Northrop Grumman's Family of Fiber-Optic Based Inertial Systems Enabling Precision Navigation and Geolocation

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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 permit 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 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.

1.0 ADVANCES IN INERTIAL TECHNOLOGY

In the 1980's the ring laser gyroscope was introduced displacing the standard mechanical spinning wheel gyroscope for aircraft accuracy navigation systems. The use of optical technology for inertial sensing was a revolutionary change that ushered in an era of significant improvements providing the user with enhanced characteristics in:

- system reliability;
- extremely high dynamic range;
- excellent linearity at high angular rates;
- volume reduction;
- power reduction; and,
- lower cost.

The ring laser gyro was one of the key developments that made strap-down inertial systems possible. Strap-down systems eliminate the need for complex mechanical gimbals required to form a stabilized platform and this advancement consequently enabled the proliferation of the application of inertial systems across a larger variety of platforms. The ring laser gyro brought along its own set of challenges resulting from the fact that this technology is nearly the last embodiment of vacuum tubes and as such bears the burdens of failure modes due to leaky gas seals and the challenges associated with packaging high voltage power supplies.

Northrop Grumman has introduced to the navigation market the next logical evolutionary step in optical inertial technology: the fiber-optic gyroscope. The fiber-optic gyroscope, just as the ring laser gyroscope, takes advantage of the Sagnac effect to measure angular rate in inertial space. In the ring laser gyroscope the beat frequency between two counter-propagating laser beams co-existing in the same optical cavity is used to measure angular motion. Creating and sustaining these two laser beams results in the challenges all too familiar with this technology. On the other hand, the interferometer fiber-optic gyroscope utilizes the phase difference measured after a split beam of light emerges from a coil of fiber-optic cable to sense angular motion. The only active elements in the gyro chain are the light source and the integrated optics chip. Both of these devices are low voltage, solid state components that exhibited both very high reliability and long life. The rest of the components that make up the fiber-optic gyro are passive and thus eliminate the technological challenges embodied in the ring laser gyro.

1.1 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 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)
- 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

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

- 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
- 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 Feature

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.

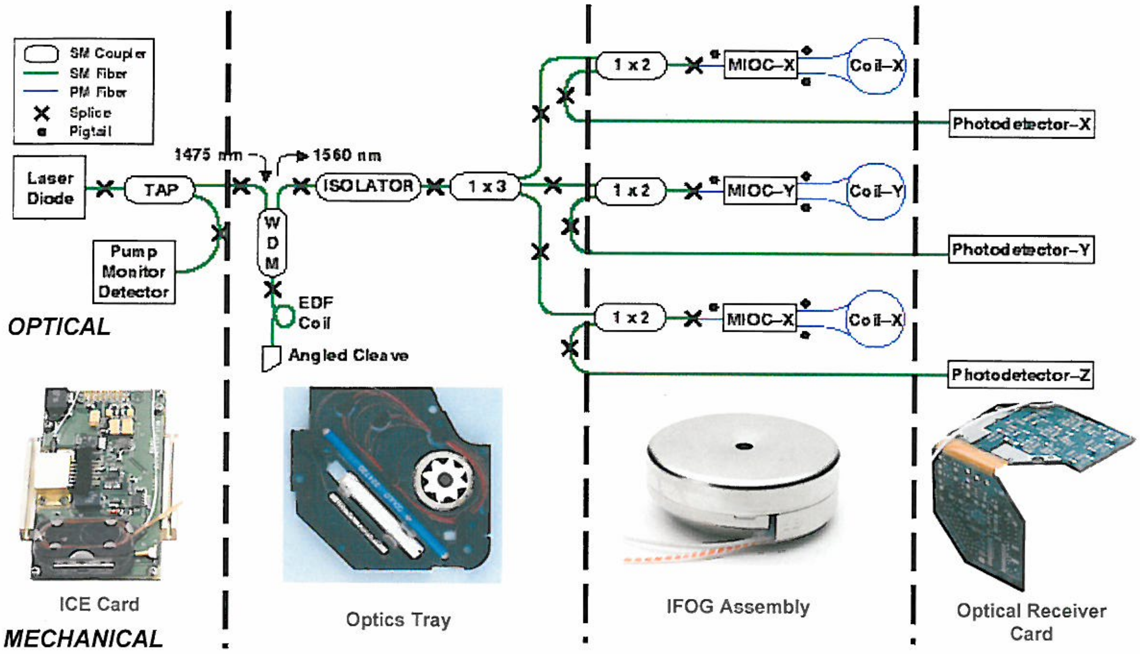

Figure 2: Fiber-optic Gyro Architecture in the LN-251

A single light source is used to operate all three fiber-optic gyro axes to minimize volume and power consumption. Laser diode lifetimes are rated in millions of hours and thus have no impact to the reliability of the LN-251. 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.

