Northrop Grumman's Family of Fiber-optic based Inertial Navigation Systems

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Abstract

Northrop Grumman Navigation Systems Division's (NSD) fiber-optic gyro (FOG) based family of inertial navigation systems; LN-251, LN-260, LN-270 and LTN-101E have demonstrated superb performance over a wide spectrum of applications ranging from high dynamic fighter aircraft, unmanned air vehicles, land vehicles and commercial aircraft. As compared to the previous generation of ring laser or mechanical gyro systems, the FOG navigation systems offer significantly smaller size, much lower weight, lower power consumption, vast improvement in life and reliability, all at the same or better level of accuracy. Using FOG technology, low noise accelerometers, high performance GPS, and sophisticated integration algorithms, NSD has demonstrated the FOG navigator's ability to provide extremely low velocity noise information, in turn enabling improved surveillance sensor compensation and reduced target location errors. Transfer alignment techniques also permits leveraging the full accuracy of the FOG navigator to smaller remote inertial measurement units used for motion compensation or stabilization of other sensors such as radar or electro-optic pods. NSD is also in the process of adding differential GPS correction capability to provide even further enhancement of absolute positional accuracy. Using this method, radial position errors have been demonstrated to be only a few 10's of centimeters.

Fiber-optic Gyro Based INS/GPS for Military Applications

The LN-251 INS/GPS is the basis of NSD's family of fiber-optic gyro based navigation grade inertial systems. The LN-251 resulted from a DARPA funded project to produce the next generation of navigation grade inertial system that would provide the smallest volume, lowest weight, lowest power consumption and highest reliability system compared to any other approach using alternate technologies such as mechanical or ring laser gyros. The features of the LN-251 are provided in Figure 1.

LN-251 Features:
- Light weight (12.5 pounds)
- Low power (25 watts)
- High MTBF (20,000 hours+)
- Aircraft carrier environment capable
- Navigation Performance
  - INS-only (0.8 nmi/hr CEP)
    - GPS-Only (10 Meters, CEP)[1]
    - INS/GPS (4 Meters, CEP)
    - INS/DGPS (0.5 Meters, CEP)
- All solid-state; no high voltage
- Stationary and moving base alignment capable
  - GC, IFA (GPS, External Position-Velocity)
- All-attitude world wide navigation
- Three simultaneous navigation solutions
  - INS-only, GPS-only, INS/GPS (blended)
- State-of-the-art fiber optic gyro technology
- Embedded GPS receiver
- RAIM and FDE IAW D0-229
- 12-channel all-in-view tracking
- Two MIL-STD-1553B data buses
- Multiple RS-485/422 data buses
- Host Application Equipment (HAE) IAW CZE-93-105A-SAASM
- AE1/GAS-1 antenna interface IAW CI-FRPA-3070

(1) Based on current GPS Space & Control Segment Error

- DS-102 crypto variable load
- PTTI and HaveQuick IAW ICD-GPS-060A
- Zeroize
- RF-FRPA/CRPA antenna interface IAW CI-FRPA-3070
- DGPS RTCM Type 1/StarFire GPS

Figure 1. LN-251 Features

The advances made with this system are due to the adoption of fiber-optic technology to provide the angular rate sensing. Fiber-optic gyros in comparison to ring laser gyros require no mechanical dither for their operation and thus eliminate a troublesome noise source; do not require high voltage for the laser plasma, hence reduce power consumption; and, with the exception of a laser diode for the light source are composed of passive optical components and thus yield extremely high reliability compared to any other available technology. The fiber-optic gyro architecture employed in the LN-251 is displayed in Figure 2.

