters
- Ethernet Communications
- Data Storage (1Gbyte Flash)

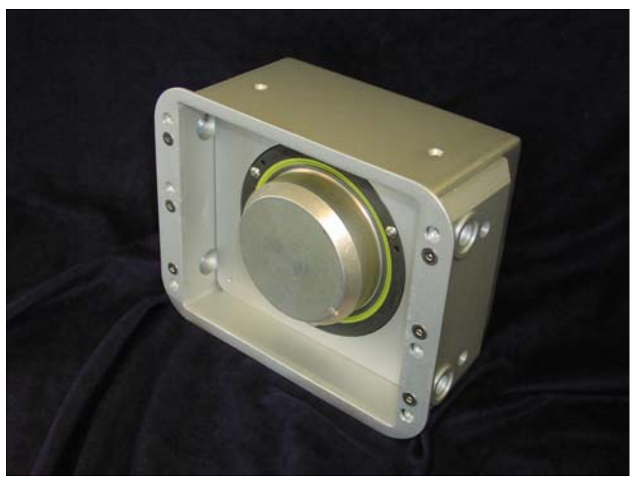

Figure 4 TSPI Inertial Unit

The inertial unit contains:

- Inertial Measurement Unit

The data collection and control software is executed within the Windows XP Embedded environment.

The information gathered by this system is downloaded, post test, to the Master Processing Station.

GROUND STATION SUBSYSTEM

The Ground Station Sub-System consists of a solar powered GPS reference station data logging system. This system also has communications capability via either cell or plain old telephone system (POTS). The information gathered by this system is downloaded, post test, to the Master Processing Station.

Figure 5 Ground Station Subsystem

MASTER PROCESSING STATION

The Master Processing Station consists of a Laptop computer, running the Windows XP operating system. The laptop includes interfaces to enable the gathering of both the airborne and ground data via one of the following interfaces:

- Ethernet
- RS-232
- POTS modem

The Master Processing Station performs all data unification, and processing necessary to produce the specified output information. This includes the calculation of correction information, as well as the kinematic processing.

TSPI SYSTEM OPERATION

TSPI Range Survey

Prior to flight, it is necessary to establish the locations of the receivers that make up the ground reference subsystem. This capability is built-in to the TSPI Master Station. As shown in Figure 6, the ground station network consists of 4 GPS Ground Stations placed approximately 30 nmi apart. This arrangement gives overlap coverage between Ground Stations, and the kinematic solutions can be generated as long as the aircraft is within approximately 25 nmi of the area covered by the Ground Stations.

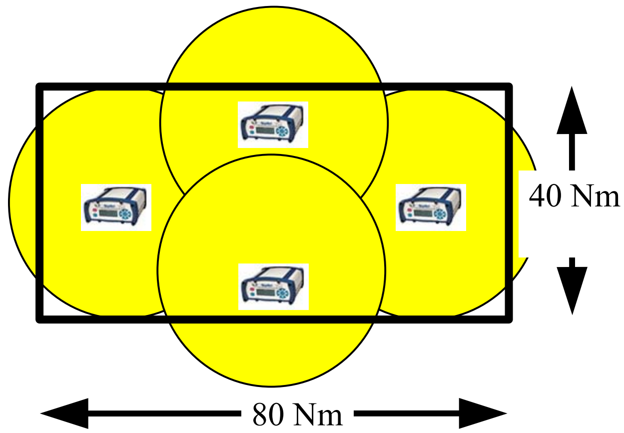

Figure 6 Range Layout (distance between receivers should be ~30 nmi.)

The location of the GPS receivers in the network are referenced to a master starting location for the range by installing one of the Ground Stations at that location. This can be a geodetic reference point, but the TSPI system is also capable of deriving the TSPI data relative to this point even without a precision survey being available. The survey method used by the TSPI system to establish the network is shown in Figure 7. This involves determining the relative kinematic GPS solution between each Ground Station. For highest accuracy, the distance between the Ground Stations should be no greater than 25 nmi. The reference Ground Station starts by transmitting RTCM differential and carrier phase corrections. This is used by the nearest remote Ground Stations to derive their relative positions to an accuracy of a few cm, using 10 to 15 minutes worth of data. Once the remote Ground Station is positioned, it is also used to RTCM corrections, and this approach is repeated until the complete network is with a third receiver. This leap-frogging approach results in a network of reference receivers tied to the known starting point.

