Navigation Using LINK-16 GPS-INS Integration

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BIOGRAPHY

Alison Brown is the President and Chief Executive Officer of NAVSYS Corporation. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. In 1986, she founded NAVSYS Corporation. Currently, she is a member of the USAF Scientific Advisory Board, a member of the Interagency GPS Executive Board Independent Advisory Team (IGEB IAT), and an Editor of GPS World Magazine. She is an ION Fellow and was indoctrinated into the SBA "Wall-of-Fame" in 2003.

Phyllis Sack is a Senior Program Manager at ViaSat, Inc. She has a BA in Mathematics from USC. She is responsible for programs involving the use of Link-16 in new applications, including optimally integrating Link-16 with GPS to benefit both, demonstrating the use of Link-16 to guide a weapon to a moving target using in-flight target updates, and demonstrating a capability to get imagery to the cockpit using TCP/IP over Link-16.

ABSTRACT

The LINK-16 standard for military anti-jam digital communications provides Anti-Jam (AJ) communications using Frequency Hop and Pseudo Noise (PN) spreading techniques. As a result, there are accurate time-of-arrival (TOA) measurements between the transmitting terminals. This paper describes the design and development of an integrated navigation filter that is capable of exploiting LINK-16 TOA measurements, along with GPS/IMU measurements, to provide robust navigation in GPS-denied conditions. Results are presented that show the advantage that a LINK-16 aided navigation system has over standard GPS/INS navigation in a hostile GPS environment.

INTRODUCTION

The LINK-16 standard for military anti-jam digital communications has been implemented in the Joint Tactical Information Distribution System (JTIDS) terminals, the F-15 Fighter Data Link (FDL) and the Multifunctional Information Distribution System (MIDS) terminals. These systems provide Anti-Jam (AJ) communications using Frequency Hop and Pseudo Noise (PN) spreading techniques. As a result, there are accurate time-of-arrival (TOA) measurements between the transmitting terminals. The Global Positioning System (GPS) uses satellites transmitting PN spread signals to measure TOA from the transmitting satellites to the receiving GPS terminals.

NAVSYS has developed an integrated navigation filter capability, the InterNav product, which optimally integrates GPS, Inertial Measurement Unit (IMU) and other sensor data. In this paper we describe an extension to this filter design where JTIDS TOA information, available from ViaSat's MIDS terminals, could be applied for use in providing a robust navigation solution, albeit at lower accuracies, under GPS-denied conditions.

INTERNAV SOFTWARE

The LINK-16 TOA measurement updates were implemented as an extension of NAVSYS' InterNav integrated GPS/inertial software product[1]. InterNav is used as an embedded software module for integrated GPS/inertial applications to process the raw IMU data and produce an inertial navigation solution. The software includes the functions illustrated in Figure 1. InterNav is designed to operate with both high quality inertial data, such as could be provided by an Enhanced GPS-Inertial (EGI) navigation system, or low grade data, such as is available from a Fiber Optic Gyro (FOG) or Micro-Electrio-Mechanical System (MEMS) IMU, through changing keywords to specify the quality of the raw IMU (delta-theta, delta-V) data inputs. .