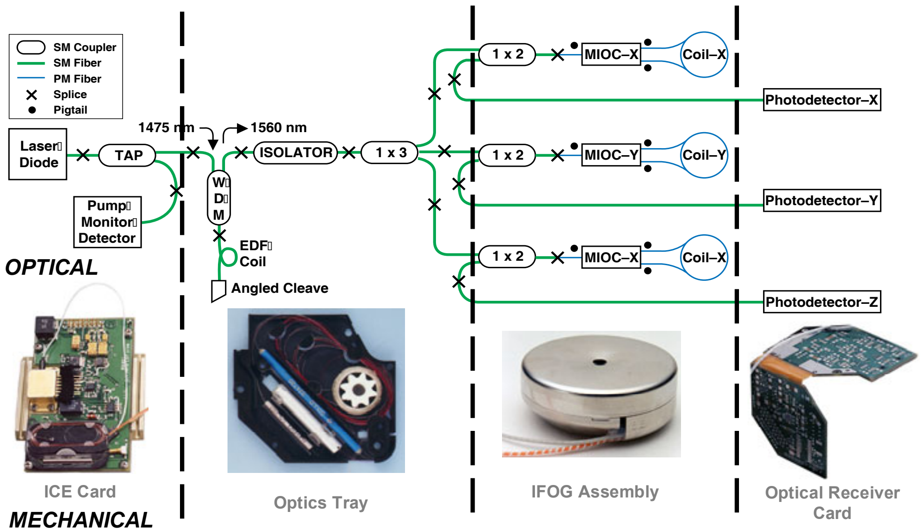

Figure 2. Fiber-optic gyro architecture in the LN-251

To minimize volume and power consumption only a single light source is used to operate all three fiber-optic gyro axes. Because the lifetime of laser diodes is rated in millions of hours, there is no impact to the reliability of the LN-251 due to failure modes of the light source. This is in strong contrast to ring laser gyro based systems for which the system reliability is a strong function of the lifetime and reliability of the ring laser gyro.

System Description

The LN-251 INS/GPS is a tightly coupled INS and GPS system, using Line-of-Sight (LOS) from the GPS to correct navigation parameters and inertial instrument errors using a Kalman filter. Figure 3 shows an exploded view of the LN-251 INS/GPS.

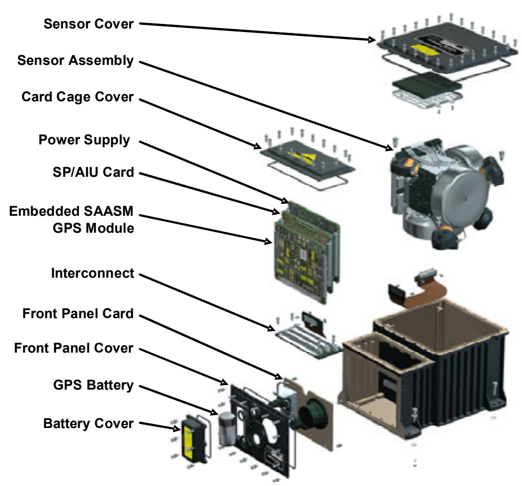

Figure 3. LN-251 Exploded View

The INS/GPS system consists of a Miniature Inertial Measurement Unit (MIMU), an Embedded GPS Receiver (ESR), a System Processor/Adaptable Interface Unit (SP/AIU), a Power Supply (PS), an adaptable front panel assembly, and a chassis. The ESR processes the GPS satellite signals and outputs satellite data to the system processor. The system processor combines the GPS data with the inertial data from the MIMU in a tightly coupled GPS/inertial mechanization using a Kalman filter. The INS-aiding data are also provided to the ESR to aid and pre-position the GPS tracking loops. The INS/GPS provides three simultaneous navigation solutions: a hybrid INS/GPS navigation solution, an INS-only navigation solution, and a GPS-only navigation solution.

All required functions are provided in a compact implementation. The functional partitioning is illustrated in Figure 4 and shows the ESR, MIMU, and SP/AIU functions.

The MIMU, Figure 5, provides precision measurements of acceleration and rotation. The integrated navigation function provides corrections to these measurements. The MIMU consists of a sensor assembly comprising three interferometric fiber-optic gyroscopes, three accelerometers, and an instrument controller electronics assembly. The inertial instruments are mounted on an iso-inertial, rugged vibration-isolated sensor block.

The ESR, is a 12-channel all-in-view GPS receiver. In addition to the Pseudo-Range (PR) and Delta Range (DR) data, the ESR provides the standard set of position, velocity, and time (PVT) data. Receiver Autonomous Integrity Monitor (RAIM) and Fault Detection and Exclusion (FDE) calculations and annunciations, in accordance with DO-229, are included.