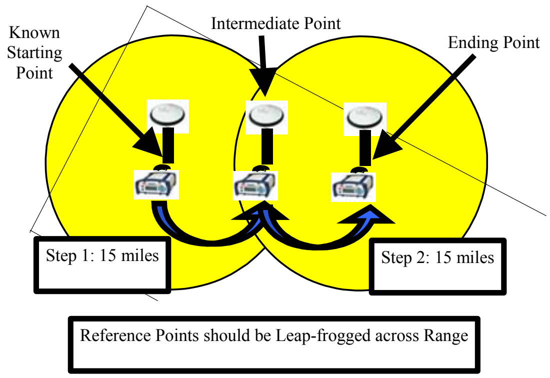

Figure 7 Range Survey Procedure

Preflight Scheduling of Ground Stations

Prior to the flight test, the Ground Stations must be commanded to acquire data during the expected flight times. This is done by connecting a laptop PC to the Ground Station either locally or via one of the installed modems, and entering the UTC start and stop times for the flight test. This process is repeated for each receiver in the network.

Post Flight Data Collection

After the flight test is completed, the data from each Ground Station and from the Airborne Subsystem are collected at the Master Processing Station. For the Ground Stations, data is recorded on 512 Mbyte flash cards which are capable of storing 78 hours of 1 Hz GPS data. The flash cards are placed in a flash card reader, and the data is downloaded to a PC either by removing the flash card from the system, see Figure 8, or via modems within each ground station. The data from the airborne systems is transferred via the airborne's Ethernet capability. This process is repeated for each station in the ground network, and for the Airborne Subsystem.

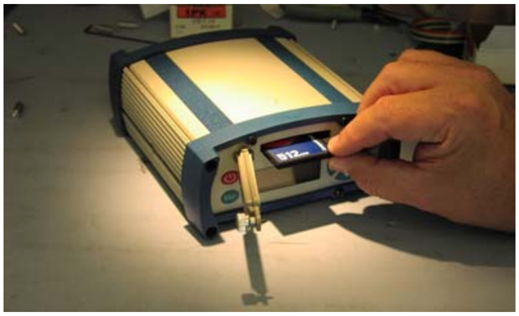

Figure 8 Data removal from ground system receiver

Post Flight Nav Solution and Report Generation

The TSPI position and velocity data is generated post-test by selecting one or more airborne data files for processing. All available ground data is automatically included in the processing, and solutions generated with the algorithms below, are collected in a Navigation data base. Several report options are available with various solution charts, graphs and text files. The data can also be exported for analysis with MS-Access, Excel or other applications. The standard output data provided by the TSPI system is Table 1.

Table 1 TSPI System Standard Output data[1]

Header Information	Flight Description
Timing data	UTC for each data sample
Position data	Lat, Lon, Alt (msl, geoid)
Attitude data	Roll, Pitch, Heading
Velocity data	NED
Angular data	Inertial Angular rate about body
Uncertainty Information	Kalman Filter covariances
Satellite tracking	Raw PR/CPH observations

KINEMATIC GPS/INERTIAL POSITIONING

The TSPI system uses an integrated GPS/inertial differential and kinematic (DGPS/KGPS) positioning technique to provide optimized performance for high dynamic TSPI data. The integrated GPS/inertial solution allows the precision to be maintained during periods of vehicle maneuvers. The DGPS corrected GPS/inertial solution facilitates creating a KGPS solution, and the kinematic positioning provides a high accuracy solution referenced to the Ground Station grid.

A functional diagram that describes the concept of the Kinematic GPS/Inertial navigation is shown in Figure 9 Starting in the lower left, IMU data and GPS pseudo-range and bias resolved carrier phase data are passed to the GPS/INS Hybrid navigator which is based on our InterNav software product[2]. This data is processed along with GPS corrections from the reference network to produce position, velocity and attitude solutions. The combined GPS/INS solution is also used to aid in resolving bias ambiguities for subsequent epochs. Once ambiguity resolution has been completed, the kinematic position updates are then applied back to the GPS/inertial filter to further improve the positioning and attitude accuracy provided by the TSPI system[3].