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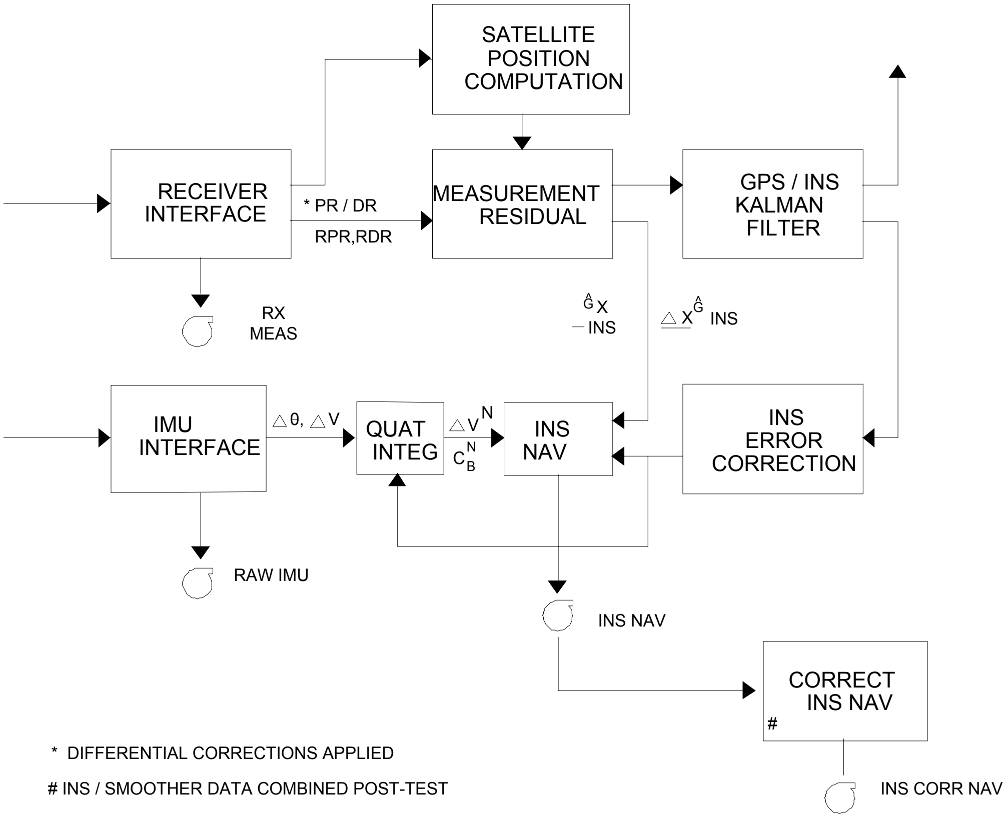

Figure 1 Base InterNav Software Architecture

The base InterNav filter states are shown in Table 1. In the conventional alignment mode, the pseudo-range and delta-range updates are applied to align the Kalman filter. When the filter is integrated with the IMU, the inertial navigation solution is used to propagate the position and velocity navigation states and the pseudo-range and carrier-phase observations are applied to estimate the navigation error.

The modular InterNav software is designed to allow alternative measurement updates to be included as shown in Figure 2. In previous publications, we have described the benefit of applying kinematic GPS updates[2] and video updates[3] for navigation enhancements. In the following sections, the extension of this filter design to apply the LINK-16 TOA updates is described.

Table 1 InterNav Kalman Filter Navigation States

State	Meaning
1-3	Position Error (navigation frame)
4-6	Velocity Error (navigation frame)
7-9	Body Attitude Error (navigation frame)
10-12	Accelerometer Bias Error
13-15	Gyro Bias Error
16	GPS Clock Bias Error
17	GPS Clock Frequency Error
18-26	Accelerometer Misalignment & sf Error
27-32	Gyro Misalignment & sf Error

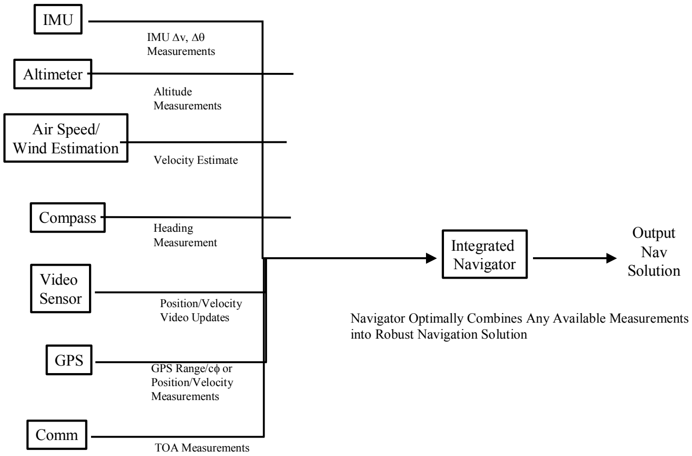

Figure 2 InterNav Suite of Measurement Updates

JTIDS/GPS/INERTIAL FILTER INTEGRATION

The design approach adopted was to use a cascaded filter approach to allow estimation and calibration of the LINK-16 TOA errors while GPS was available, and permit graceful degradation to the less accurate, but GPS-jamming insensitive, TOA-aided solution when GPS is not available. To achieve this, a calibration Kalman filter was added for each JTIDS unit (JU). Figure 3 shows how this filter interacts with the core InterNav functions.

The GPS/INS Filter is configured to process incoming JTIDS measurements only when the application of such measurements would improve the navigation performance, as determined by the measurement and navigation solution uncertainties.