1.1.1 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.

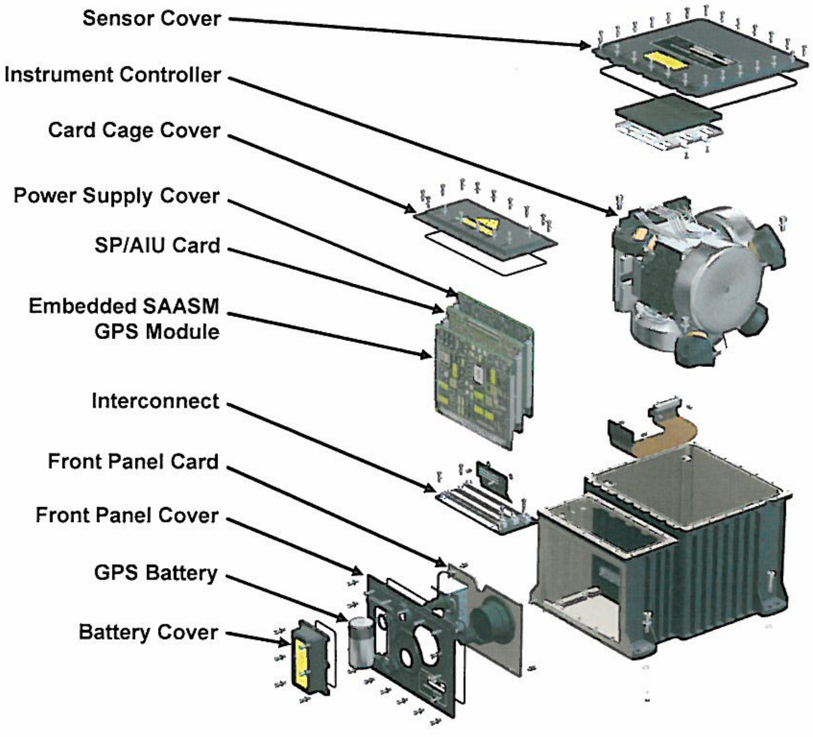

Figure 3: LN-251 Exploded View

The INS/GPS system consists of a Miniature Inertial Measurement Unit (MIMU), an Embedded GPS Receiver, a System Processor/Adaptable Interface Unit (SP/AIU), a Power Supply (PS), an adaptable front panel assembly, and a chassis. The EGR 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 EGR 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 EGR, MIMU, and SP/AIU functions.