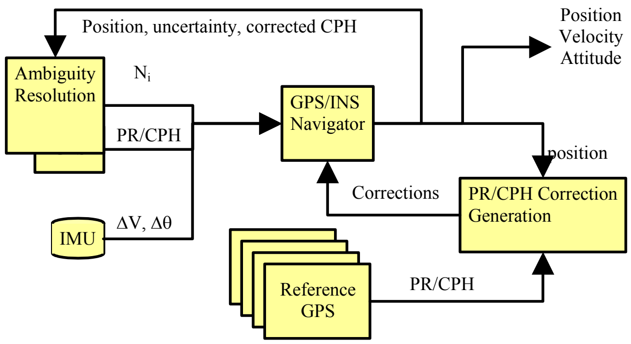

Figure 9 Kinematic GPS/Inertial Navigation

AMBIGUITY RESOLUTION ALGORITHM

The essential element of Kinematic positioning relies on estimating the carrier phase cycle ambiguity between the carrier phase observations and the range observations as described in the following equation.

Equation 1

$$PR_1 = R + bu_1 + bsv_{PR1} + T + I_1 + n_{PR1}$$

$$PR_2 = R + bu_2 + bsv_{PR2} + T + I_1 \frac{\lambda_2^2}{\lambda_1^2} + n_{PR2}$$

$$-CPH_1 = R + bu_{CPH1} + bsv_{CPH1} + T - I_1 + n_{CPH1} - N_1 \lambda_1$$

$$-CPH_2 = R + bu_{CPH2} + bsv_{CPH2} + T - I_1 \frac{\lambda_2^2}{\lambda_1^2} + n_{CPH2} - N_2 \lambda_2$$

where
PR = pseudo-range on L1 or L2 frequencies (meters)
CPH = carrier phase on L1 or L2 frequencies converted to meters
R_T = true range (meters)
bu = range equivalent receiver clock offset (meters)
bsv = range equivalent satellite clock offset (meters)
T = tropospheric delay (meters)
I = ionospheric delay (meters)
n = measurement noise (meters)
N = CPH integer
λ = carrier wavelength (meters)

The TSPI kinematic solution uses a combination of modeling and Ground Station data to estimate the tropospheric delay (T) and the ionospheric delay (I) on each of the satellite observations. The DGPS corrected GPS/INS solution derived from the integrated Kalman Filter is used to initiate the kinematic ambiguity resolution process as shown in Figure 10. The following steps are then executed to derive the CPH integer ambiguity.

rkp_ambiguity

The first step is to create the carrier phase corrected measurement residuals. These are derived from Equation 2 and include: carrier phase corrections (CPC) from the reference location, estimated range to the satellite from the DGPS solution and the estimated atmospheric errors from the Ground Station network (tropo and iono). As shown in the following equation, this measurement residual observes the position error in the DGPS solution (relative to the reference location), the residual ionospheric and tropospheric errors and the integer ambiguity offset. Since the aircraft is always operating in the area of the Ground Station network, wide-laning can be used to simplify the ambiguity resolution process since the ionospheric delay can be assumed to have been corrected.

Wide-lane ambiguity resolution involves creating the wide-lane L1-L2 observation difference, as described in the following equations. This reduces the ambiguity resolution process to a single (wide-lane) ambiguity $N_W=N_1-N_2$. The wide-lane wavelength is 86 cm as opposed to the L1 wavelength of 19 cm. This larger resolution wavelength is easier to observe allowing ambiguity resolution to occur much faster with L1/L2 dual frequency observations than for single frequency (L1 only) GPS. To remove the effect of the clock bias, the single-differenced observations are used (zsd) since the clock bias is common between the GPS satellite observations.

Equation 2

$$z_{CPH1} = -CPH_1 - \hat{R} - \hat{b}sv_{CPH1} + \hat{CPC}_1 - \Delta\hat{T} + \Delta\hat{I}_1 = \underline{1}^T \underline{\tilde{x}} + bu_{CPH1} + (\tilde{T} - \tilde{I}_1) + n_{CPH1} - N_1 \lambda_1$$

$$z_{CPH2} = -CPH_2 - \hat{R} - \hat{b}sv_{CPH2} + \hat{CPC}_2 - \Delta\hat{T} + \Delta\hat{I}_2 = \underline{1}^T \underline{\tilde{x}} + bu_{CPH1} + (\tilde{T} - \tilde{I}_1 \frac{\lambda_2^2}{\lambda_1^2}) + n_{CPH2} - N_2 \lambda_2$$