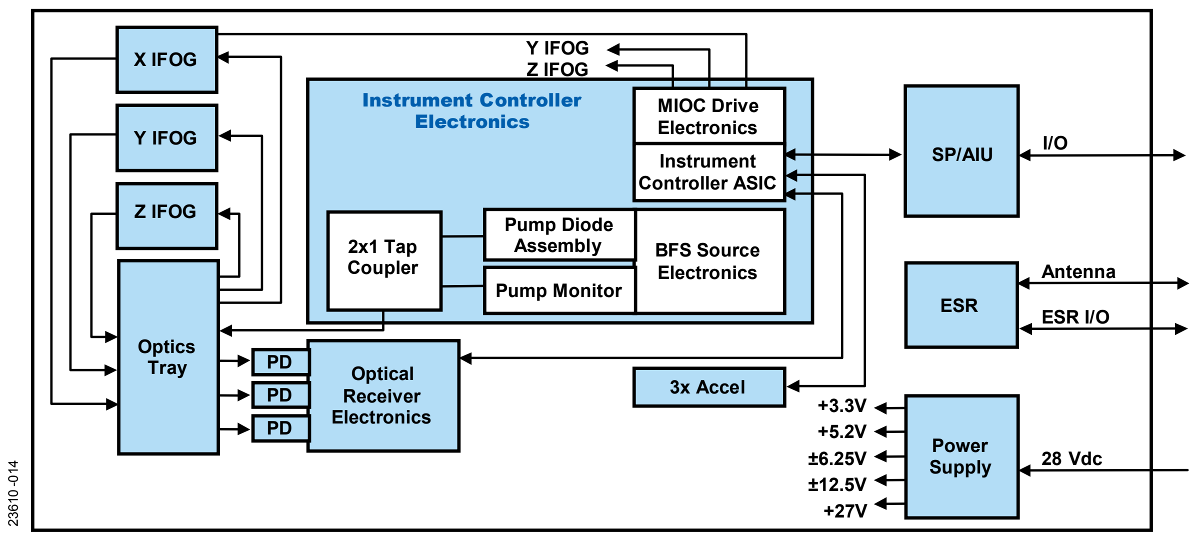

Figure 4. Functional Partitioning of LN-251 Equipment

Figure 5. Miniature Inertial Measurement Unit

Software

The system processor Computer Software Configuration Item (CSCI) is modular for proper control, ease of maintenance, and straightforward adaptability to new applications without complex modifications. The software is programmed in Ada and executes on the PowerPC™ microprocessor. The SP/AIU CSCI performs four main functions: MIMU processing, navigation processing, integrity processing, and application processing.

The system processor CSCI compensates gyro and accelerometer data for temperature and other effects using calibration data. Body frame incremental velocity and angle data are produced. The gyro secondary control loops are closed and monitored for optimal performance.

The system processor CSCI computes a navigation solution for host vehicle position and velocity using incremental velocity and angle data from the MIMU processing. A Kalman filter uses GPS measurement data, baro altitude, and external reference data to estimate and correct errors in the navigation solution, in host vehicle attitude, and in inertial sensor outputs. The system processor uses its navigation solution, position, and velocity data to compute inertial aiding data to be used by the GPS tracking loops.

Mode Control. Alignment modes include stationary and moving based alignments. Moving based alignments support GPS and external Position/Velocity aiding. The INS/GPS will provide on-deck GPS aided carrier alignment capability. Independent navigation modes of INS-only, GPS-only, and hybrid (INS/GPS) are provided. Built-in-Test provides start-up (SBIT), periodic (PBIT) and commanded test (IBIT) modes.

Performance

The inertial navigation solution is bounded over long periods of time by the GPS, and the long-term system position, velocity and time (PVT) accuracy is limited by the errors in the GPS system. High frequency errors (defined as errors which have a correlation time much, much less that a Schuler period) are largely driven by the noise characteristics of the inertial instruments and white noise in the GPS measurements. The INS/GPS Kalman navigation filter contains states that estimate and compensate for modelable errors in the inertial instruments and GPS system. By nature these modelable errors tend to have relatively long correlation times. The navigation performance of the LN-251 is summarized in Figure 1.