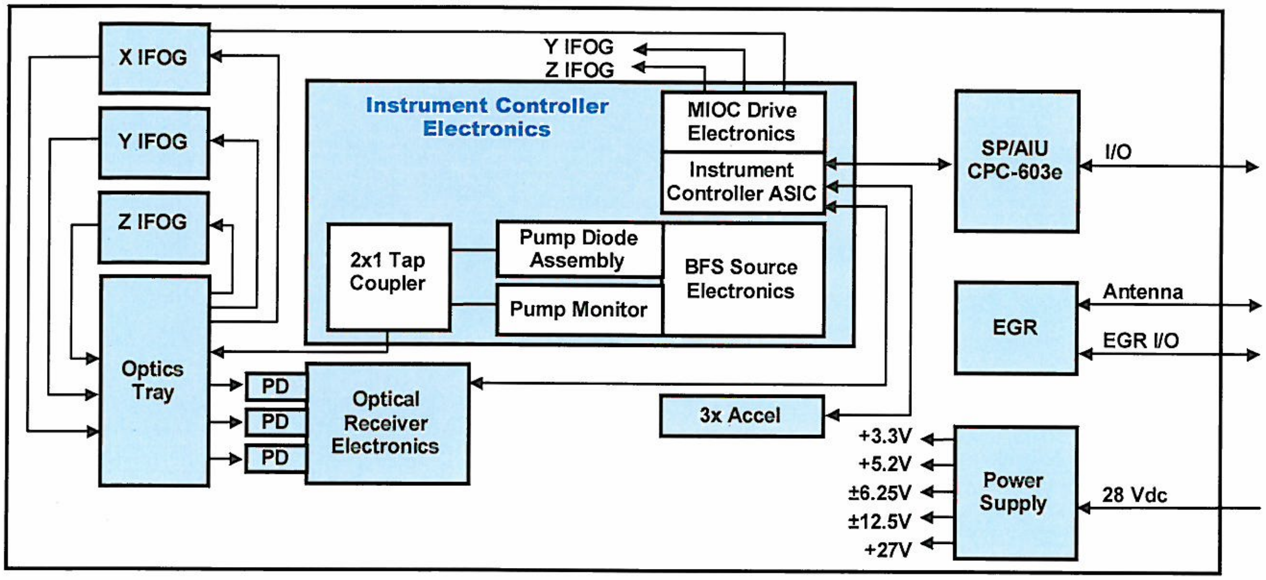

Figure 4: Functional Partitioning of LN-251 Equipment

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.

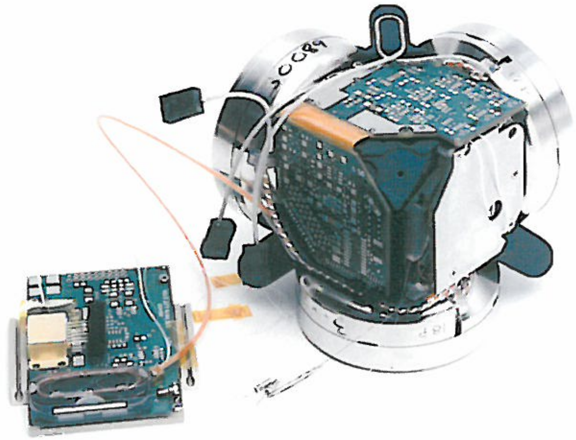

Figure 5: Miniature Inertial Measurement Unit

The EGR, is a 12-channel all-in-view GPS receiver. In addition to the Pseudo-Range (PR) and Carrier Phase (CP) data, the EGR 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.

1.1.2 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, satellite 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.

1.1.3 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.

1.1.4 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 software. The LN-270 includes provision to interface to a land vehicle Velocity Measurement System (VMS), such as the standard MIL-PRF-71196 odometer. 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.

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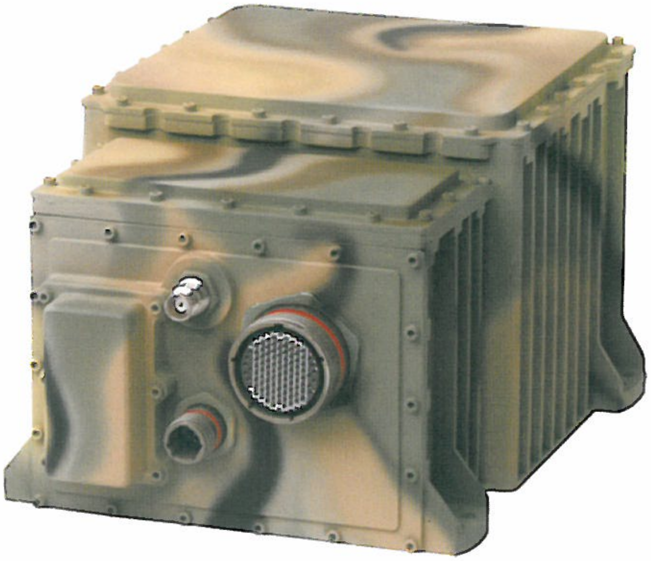


Figure 6: NSD's LN-270 for Land Navigation Applications

Due to its low noise, high bandwidth fiber optic gyros and high performance accelerometer, the LN-270 is capable of high accuracy land navigation with or without GPS aiding. In fact, utilizing odometer aiding in the Kalman filter, the LN-270 is able to reach accuracies comparable to GPS even when GPS is totally unavailable. Most impressively, the LN-270 has demonstrated accuracy of under 10 meters CEP on tracked vehicles over rough terrain with no GPS using a track-based odometer and zero velocity updates (ZUPTs) only once per hour. Performance measurements are summarized in Table 1. As seen in these measurements, accuracy can be further improved to better than 5 meters with more frequent zero velocity updates.