$$z_{CPHW} = \left(\frac{z_{CPH1}}{\lambda_1} - \frac{z_{CPH2}}{\lambda_2}\right)\lambda_W = \underline{1}^T \underline{\tilde{x}} + bu_{CPH1} + \tilde{T} - \tilde{I}_1 \frac{\lambda_W}{\lambda_1}\left(1 - \frac{\lambda_2}{\lambda_1}\right) + n_{CPH1}\frac{\lambda_W}{\lambda_1} - n_{CPH2}\frac{\lambda_W}{\lambda_2} - N_W \lambda_W$$

$$\lambda_W^{-1} = \lambda_1^{-1} - \lambda_2^{-1} \qquad N_W = N_1 - N_2$$

$$z_{SD1}^i = z_{CPH1}{}^i - z_{CPH1}{}^0$$

$$z_{SD2}^i = z_{CPH2}{}^i - z_{CPH2}{}^0$$

calc_rkp

The purpose of the calc_rkp function is to compute the set of possible ambiguities for each of the satellite observations. This is performed by computing all of the likely ambiguities based on an initial search space that the ambiguity solution must fall within. The search space is dictated by the initial uncertainty of the GPS/inertial navigation solution (P_{DGPS}), as illustrated in Figure 11.

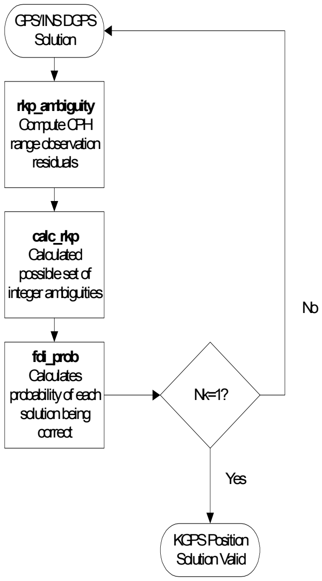

Figure 10 Kinematic Positioning Algorithm

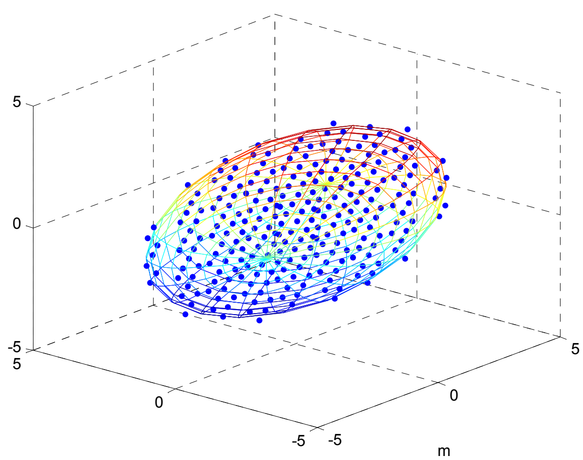

Figure 11 Ambiguity Set is defined by the initial DGPS/inertial position uncertainty space

Each ambiguity must pass the following criteria shown in Equation 3 to be considered a valid member of the ambiguity set (Nset). The geometry vector H is calculated from the satellite line of sight vectors. The scale factor α is computed based on the desired probability of missed detection (P_{MD}) for the KGPS solution, based on the equation below.

Equation 3

$$\underline{N}\,\underline{N}^T < \alpha\, H\, E\left[\underline{\tilde{x}}\,\underline{\tilde{x}}^T\right] H^T / \lambda_W^2 = \alpha\, H \frac{P_{DGPS}}{\lambda_W^2} H^T \qquad \underline{N} \in Nset$$

$$P_{MD} = \chi^2\left(\alpha \middle| 3\right) \qquad \text{(Chi square probability distribution)}$$

fdi_prob

The correct ambiguity from the set is isolated by using an integrity check to reject the incorrect solutions. For the correct ambiguity solution, the fault vector (f), computed from Equation 4, will include only the receiver noise errors. For all other values, the f vector will also include errors due to the ambiguity error. The S matrix has Nsv-4 degrees of freedom. As the number of GPS satellites in the solution increases, the ability to distinguish between the different members of Nset improves, and also the initial DGPS search space ellipse gets smaller.