Land Navigation

The LN-270 INS / GPS system is the land production configuration of the LN-251 INS / GPS. NSD is currently delivering production LN-270 systems for an international howitzer program. The difference between the LN-270 and LN-251 is in the application table-driver software. The LN-270 includes provisions to interface to a land vehicle Velocity Measurement System (VMS), such as the standard MIL-PRF-71196 odometer. The LN-270 GPS / INS provides the level of performance necessary to achieve 1 mil azimuth accuracy at 75 degrees latitude (north or south). The same airborne GPS receiver as in the LN-251 is embedded in the LN-270 forming a tightly-coupled INS/GPS suitable for all land navigation applications. The LN-270 is pictured in Figure 6.

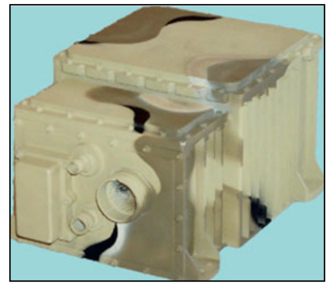

Figure 6. NSD's LN-270 for Land Navigation Applications

Aircraft Retrofit Applications

Not all aircraft applications can take advantage of the LN-251 features, in particular in retrofit applications due to the expense of aircraft modification that might be required. For these situations, NSD has developed the LN-260 which combines the features of the LN-100 including missioninzation software and I/O protocol with the benefits of the fiber-optic gyro sensor assembly.

The LN-260 provides:

- Increased operating life, based on the FOG LN-251 inertial sensor
- More than double the reliability of Ring Laser Gyro (RLG) based designs
- Commonality with the F-16, SNU 84 interfaces
- Growth to include CNS/ATM GATM requirements
- Enhanced INS performance, required to maximize the surveillance sensor performance

The LN-260 represents the state-of-the-art in aircraft navigation. The first application for the LN-260 will be in the recently awarded F-16 upgrade application. The LN-260 is pictured in Figure 7. The sensor assembly is identical with that used in the LN-251 while the I/O and missionization has been borrowed from the proven Northrop Grumman LN-100 product line.

Figure 7. LN-260 showing LN-251 sensor assembly

Two prototype LN-260 INS/GPS recently completed flight testing in a high dynamic, fighter aircraft environment to demonstrate the maturity of the fiber-optic gyro technology and the capabilities of the LN-260 system. A typical flight trajectory is shown in Figure 8.

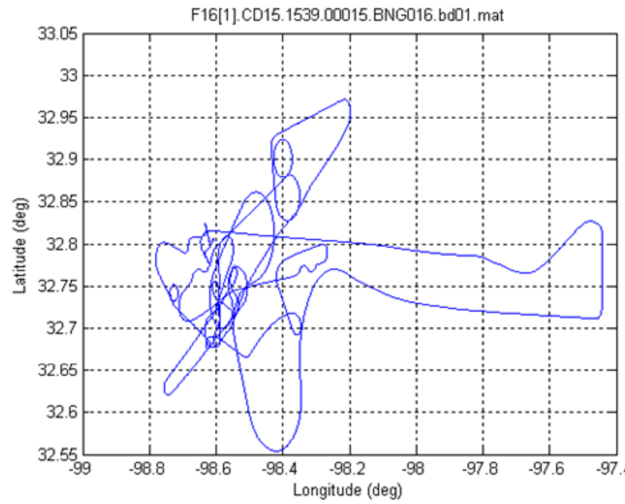

Figure 8. Typical flight trajectory for LN-260 testing

A total of nine test flights were performed with seven of those flights including maneuvers in excess of 9 g's. The results of the flight tests are displayed in Table 1.