Table 1: LN-270 Navigation Performance – Free Inertial + Odometer Aiding
Tracked vehicle – rough terrain

	INS + Odom + 60 min ZUPTs	**INS + Odom + 10 min ZUPTs**
Hor Pos CEP (m)	8.1m	4.7m
Vert Pos PE (m)	9.5m	2.4m

In addition to its excellent navigation capabilities in harsh environments, the LN-270 also provides excellent true heading readout. The gyrocompass alignment implemented within the LN-270 software, enables acquisition of heading within minutes of turn-on and provides a superior pointing for the vehicle or weapon platform. Figure 7 shows a distribution of over 180 pointing tests at various headings and across over 30 different systems measured at 40 degree Latitude. The results indicate an excellent root-mean-square heading error of 0.55 mil. This error, even when normalized to 65 degrees latitude, still remains within 1 mil RMS.

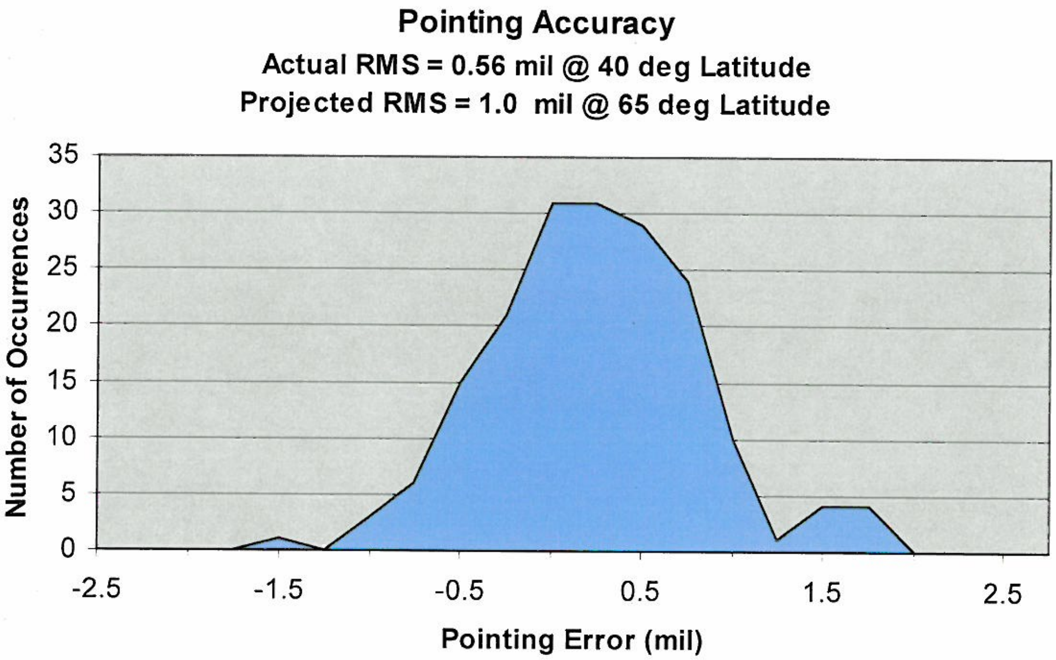


Figure 7: Pointing Error Histogram

The data obtained with the LN-270 system both in lab and field tests demonstrate its ability to meet a wide range of land navigation applications while providing significant weight, power, and reliability advantages over competing technologies.

1.1.5 Aircraft Retrofit Applications

Not all aircraft applications can take advantage of the LN-251 features, in particular in retrofit applications due to the extent 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 missionization 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 picture in Figure 8. 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.

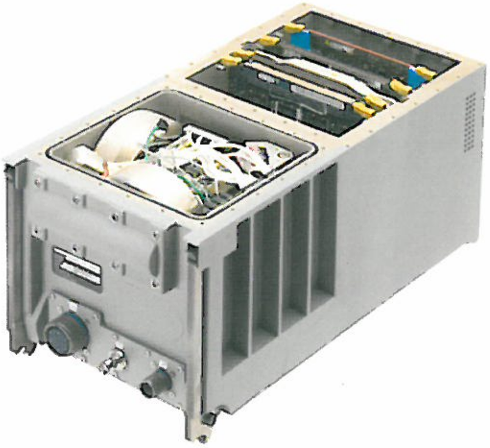


Figure 8: LN-260 showing LN-251 Sensor Assembly

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 9.