Equation 4

$$\underline{f} = S(N_W \lambda_W + z_{CPHW}) = S\left(H\underline{\tilde{x}} + \underline{\tilde{T}} - \underline{\tilde{I}}_1 \frac{\lambda_W}{\lambda_1}\left(1 - \frac{\lambda_2}{\lambda_1}\right) + \underline{n}_{CPH1}\frac{\lambda_W}{\lambda_1} - \underline{n}_{CPH2}\frac{\lambda_W}{\lambda_2}\right) \approx \underline{n}$$

$$S = I - HH^* \qquad SH = 0 \qquad H^* = \left(H^T H\right)^{-1} H^T$$

Figure 12 shows the fault vectors for all candidate integer sets along with the f value for the correct integers. With the excellent discrimination provided by the inertial filtering and the fault vector test, the correct ambiguity is quickly resolved.

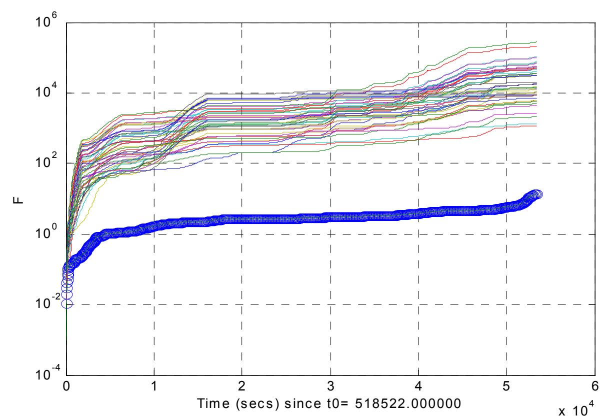

Figure 12 KGPS Fault Vector Convergence

Once the solution has converged to a single ambiguity, the CPH measurement update can be applied to the GPS/inertial navigation solution in the same manner as a PR update. The results of this solution are illustrated in Figure 13 and Figure 14 for a widelane ambiguity test case.

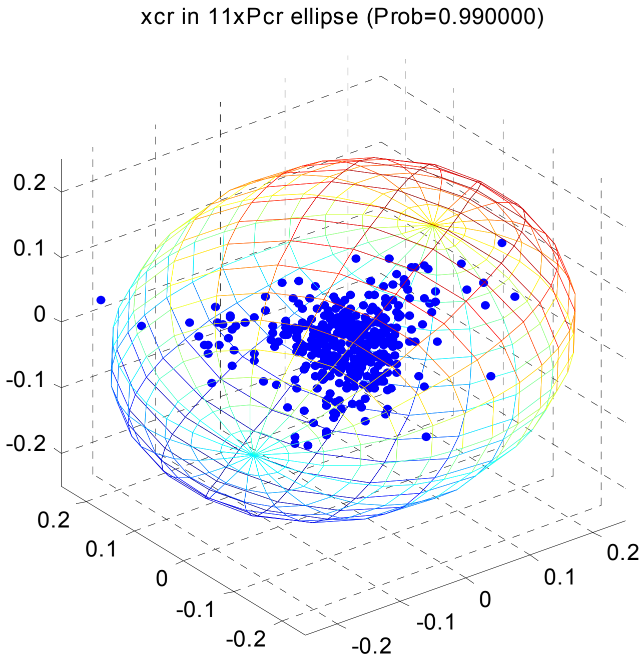

Figure 13 Widelane KCPT Position Solution (NED)

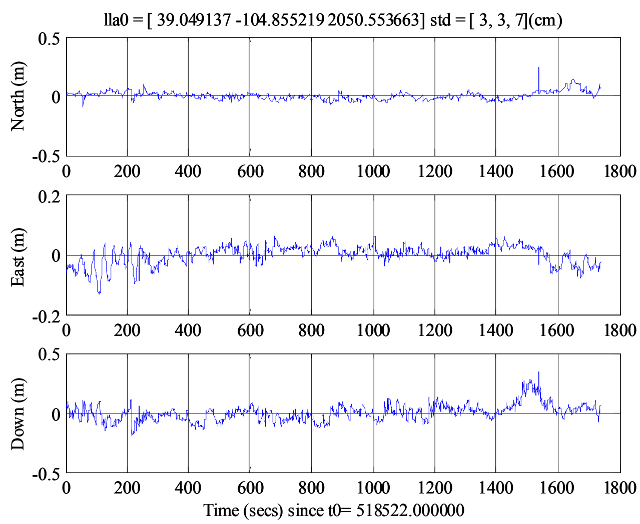

Figure 14 Widelane KCPT Position Solution

PRELIMINARY F/A 16 FLIGHT TEST DATA

To test the TSPI system, flight data was collected at the Shepherd 2 MOA High Altitude test range near Ft. Worth, Texas, in late August of 2003. Figure 15 shows a 3-Dimensional plot of the F-16's trajectory during the flight test. The aircraft followed standard procedure and climbed in a tight circle for the first segment of the flight after take off, then climbed higher and executed various high G-Force maneuvers. Figure 16 shows the G-forces experienced by the plane during various segments of the flight.