CD15 Flight # / Date	V North Error (Ft/Sec RMS)	V East Error (Ft/Sec RMS)	RER (NMi/Hr)	Comments
Specification	< 2.5 F/S RMS	< 2.5 F/S RMS	< 0.8 @ 50% CEP	
1539 / 7-1-05	3.51	2.37	0.44	PROD 2, High Dynamics, No TPSI
1542 / 7-12-05	0.98 / 1.08	0.44 / 0.49	0.17 / 0.16	PROD 2, Medium Dynamics, TPSI
1543 / 7-13-05	0.85 / 0.92	1.18 / 1.19	0.28 / 0.23	PROD 2, High Dynamics, TPSI
1545 / 7-15-05	1.48 / 1.50	3.36 / 3.49	0.73 / 0.59	PROD 2, High Dynamics, TPSI
1598 / 9-14-05	1.47	2.86	0.60	PROD 4, Medium Dynamics, No TPSI
1599 / 9-14-05	1.57	2.97	0.93	PROD 4, High Dynamics, No TPSI
Total RMS/CEP	1.86	2.43	0.49	

Table 1. Summary of Flight Test Results for the LN-260 in High Dynamic Environment

Table 1 clearly shows that the LN-260 meets or exceeds the SNU-84 requirements.

Commercial Applications

NSD is also bringing the advantages of fiber-optic gyro technology to the commercial aircraft navigation market with the LTN-101E Inertial Reference System. Of extreme importance in this market is the very high reliability and long life that fiber-optics brings as compared to current ring laser gyro technology. The LTN-101E provides highly reliable velocity and attitude information for the aircraft. The LTN-101E subassemblies are shown in Figure 9.

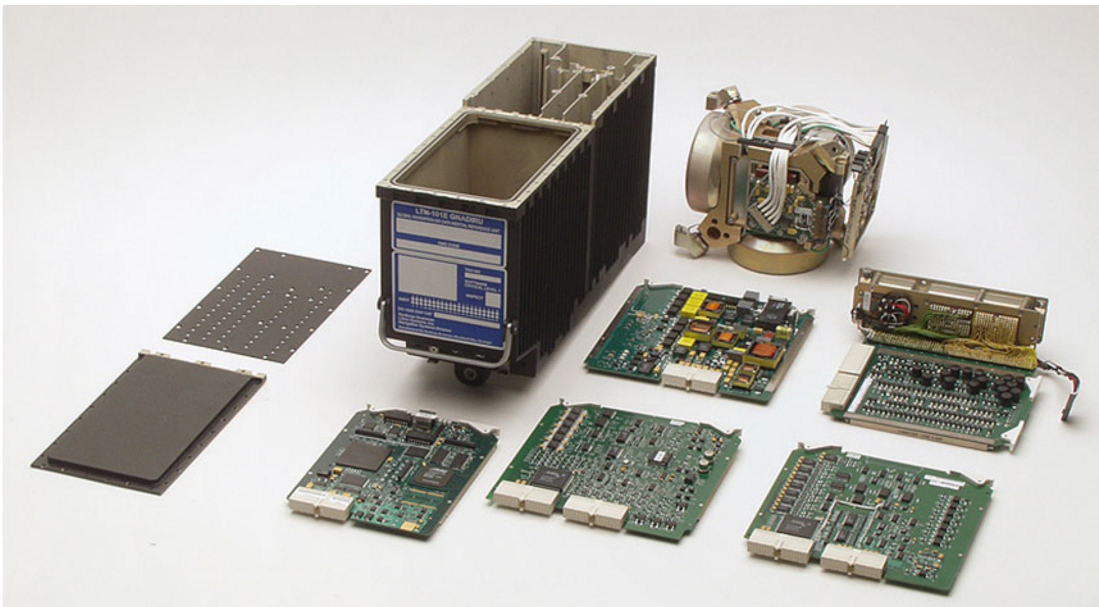

Figure 9. LTN-101E Subassemblies

The system is composed of the sensor assembly; power supply; HIRF/Lightning module; processor; air data; and the module that mixes with external GPS the inertial data. The LTN-101E sensor assembly uses the same fiber-optic gyro technology as the LN-251; however, the gyros are screened specifically for the export market and mounted on a sensor block that precludes the use of the LTN-101E in high dynamic military applications.