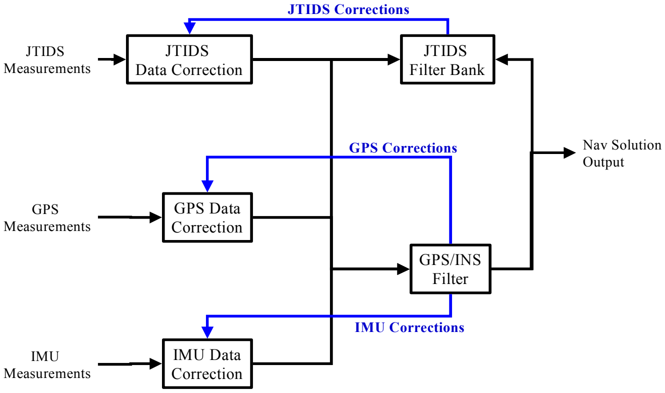

Figure 3 JTIDS Integrated Navigator

By tuning the state transition matrix (Φ) of the JTIDS filter, the JTIDS error calibration solution is designed gradually to decay in confidence and magnitude when the ownship position solution begins to degrade in response to the loss or degradation of GPS data. Since each JU has a different error characteristic and viewing geometry, some JU's may retain good confidence and continue to calibrate while others degrade back to a default calibration of zero, depending on which GPS satellites are lost and the error growth in the ownship navigator. This design provides graceful degradation of the navigation accuracy when GPS is lost. In the next section, we describe the JTIDS error characteristics that are calibrated by this process.

Figure 4 shows the way the filter will behave. In the example shown, the JU being calibrated has a 70 meter pseudo-range error. (For simplicity in the exposition, we show only one state as contributing to the nav error). The blue line shows the filter deriving the calibration value while a good onboard navigation solution exists. When GPS is lost, the onboard solution begins to degrade, reducing the ability of the JTIDS filter to continue to estimate the calibration value. As this happens, the filter will automatically decay the correction value to zero, in effect gradually removing the correction coefficient and reverting to "raw" JTIDS TOA measurement processing. Thus, the JTIDS data will be "partially" corrected for a time. As it does this, it will also gradually increase the JTIDS measurement uncertainty going into the onboard navigation system. The time constant of this process is a tuning parameter to be set in the filter by analysis of the time-correlation behavior of real JTIDS data; current analysis with the three available data sets indicates a time constant of somewhat less than 1 minute for this exponential decay process.

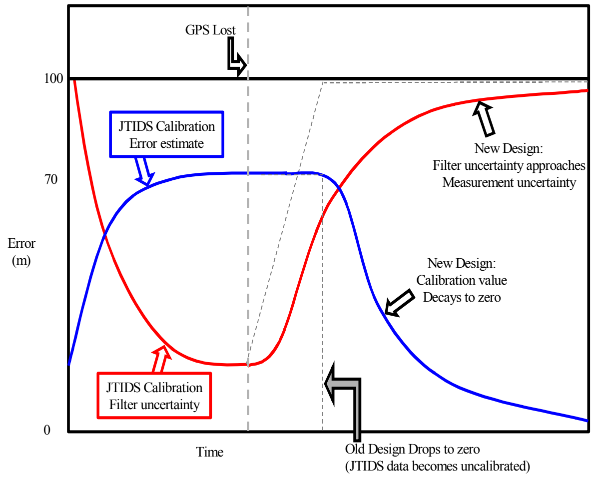

Figure 4 Example Filter Behavior for a 70m PR error

The resulting navigation error behavior for this system is illustrated Figure 5. The additional accuracy of this design after GPS loss is shown. Again, the time-constant of the growth in navigation error will depend on the time-behavior of the JTIDS source errors. Of course, in practice, there will be many JUs, each with its own error characteristics and geometry, contributing to the navigation error behavior as described in the following section.