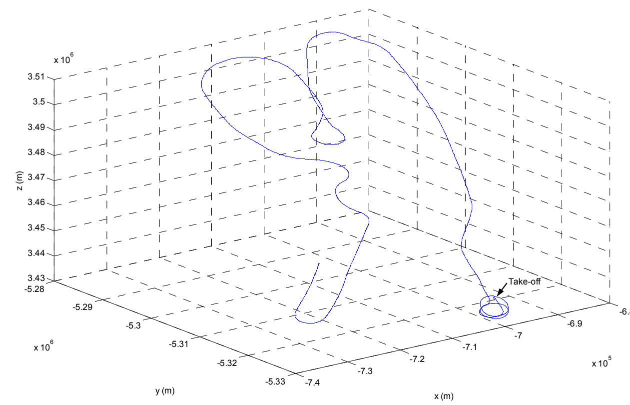

Figure 15 Flight Profile of the F-16 during testing

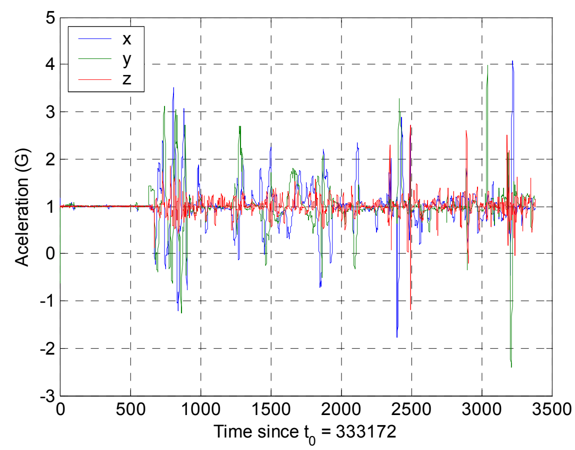

Figure 16 G-Forces as a function of time.

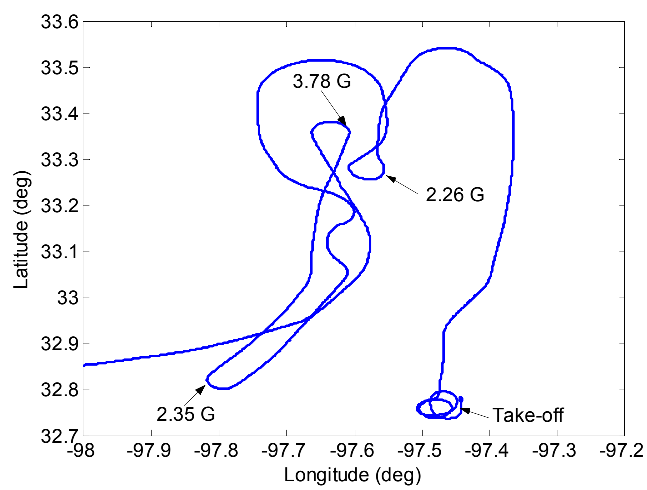

Figure 17 G-Forces shown with horizontal position.

Processing was performed post-test in both the DGPS and the KGPS modes of operation. The receiver was able to maintain lock during most of the flight. During high speed maneuvers, the satellites did lose lock. Figure 18 shows the numbers of satellites that were tracked and Figure 19 shows the satellite locktime. It can be seen that during a couple of maneuvers all satellites lost lock causing a total KGPS reset. However, the GPS/inertial solution error was kept at a small level during this period which allowed the KGPS algorithm to rapidly recover the cycle ambiguities following loss of lock. The number of ambiguities within the 1-sigma probability ellipse is shown in Figure 20. To ensure that the correct ambiguity is included in the set tested, a 98% probability ellipse is used for the search. This increases the numbers of ambiguities that need to be tested as shown in Figure 21. By testing over the time period following loss of carrier lock, the correct ambiguity can be resolved from within this initial selection set resulting in a KGPS solution. In the post-processing software, backwards propagation of the resolved ambiguity allows the KGPS solution to be generated over the complete data set providing the high accuracy TSPI solution output.