Future Improvements

The geolocation problem is pushing the requirements for positional accuracies. NSD has been investigating the use of differential GPS corrections in the LN-251 and LN-260 to provide the user with the most accurate positional information possible. Differential GPS is the process in which corrections are applied to the GPS signal to compensate errors in the broadcast GPS signal. These errors are composed of errors in the knowledge of the position of the GPS satellite and errors in the satellites onboard clock, as well as atmospheric disturbances that corrupt the GPS signal in the local area. In the standard operation of GPS, positional information is derived by the receiver by interpreting the timing data on the signal and the broadcast location of the satellite. In differential GPS, the differential reference receiver knows its location very precisely and thus can invert the normal process and derive equivalent timing errors on the signal by comparing the known and derived locations. These timing errors are a result of dynamic conditions in the ionosphere which can change quite rapidly as well as errors in the GPS satellite clock and orbit information which change quite slowly. As such these errors have to be continuously derived and provided back to the roving GPS receiver to compensate for errors created by the atmospheric conditions, both in the ionosphere and the troposphere and satellite errors. In the most simple of DGPS approaches the errors are treated as a lump sum whereas in the more sophisticated approaches attempts are made to separate out the satellite position, satellite clock, ionosphere and troposphere propagation errors and handle them individually. Applying differential GPS corrections can reduce positional errors to achieve sub-meter accuracies.

NSD has demonstrated the improvements in position accuracies available in the LN-251 using the differential GPS corrections available from the StarFire subscription service, available from NavCom of Torrance, CA.

Figure 9a and b show almost an order of magnitude improve in postion accuracy with the StarFire corrections as compared to using only the GPS signal.

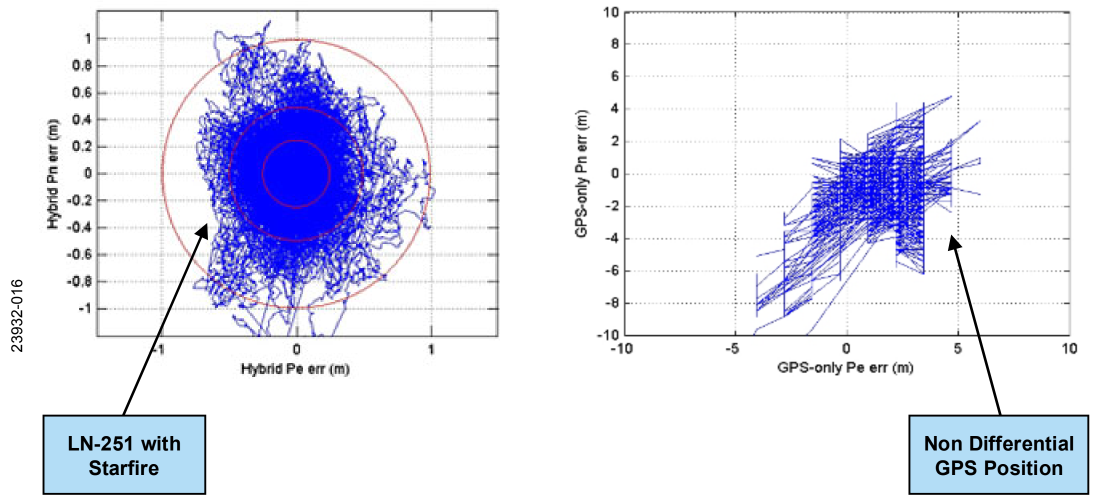

Figure 9a and 9b. Positional accuracies with and without the differential GPS corrections

In Figure 9a the distribution of position as computed from the INS/GPS solution over a 24 hour period in which the differential corrections available from the StarFire system were employed resulted in an rms value of less than 40 cm. Figure 9b shows the same 24 period however in this case only the INS/GPS hybrid solution was computed without the differential GPS corrections. The rms positional accuracy is this case was about 3 m.