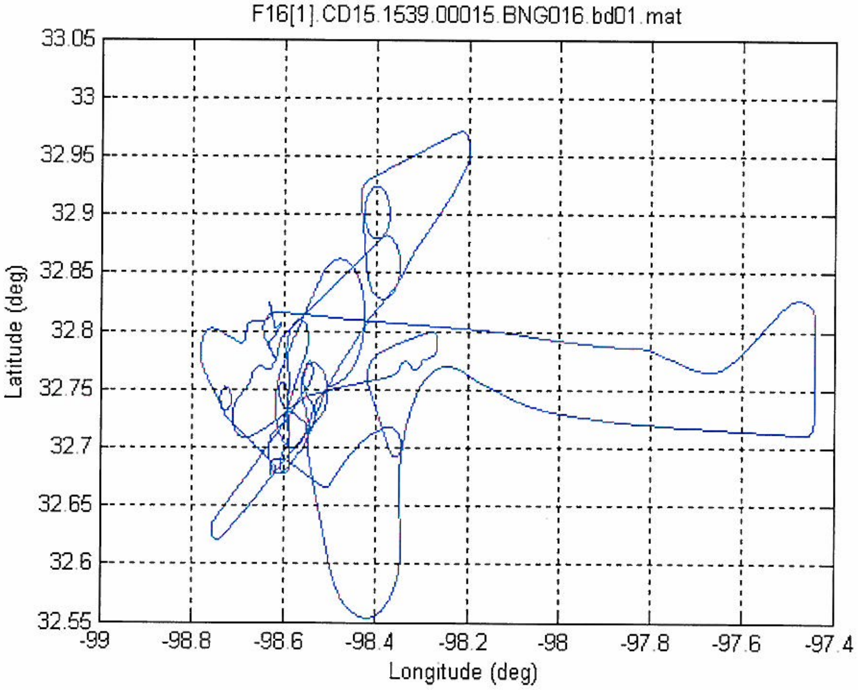


Figure 9: Typical Flight Trajectory for LN-260 Testing

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 2.

Table 2: Summary of Flight Test Results
for the LN-260 in High Dynamic Environment

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	

1.1.6 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 that fiber-optics brings as compared to current ring laser gyro technology. The LTN-101E provides highly accurate velocity and attitude information for the aircraft. The LTN-101E subassemblies are shown in Figure 10.