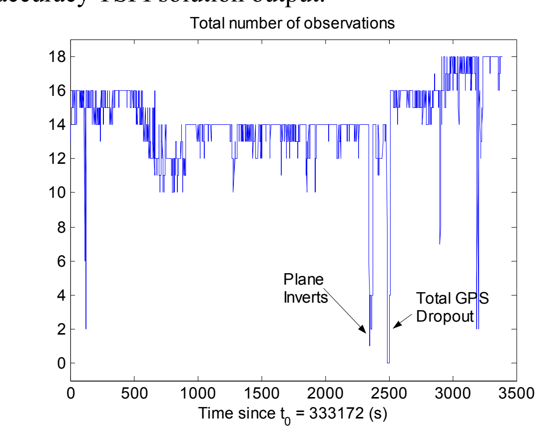

Figure 18 Number of L1 and L2 observations during the flight

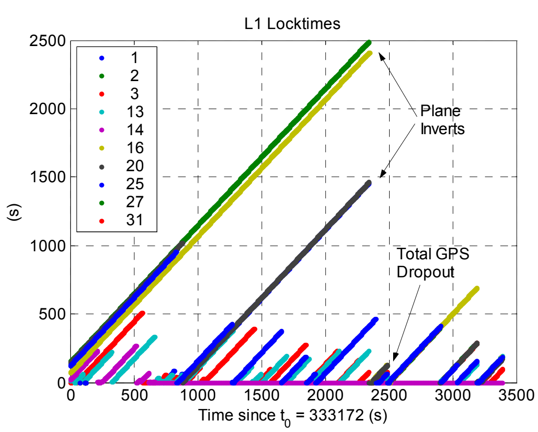

Figure 19 GPS locktime during the flight

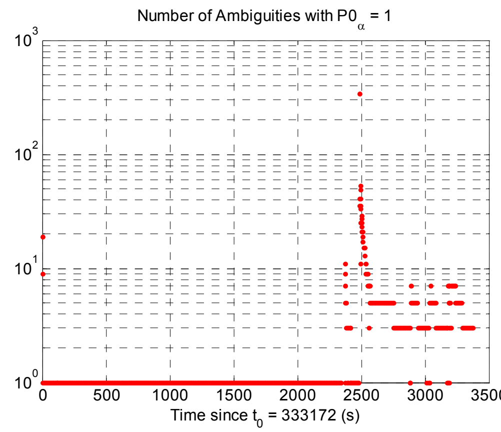

Figure 20 Number of ambiguities within 1xP0 ellipse (20% probability)

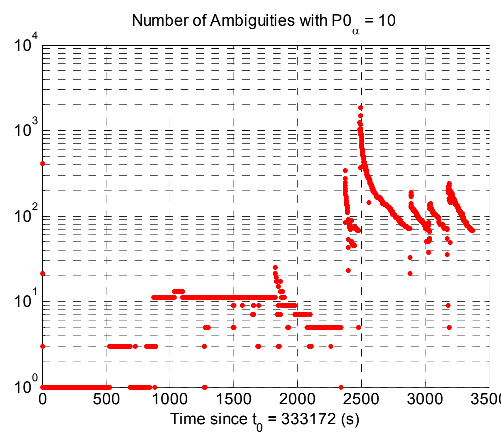

Figure 21 Number of ambiguities within 10 x P0 ellipse (98% probability)

Initial processing of the data from the F-16 test has shown promising results with the early combined GPS/Inertial solutions. However, since these flight tests were not instrumented, we do not yet have performance results to present. An instrumented flight test is planned to be conducted later this year that will be used for validation of the final KGPS TSPI solution.

CONCLUSION

The TSPI system described in this paper will provide an inexpensive, portable method for instrumenting high performance jet aircraft, world-wide. Initial test data sets collected in late August of 2003 show that precision Differential GPS and Kinematic GPS processing is possible by using a tightly integrated GPS/inertial solution to maintain continuity throughout the aircraft maneuvers. Further flight tests and data analysis are planned to show the full performance possible of this precision TSPI instrumentation system.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Interface Control Document No. FTI-2002-03, Time Space Positioning System (TSPI)
[2] http://www.navsys.com/Products/internav.htm
[3] A. Brown and D. Sullivan, "Precision Kinematic Alignment Using a Low-Cost GPS/INS System", Proceedings of ION GPS 2002, Portland, OR, Sept. 2002, http://www.navsys.com/Papers/02-09-002.pdf