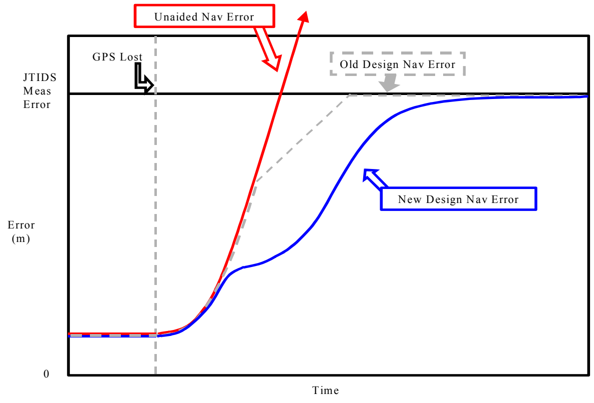

Figure 5 Integrated Navigation Error Behavior

LINK-16 ERROR MODELING

The Link-16 terminal contains a Relative Navigation (RELNAV) function that operates on navigation data received from the host together with TOA measurements and position data obtained from the Link-16 network. Position data is contained in received Precise Participant Location and Identification (PPLI) messages from multiple JUs. This function, operating in each participant's terminal, determines the position that is subsequently reported in that unit's PPLI.

A RELNAV tool was developed by ViaSat to simulate the JTIDS PPLI and TOA data based on the MIDS specifications. A series of real-world TOA data was then analyzed to see if the real-world behavior of the current JTIDS system matched the expected performance indicated in the specification and reflected in the RelNav simulator. An example of the data extracted from the exercise recordings is summarized in Table 2.

Table 2 JTIDS PPLI Extraction Format

value	**Quantity**	**units**
00013739	propagation delay	12.5 ns
13:31:00.041	JTIDS time	hr/min/sec.*timeslots* (128 timeslots/sec)
00071	JTIDS unit number	N/A
N30:10:39.68	Latitude	deg/min/sec
W088:38:21.14	Longitude	deg/min/sec
125	Altitude	feet
192	Course	deg
16	Speed	2 "datamiles"/hr = 12 kft/hr
12	position quality factor	σ (ft) = $2260\text{x}10^{-0.15\text{x}(\text{qf}-4)}$ (for qf ≥ 4)
15	altitude quality factor	σ (ft) = $2260\text{x}10^{-0.15\text{x}(\text{qf}-4)}$ (for qf ≥ 4)
14	time quality factor	σ (ns) = $2260\text{x}10^{-0.15\text{x}(\text{qf}-4)}$ (for qf ≥ 4)

The error model derived from the test data assumed that the JTIDS TOA derived range measurement equals sum of the following components:

- distance from receiver to *reported* JTIDS unit location (ideal range, ρ);
- slowly changing term (ε), describing the *combined* influence of low frequency misreports in position and propagation delay;
- near-white noise term (η) which represents receiver noise and multipath errors on the TOA observations

In the simulations, the measured JTIDS range was modeled as the sum of these terms as shown below.

$$\rho_m = \left|\vec{x}_{REP} - \vec{x}_{RCV}\right| + \varepsilon + \eta = \rho + \varepsilon + \eta$$

SIMULATION SCENARIOS

The purpose of the scenario development was to simulate the expected navigation performance that could be achieved by a platform by applying aiding data to the GPS/inertial filter in the event of GPS jamming using TOA information for other JTIDS platforms in the region. A trajectory was developed which is representative of a typical flight pattern and GPS areas of denial were predicted using notional, unclassified information.

In the notional simulation, baseline GPS jammers are placed along the simulated flight path with the jammer locations shown in red in Figure 6.

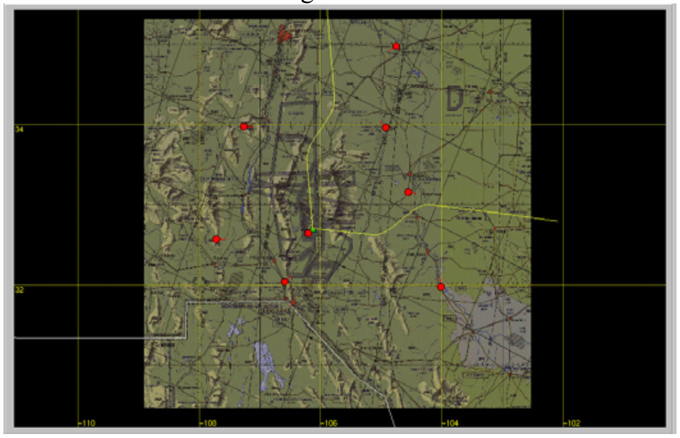

Figure 6 Notional Scenario – Two Routes and Jammer Locations

The navigation system was modeled as a FOG IMU with a P-code GPS receiver providing position and velocity measurements at 1 Hz. Two routes were modeled, one from the north and one from the east. The platform was simulated as flying along the route shown at an altitude of 22,000 feet.

