THE B-2 NAVIGATION SYSTEM

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ABSTRACT

The B-2 Navigation Subsystem (NSS) is a complex multi-sensor system integrating tuned rotor gyro inertial, ring laser gyro inertial and astro-inertial navigation systems as well as position and velocity aiding from the Radar Subsystem (RSS), a Synthetic Aperture Radar (SAR). The NSS is designed to provide an extremely precise navigation solution for use in the B-2 avionics suite. The NSS is also being upgraded with a Global Positioning System (GPS) update capability. This paper describes the overall top level unclassified requirements for the NSS. The paper also describes the architecture and operation of the NSS and the interface with the rest of the B-2 avionics suite.

INTRODUCTION

The B-2 NSS design was driven by the user requirement for precise long range autonomous navigation. Strategic bomber missions require navigation systems which provide accurate navigation information for long periods of time. Both the B-52 and the B-1B have low drift systems which are updated periodically by radar velocity and position information. Since the B-2 is intended to penetrate enemy territory "unseen", it is undesirable to radiate RF energy by taking multiple radar updates. This requirement drove the NSS to include a star tracker which dramatically improves the long term unaided navigation accuracy. The star tracker significantly reduces or eliminates the need for radar updates in the weapon delivery portion of the B-2 mission.

SYSTEM DESCRIPTION

The baseline B-2 Navigation Subsystem (NSS) provides an extremely accurate navigation solution to the B-2 avionics suite for use by the radar system, terrain following system and weapon delivery system. The NSS is well suited to the high altitude, long duration cruise missions of the B-2. The NSS provides the most accurate autonomous navigation information of any currently available Air Force navigation system. The extremely high accuracy of the NSS is primarily attributable to the incorporation of an Astro-Inertial Unit (AIU) as the primary component of the system. In addition incorporation of a gravity compensation algorithm further improves the performance of the NSS.

The B-2 Navigation Subsystem (NSS) is composed of an Astro Inertial Unit (AIU), an Inertial Measurement Unit (IMU), an AIU Power Supply Unit (PSU), an Airborne Time Transfer Unit (ATTU) and two Avionics Control Units (ACU), as shown in Figure 1. Northrop Electronic Systems Division (NESD) is the contractor developing the NSS. NESD provides the navigation software and builds the AIU, PSU and ATTU. The IMU is subcontracted to Kearfott, Guidance and Navigation Division. The ACU, which is the common computer for all major B-2 subsystems is built by UNISYS.