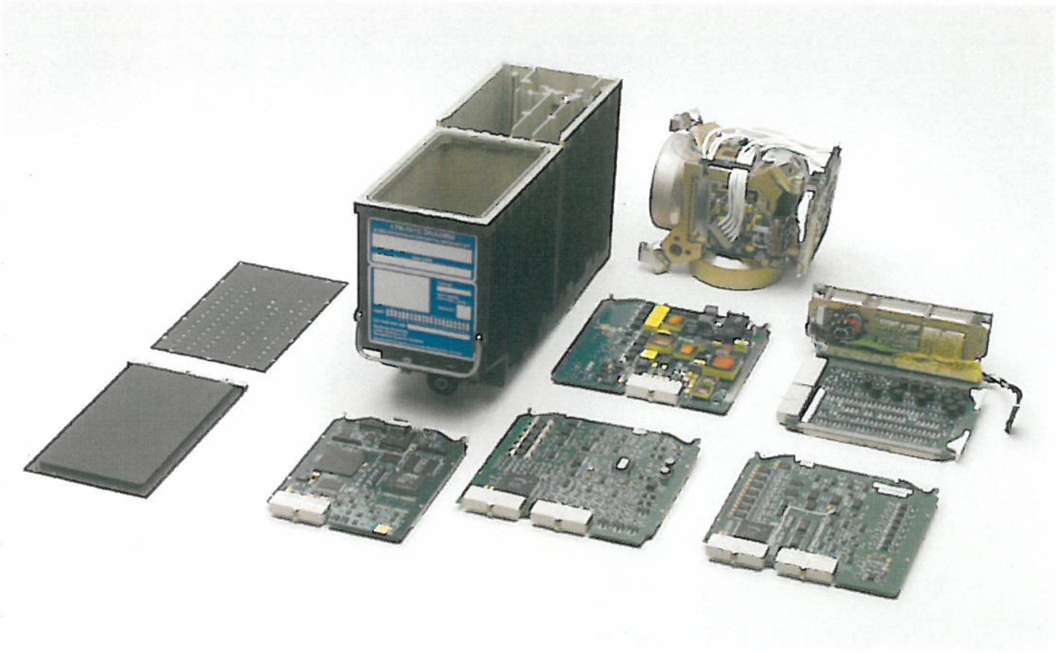


Figure 10: LTN-101E Subassemblies

The system is composed of the sensor assembly; power supply; HIRF/Lightning module; processor; air data; and the module that mixes with external GPS with 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.

1.1.7 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 positional accuracies available in the LN-251 using the differential GPS corrections available from the StarFire subscription service, available from NavCom of Torrance, CA. Figure 11 show almost an order of magnitude improve in position accuracy with the StarFire corrections as compared to using only the GPS signal.

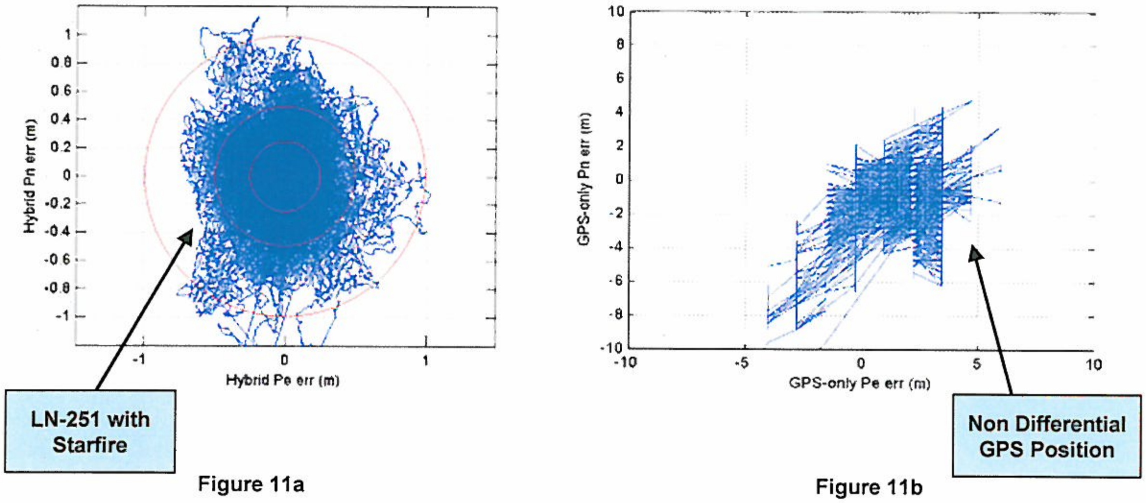


Figure 11a

Figure 11b

Figure 11: Positional Accuracies with and without the Differential GPS Corrections

In Figure11a the distribution of position as computed from the INS/GPS solutions over a 24 hour period in which the differential corrections available from the StarFire system were employed resulted in an rms value of approximately 50 cm. Figure 11b 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.

Synthetic aperture radars and lidars and electro-optical devices with laser range finders employed for targeting enemy assets are optimized by physically embedding small inertial measurement units (IMU's) in their designs to achieve the required linear and angular motion compensation relative to the earth-fixed coordinate frame of reference at the location of the targeting sensor on the vehicle. The dynamic effects at different points on a vehicle where the targeting sensors are located can be quite different due to vehicle flexibility and angular motion, especially during maneuvers as shown below.

These small targeting sensor embedded IMU's are lighter and lower cost but less accurate than the high grade INS/GPS vehicle reference "Master" navigator such as the LN-260. However by employing the process of "Transfer Alignment", these embedded IMU's such as the LN-200, provide high bandwidth position, velocity and pointing information at the remote points where the targeting sensors are located with accuracy commensurate with that of the Master navigator.

1.1.8 Targeting Error Minimization with Multiple Targeting Sensors

Individual targeting sensors realize improved performance when Transfer Alignment is implemented.

For Synthetic Aperture Radar (SAR), the high frequency local linear motion of the antenna phase center is measured by the embedded IMU while the error in low frequency linear motion computed by the IMU is corrected by using the Master navigator through the transfer alignment process. Transfer alignment optimizes the Motion Compensation (MoComp) required by the SAR. The velocity accuracy for MoComp provided by the Master navigator can be extremely accurate.