JTIDS units were placed randomly in the mission area as shown in Figure 7. There are two different types of airborne units, and one group of ground based units. Each of the JTIDS units moves in an elliptical path. Different types of receivers are modeled by changing parameters, such as velocity, location, and altitude of the unit, as well as quality factors. All units here have the same quality factors, however, one set of airborne units moves at 400km/hr, another group moves at 200km/hour. Their altitude is set at 20,600 ft. The ground units have velocity set to 0.

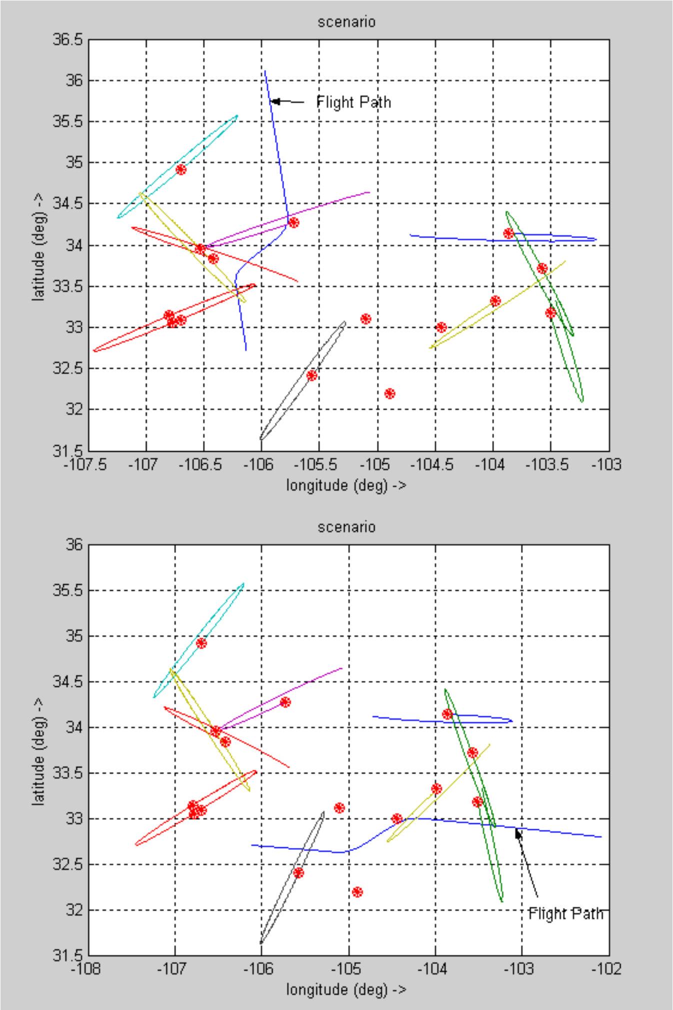

Figure 7 JU Layout for North and East Scenarios

The JTIDS messages have quality factors associated with time, position and velocity measurements. The quality factor for time (Qt) was 13, and the position quality factor (Qp) was 9. Quality factors can range between 1 and 15, where 1 is poor quality or large uncertainty, and 15 is high quality or small uncertainty. A Qt of 13 corresponds to 100 nsec (100 ft) of clock error. A Qp of 9 corresponds to 400 ft. of position error. These values were chosen as fairly representative of JTIDS qualities seen in previous real-world exercise data. ViaSat's LINK-16 RELNAV simulation tool was used to generate the JTIDS TOA measurement data for input to the navigator for each trajectory.

JAMMED AND UNJAMMED PERFORMANCE

The above-referenced trajectory was used to evaluate the navigation accuracy possible both with and without GPS jamming. Jamming conditions and their effects on the GPS receiver were modeled using the GIANT simulation tool developed by Veridian Corporation[4]. The output of GIANT is a prediction for the GPS receiver status throughout the entire flight time of the weapon. This GPS status was used as input to enable and disable GPS measurement data into the navigation filter as the weapon flew through the jamming area.

The following figures show the navigation error for each of the two routes in various conditions of jamming and JTIDS availability.

Figure 8 and Figure 9 show the position errors in a non-jammed environment. These plots form a baseline for comparing the performance in more hostile GPS conditions.