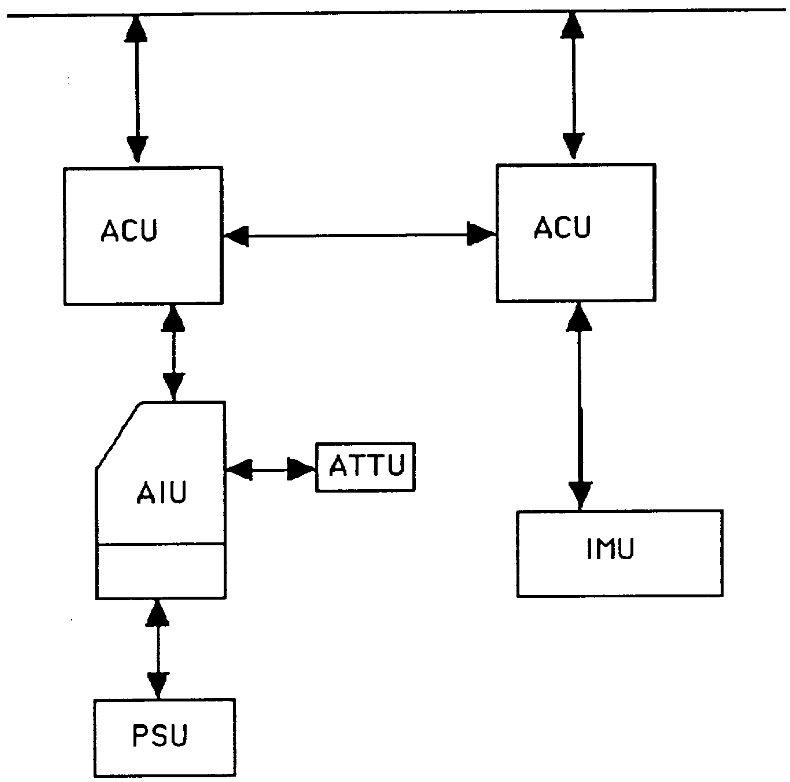

Figure 1. Navigation Subsystem block diagram

During optimal operation the IMU ACU operates as the primary navigation system computer. Within this computer resides the NSS kalman filter. This kalman filter optimally integrates the sensor information from both inertial systems and the star tracking information from the single AIU to produce an extremely accurate navigation solution. The filter also compensates for anomalies in the gravity field. The gravity compensation algorithm is a co-location algorithm which uses gridded gravity disturbance data provided to the Air Force by the Defense Mapping Agency. This data is stored in the Mass Storage Unit (MSU) as shown in Figure 2. Preprocessing is completed prior to flight by performing all geometry independent computations. This significantly reduces the in-flight computational requirements. The algorithm uses this preprocessed data to provide real time correction of errors induced by gravity anomalies. In addition radar velocity and position updates can be incorporated into the kalman filter to further refine the navigation solution. The B-2 System Program Office (SPO) has also begun preliminary work to incorporate navigation information from the satellite based Global Positioning System (GPS) into the NSS navigation solution. The NSS capabilities are pictorially illustrated in Figure 3.

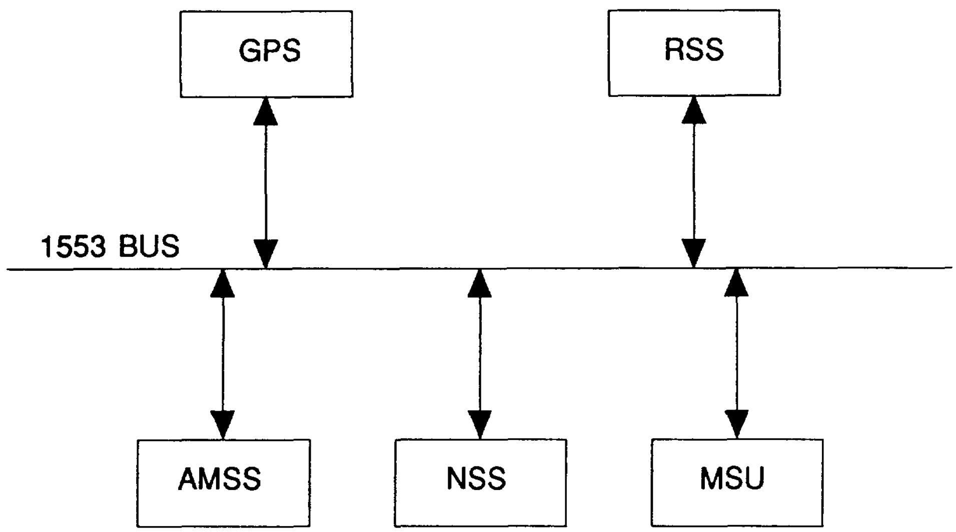

Figure 2. NSS Interface Simplified Block Diagram

Both the AIU and the IMU utilize inertial instruments (gyros and accelerometers) manufactured by Kearfott, Guidance and Navigation Division. These instruments are of the same quality as those used in the B-1B and the Advanced Cruise Missile navigation systems. The free inertial drift qualities of the AIU and IMU are therefore nearly identical. In the NSS implementation the inertial performance is augmented by star azimuth and elevation data which is used to provide leveling information to the inertial platforms. Precise time is required to track stars to the accuracy required. Time is provided by the Airborne Time Transfer Unit (ATTU). The improvement in maintaining level platforms significantly reduces the inertial drift of the system. In the event of an interruption of star tracking the system will begin to drift as a highly calibrated free inertial unit. When star tracking resumes, the system will again drift at the reduced rate.