In a typical E/O targeting sensor an embedded IMU can be used to measure and compensate for high frequency angular motion while the low frequency error in orientation of the sighting axis relative to the earth-fixed frame of reference (i.e. tilt and azimuth error) can be corrected by a properly mechanized transfer alignment process between the Master navigator and the embedded IMU.

When disparate targeting sensors are employed for measuring a target location, additional possibilities exist for minimizing the target location error. For example differences in the computed target location of a particular point measured by the SAR and the E/O Laser targeting sensor provide a basis for correction of the different sources of targeting error for the two sensors. For SAR, velocity bias error causes an azimuth error in the target location while for the E/O Laser targeting sensor, pointing error is the primary cause of targeting error.

1.1.9 Methods of Transfer Alignment

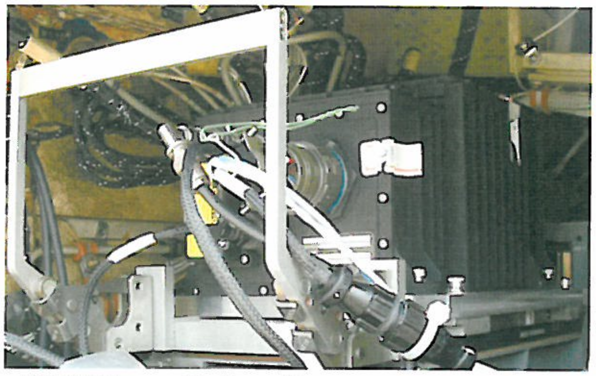
Standard and more sophisticated high capability methods of transfer alignment exist.

A standard method of transfer alignment employs "Velocity Matching" between the navigation solution computed by the Master navigator and the navigation solution computed by the embedded IMU in the targeting sensor. Correction for the relative velocity between the two units is required when the solutions are compared due to vehicle angular rate and the lever arm between the two units

More sophisticated methods of transfer alignment have been mechanized wherein a solution for the unknown lever arm between the two units is included in the transfer alignment process. The most sophisticated transfer alignment method of this type was mechanized by Northrop Grumman NSD decades ago for the alignment of inertial navigation systems in aircraft on the decks of aircraft carriers where the location of the aircraft on the deck relative to the reference Ship Inertial Navigation System (SINS) below deck was unknown.

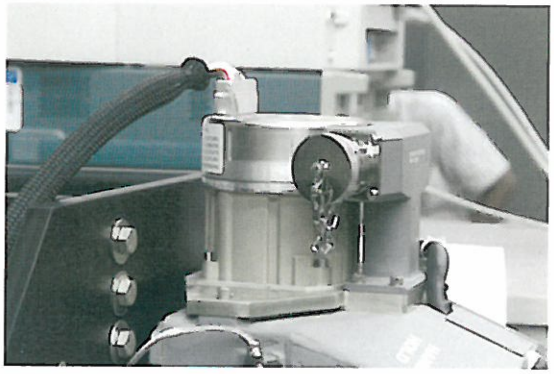
The performance of standard methods of Transfer Alignment can be improved by also comparing the vehicle angular rates measured in the two navigation coordinate frames computed by the Master INS/GPS and the targeting sensor embedded IMU. The difference in the angular rates in the two computed earth-fixed reference coordinate frames provides a basis for detection of the orientation error (i.e. tilt and azimuth error) of the frame computed by the embedded IMU relative to the earth. This is a useful technique for minimizing the Target Location Error (TLE) for an E/O Laser targeting sensors.

To demonstrate the advantages of the LN-251 in a SAR application, a series of test flight were conducted using a Northrop Grumman aircraft and radar used in the SAR mode. The LN-251 provided the master INS data. The radar used NSD's LN-200, 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 Figure 12.



LN-251 Mounted in Front Electronics Bay the Aircraft

Figure 12a



LN-200 IMU Mounted on the Radar

Figure 12b

Figure 12: LN-251 and LN-200

The results of 148 SAR maps are summarized in Table 3, which shows velocity accuracies over the ensemble of flight less than 0.05 ft/sec.

Table 3: Average Velocity Error Over Series of SAR Flight Tests

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**

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.

2.0 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.