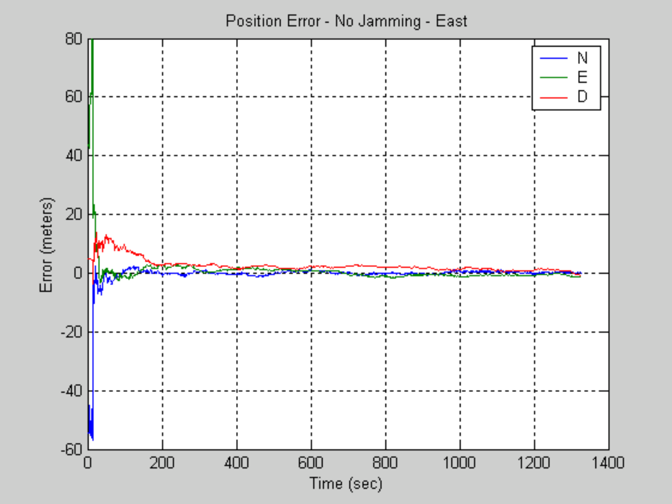

Figure 8 East Trajectory No Jamming

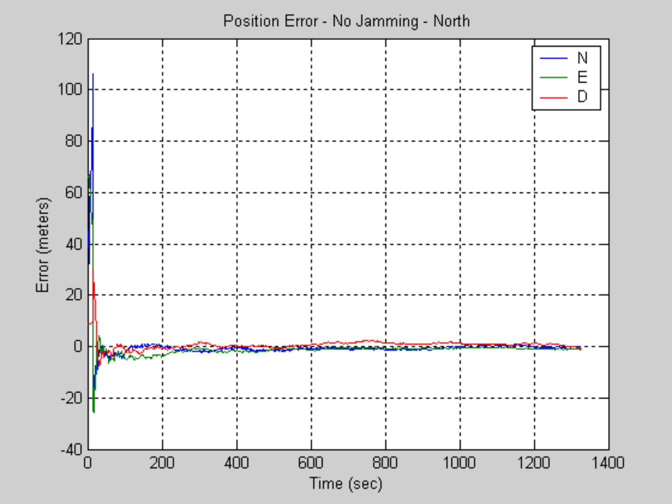

Figure 9 North Trajectory No Jamming

Figure 10 and Figure 11 show drift of the inertial navigation solution when GPS is lost. Jamming in this case starts at 440 seconds. However, an altimeter is being used and the “down” error has been reduced.