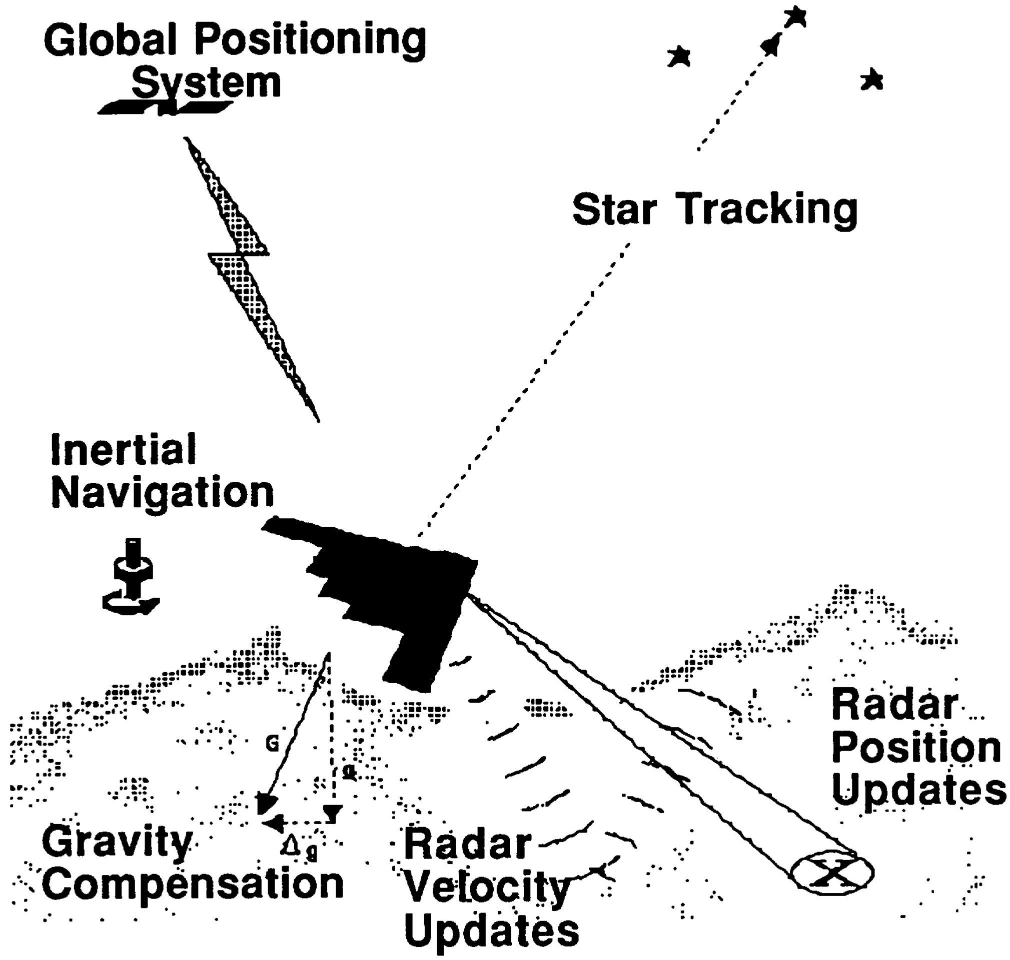

Figure 3. Navigation Subsystem capabilities

NAVIGATION MODES

The NSS has both ground and air alignment capabilities. In both cases the NSS is initialized by the Attitude Motion Sensor Set (AMSS), a low accuracy ring laser gyro inertial navigation system built by Kearfott, Guidance and Navigation Division (Figure 2). The primary function of the quad redundant AMSS is flight control. However as a secondary function the AMSS provides position, velocity and attitude data for initialization of the NSS. In the ground alignment modes the AMSS data is available to the NSS after a 90 second AMSS stored heading alignment. The NSS has three ground alignment modes, Gyro Compass Ground Alignment (GAGC), Rapid Ground Alignment (RGA) and Scramble Alignment (SA). During air alignment the AMSS acts as the primary navigation system while the NSS thermally stabilizes. When this is complete the NSS transfer aligns to the AMSS and then begins radar velocity and position updates (Figure 3) to complete the air alignment process.