Surveillance Sensor Enhancement

Precision surveillance and geolocation requires accurate attitude and velocity information of the sensor itself. It is not sufficient to have only the navigation solution for the platform since the attitude of the sensor can be independent of the host platform. Mounting a navigation grade INS/GPS to the surveillance sensor would be an ideal solution from a precision and accuracy point of view but is typically not practical due to the size, weight and power dissipation of the inertial unit which would adversely affect the performance of the surveillance sensor. An alternate approach is to employ a small, lightweight and low power inertial measurement unit, IMU, on the sensor and then mechanize a transfer alignment from the navigation grade INS/GPS on the platform to the IMU on the sensor.

The LN-251 enhances this transfer alignment due to the low noise characteristics of the fiber-optic gyro technology. Unlike standard ring laser gyros, which employ a dither motor to eliminate the lock-in effect, the fiber-optic gyro does not need mechanical dither and thus does not inject extraneous noise into the process. This is very important when mechanizing a velocity-matching algorithm in the transfer alignment process. Velocity matching is clearly the desired approach for SAR applications because any uncertainty or noise in the velocity estimates will result in blurring of the SAR imagery.

To demonstrate the advantages of the LN-251 in the SAR application, a series of test flights were conducted using a Sabreliner aircraft and Northrop Grumman's APG-68 fire control radar in the SAR mode. The LN-251 provided the master INS data. The APG-68 used NSD's LN-200, a fiber-optic gyro IMU mounted directly on the radar unit for basic stabilization. A velocity matching transfer alignment mechanization was implemented between the LN-251 and the LN-200. The setup for these flight tests is shown in Figures 10 a – c.

Figure 10a. Sabreliner Aircraft Used for Flight Tests

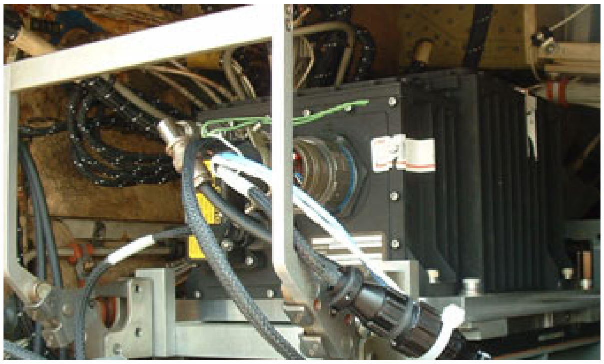

Figure 10b. LN-251 Mounted in Front Electronics Bay of the Sabreliner

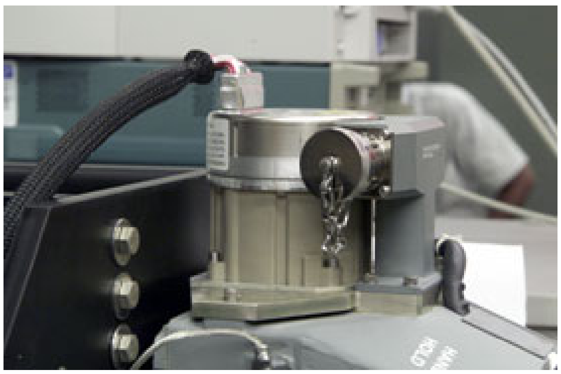

Figure 10c. LN-200 IMU mounted on the APG-68 Radar

The results of 188 SAR maps are summarized in Table 2, which shows velocity accuracies over the ensemble of flights less than 0.05 ft/sec.

FLT	Sample Size (# of Maps)	Velocity Error (fps)		
		Mean	Std	Rms
213	40	0.019	0.023	0.029
231-234	148	0.016	0.041	0.044

Table 2. Average Velocity Error Over Series of SAR Flight Tests

Target location errors derived from these tests showed average error in range of 4 ft with a standard deviation of 2 ft and average azimuth error of 13 ft with a standard deviation of 8 ft.

Summary

Northrop Grumman's Navigation System Division has introduced a family of fiber-optic gyro based inertial navigation systems to fulfill a large variety of applications. The introduction of fiber-optic gyro technology in these applications have resulted in systems of superb reliability that are ideally suited for the geolocation and surveillance sensor applications as well as military and commercial aircraft and land navigation.