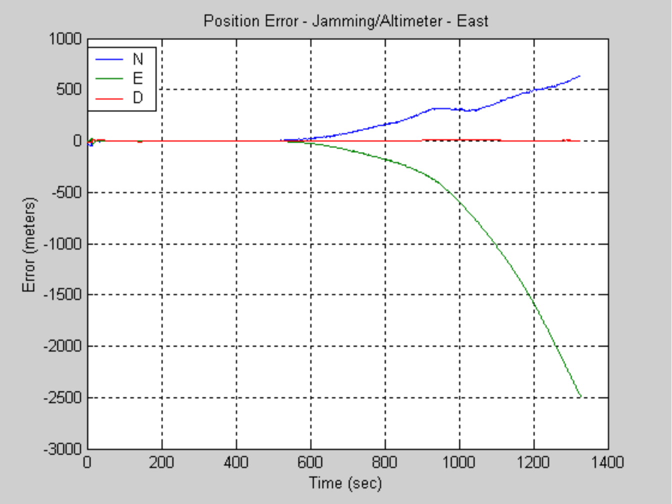

Figure 10 East Trajectory with Jamming at 440 seconds

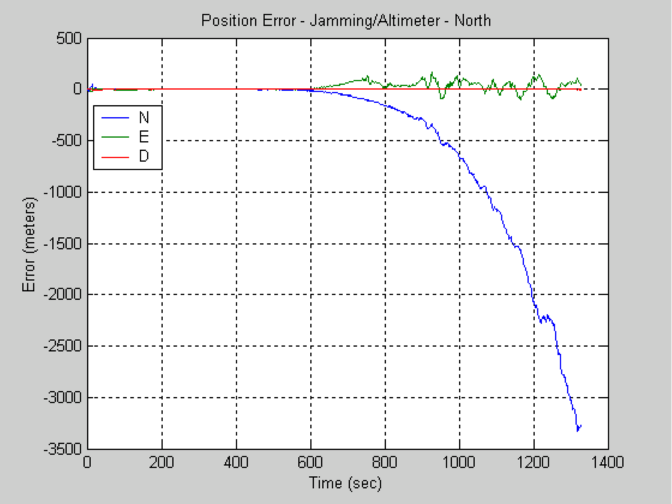

Figure 11 North Trajectory with Jamming at 444 Seconds

Figure 12 and Figure 13 show that the use of JTIDS data has bounded the error in the navigation solution. The error no longer grows unbounded; this plot is similar to previously-reported results for JTIDS aiding. Because of the high noise figure on the JTIDS data (compared with previously-simulated runs), the solution drifts a significant distance before the filter responds to the JTIDS measurements. This performance can likely be improved with better filter tuning.

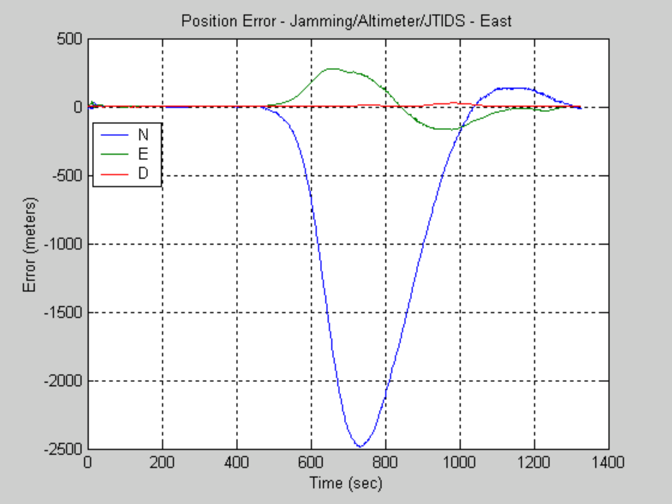

Figure 12 East Trajectory Error with JTIDS

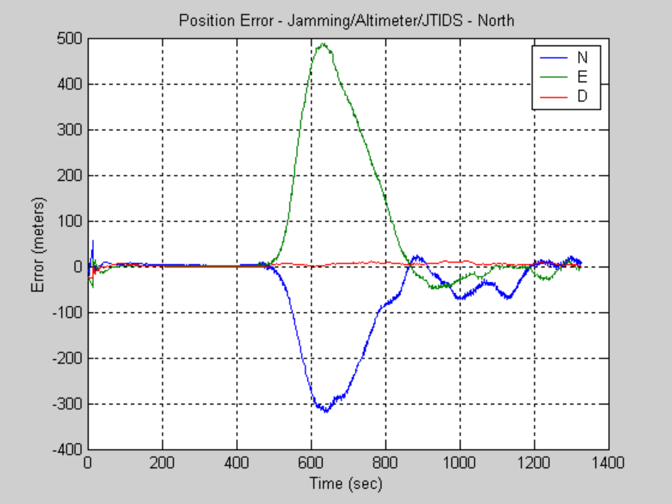

Figure 13 North Trajectory Error with JTIDS

Table 3 shows a summary of navigation errors for the different conditions simulated.

Table 3 RELNAV/InterNav Error Summary

		Navigation Error (meters)			
		N	E	D	Total
North	Non-Jammed	-0.7	-0.2	1.1	**1.3**
	J w/Altimeter	-3265.5	23.6	-1.9	**3265.6**
	JTIDS	5.7	-5.1	0.6	**7.7**
East	Non-Jammed	-0.8	1.0	-3.2	**3.5**
	J w/Altimeter	639.8	-2500.3	2.2	**2580.9**
	JTIDS	-16.9	5.2	2.8	**17.9**

CONCLUSION

It is clear from the analysis that the use of JTIDS TOA data has a measurable and significant impact on the navigation accuracy in the face of GPS jamming.

This analysis has been used by the Navy to assess the operational impact of the improved navigation capability for specific platforms that could leverage this capability[5].

With the deployment of anti-jam communications systems that incorporate range measurement capabilities (like EPLRS and JTIDS) and the added priority for anti-jam navigation since the Operation Iraqi Freedom, platform and weapon sponsors are becoming more aware that there are alternative methods than AJ antennas alone to provide jam resistant navigation. Further work to identify the optimal approach to integrating the InterNav capability into existing and future systems is being discussed.

ACKNOWLEDGEMENTS

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