During navigation the NSS operates in coupled or uncoupled modes. When coupled, data from both the IMU and the AIU are integrated in a kalman filter operating in the IMU ACU. The AIU ACU operates concurrently with an AIU only solution. In the event the data from the AIU and the IMU diverge the NSS filter will uncouple and the two systems will operate independently with reduced filter sizes. The B-2 Operational Flight Program (OFP) will then select the best solution as the Preferred Navigation System (PNS). The uncoupled mode can also be selected by the operator for intentional independent operation. If desired the operator can manually select the PNS in both manual and automatic uncoupled operation.

The NSS navigational modes are Stellar Doppler Inertial (SDI), Doppler Inertial (DI), Stellar Inertial (SI) and Inertial (I). The primary navigation mode during cruise is coupled Stellar Inertial.

THE GLOBAL POSITIONING SYSTEM

The Global Positioning System (GPS) is currently in the early stages of incorporation into the B-2 Navigation Subsystem. The satellite based system provides extremely accurate navigation information and will be integrated to enhance NSS performance. In addition GPS is a required replacement for the TACAN system and will be integrated to provide a "sole means of navigation" per the Minimum Avionics Requirement (MAR) document. Use of GPS data dramatically reduces or eliminates the need for radar position and velocity updates for air alignment of the NSS. The GPS aided NSS solution will also provide better accuracy for weapon delivery in conventional scenarios. In nuclear scenarios the GPS aiding will improve performance as long as the GPS signal is available . Upon loss of the GPS signal due to jamming, nuclear scintillation effects or loss of satellites the NSS will begin to revert to stellar-inertial performance levels.

The B-2 System Program Office (SPO) initiated a GPS integration study with Northrop B-2 Division, the B-2 prime contractor, to evaluate potential implementations of GPS into the B-2. The results of this study indicated the Air Force standard Miniaturized Airborne GPS Receiver (MAGR) would not work due to increased signal losses associated with Low Observable (LO) GPS antenna technology. The contractor recommended development of an alternate GPS receiver with improved receiver sensitivity over the MAGR specification. This improved receiver was to overcome the large signal losses from the proposed GPS antenna. Development of a B-2 unique receiver was undesirable due to the increased acquisition and logistics costs involved. With assistance from the GPS Joint Program Office (JPO) and Rockwell Collins, the MAGR contractor, an assessment of actual MAGR performance was conducted. The results revealed the receiver actually performed better than specified.

This team also determined this "better than spec" performance could be improved even more with software enhancements. Some of these enhancements will take advantage of the B-2's inherent low vehicle dynamics. Changes being investigated are: GPS navigation filter tuning to NSS model, using ionospheric delay estimates in state 3 operation, defining the B-2 antenna orientation/gain pattern to the MAGR, and allowing longer time to first fix for initial satellite acquisition. Details of these possible specification changes are currently being worked by the B-2 Navigation group, GPS JPO and Rockwell Collins. In addition to the improved performance expected of the MAGR, the integration of GPS with the highly accurate NSS will result in even greater performance. The GPS receiver will be inertially aided by the NSS for improved satellite tracking stability. Altitude and time aiding of the receiver is also being considered. Additionally the receiver sensitivity requirements for LO applications have been reduced from our original estimate. This is due to the better than expected performance of prototype LO GPS antennas. As a result of these recent findings and much analysis, the B-2 SPO decided the MAGR will meet the B-2 requirements.

Another challenge of integrating GPS on the B-2 was meeting the jamming suppression requirements with an LO antenna. The Anti-Jamming (AJ) capability of the MAGR was determined to be insufficient. Additional AJ could be provided by the use of a Controlled Reception Pattern Antenna (CRPA). However a CRPA which would meet the Radar Cross Section (RCS) requirements of an LO vehicle would have lower signal gain than a FRPA. This reduced signal gain further complicates the receiver sensitivity issue. Another concern with using a new LO CRPA was potential incompatibility with the existing Antenna Electronics (AE-1). This incompatibility would drive the development of a new or modified antenna electronics unit. The FRPA (Fixed Reception Pattern Antenna) prototypes had significantly better gain performance than CRPA prototypes and also came closer to meeting the B-2 LO requirements. However the FRPA does not increase the AJ of the MAGR. Fortunately the JPO and Wright Labs (WL) have been working on a number of technology insertion programs designed to increase the AJ of the MAGR. They have developed adaptive filter processing techniques which can be added to the receiver. Testing to date has shown these filters will increase the AJ performance of the MAGR to the required level.

Consequently our current direction for GPS integration is to proceed with the MAGR and an LO FRPA. The MAGR will be upgraded with the technologies insertion programs upon their completion. We will also make provisions for a CRPA antenna and its associated antenna electronics unit as a risk reduction and to protect against the possibility of a changing threat in the future.

FLIGHT TESTING

Inherent in the development of a highly accurate navigation system such as the NSS are the difficult challenges of flight test evaluation and performance verification. In order to reduce the risk associated with these challenges several flight test tools were developed. Two of the most important are a very precise reference system to aid with the analysis of flight test anomalies and the Avionics Flying Test Bed (AFTB), which was developed to allow dedicated preliminary integration and flight test analysis of both the Navigation Subsystem and the Radar Subsystem at a greatly reduced cost.

A navigation reference system with an order of magnitude greater accuracy than the navigation system under test is desired for confident analysis. Developing a practical system of this accuracy was beyond the capability available at flight test facilities when NSS flight testing began in 1987. Consequently a differential GPS system, developed by the GPS Joint Program Office and GD Services, was chosen as the best suited reference system for the B-2's needs. A GPS receiver was installed on board the test platform and continuous position and velocity reference data were recorded. The GPS receiver also utilized clock aiding in order to derive a GPS navigation solution when only three satellites are available, this was imperative due to the limitations in GPS coverage. In order to improve the quality of the raw GPS data post processing was performed utilizing differential GPS techniques to merge the in-flight GPS data and data simultaneously recorded at a dedicated ground station. This processing significantly improved the accuracy of the data. This GPS ground station is now operated by Intermetrics and managed by the Central Inertial Guidance Test Facility at Holloman AFB, NM.

The AFTB is an NKC-135A configured with portions of the B-2 avionics. The AFTB was successfully used to test individual sensors and modes and then to integrate and fine tune these into a highly accurate navigation system. The AFTB flight testing provided an initial assessment of NSS ground and air alignment modes and navigation modes. The NSS AFTB flight test performance met or exceeded all accuracy goals of the initial flight test program. Through this testing, a nearly developed navigation system was delivered to the B-2 avionics flight test program. Since the cost per flight hour for the AFTB is significantly less than for the B-2, this program has proven to be a very cost effective tool to reduce development and integration risk to the overall B-2 flight test program.

NESD also developed detailed post flight analysis tools to efficiently reduce and analyze data. These tools include OFPNAVSIM. This post flight emulator allows "re-flight" of actual flight test data in the lab. The results of the actual flight can be reproduced with remarkable accuracy. Then variations in external data (e.g. gravity, air data) or internal processing can be introduced to aid in the correction of flight test anomalies and in the fine tuning of the kalman filter. This data analysis tool, developed by NESD on their own initiative, has proven to be extremely valuable; allowing one actual flight to be used over and over with different variations. This has significantly lowered the number of flight hours required to develop and integrate the B-2 NSS.

These flight test tools, an extremely accurate reference system, a dedicated flight test bed and detailed post test analysis tools have reduced risk to the overall B-2 development program.

SUMMARY

The B-2 Navigation Subsystem has completed initial flight testing on the AFTB. An initial assessment of NSS ground and air alignment modes and navigation modes is complete. The results of this testing have been better than the original long term flight test accuracy draw down plan. Initial testing of NSS ground alignment and navigation modes on the B-2 has shown results consistent with the AFTB results. Completion of development and performance verification will continue on both the AFTB and the B-2. The flight test results indicate the NSS will meet all specifications and operational requirements.