INDEPENDENT VERIFICATION AND VALIDATION (IV&V) TESTING OF THE TOMAHAWK LAND ATTACK MISSILE (TLAM) GPS RECEIVER

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ABSTRACT

Under the Block I11 Conventional Tomahawk Land Attack Missile (TLAM) upgrade program a two-channel Global Positioning System (GPS) receiver manufactured by Rockwell-Collins was integrated with the existing cruise missile navigation system by the missile manufacturer McDonnell Douglas Missile Systems Company (MDMSC). The Naval Air Development Center (NAVAIRDEVCEN) was tasked by NAVAIR to perform Independent Validation and Verification (IV&V) of the GPS Flight Software (GFS) hosted in the GPS Receiver Processor Unit. Modifications were made to our GPS Central Engineering Activity (CEA) facility to allow for the testing of the GFS under simulated TLAM operational conditions. This paper presents the methodology for conducting the GFS IV&V, the test requirements, and test plans and results. The lessons learned and test results obtained from the TLAM GPS IV&V are extrapolated for future GPS missile design requirements.

INTRODUCTION

The currently deployed (Block II) TLAM navigates via Terrain Contour Matching (TERCOM) maps and Digital Scene Matching Area Correlator (DSMAC) scenes. This causes delays in mission planning due to the time expended in acquiring geographic data and to prepare maps and scenes for, at times, a real-time changing condition. The limited number of available maps and scenes further complicates mission planning and adds to the response time. Routing the missile flight path through the TERCOM maps and DSMAC scenes consumes fuel, reduces standoff range for the launch platform, and may increase response time. Further, missile survivability and mission success are degraded if the only available routes penetrate heavily defended areas.

Modifications were made to the Tomahawk Weapon System which provided increased enroute navigational accuracy, an increased number of available Tomahawk targets, increased operational effectiveness, and extended range. These modifications were combined into the TLAM Block III Upgrade Program. Block III enhanced the TLAM by adding a GPS subsystem; an improved version DSMAC IIA; Time of Arrival (TOA) Control; an improved engine; and a lighter, smaller insensitive warhead.

The physical configuration of the TLAM GPS RPU is depicted in Figure 1. It consists of the TLAM Signal Processor (TSP), Power Supply (PS), and Advanced Architecture Microprocessor (AAMP) Input/Output (I/O) Shop Replaceable Units (SRUs). The TSP provides the Radio Frequency (RF) downconversion, signal digitizing, and two independent baseband processing channels which allow simultaneous tracking of two SVs. The PS consist of power conditioning and distribution circuitry which supports the other SRUs. The AAMP I/O consists of the AAMP II Central Processing Unit (CPU), Electrically Erasable Programmable Read Only Memory (EEPROM), Dual Port Random Access Memory (RAM), external interface support, and other related circuitry. The GPS is loaded into the EEPROM of this SRU via the MX-82 external interface, and executed by the AAMP II CPU. Specific requirements were established in the MDMSC Critical Item Development Specification (CIDS) for the TLAM GPS RPU and amplified in the Software Requirements Specification (SRS) for the TLAM GPS RPU.

The integration of the GPS capability improves enroute navigation and allows more timely and flexible routing to the target by reducing or eliminating reliance on TERCOM maps and DSMAC scenes. The three possible mission modes are GPS/TERCOM/DSMAC, GPS/DSMAC, or GPS only. The GPS capability reduces the overland flight distance required to successfully attack near coastal targets. These shorter overland routes are intended to improve missile survivability (from enroute land based defenses) and reduce launch platform vulnerability by allowing longer standoff ranges. The GPS receiver is reprogrammable to allow for new GFS to be downloaded by the launch platform.

The TLAM GPS Receiver Processor Unit (RPU) function, is to provide position updates to the Cruise Missile Guidance Set (CMGS) at a nominal rate of every 32 seconds. This is accomplished through range and range rate measurements from four GPS Satellite Vehicles (SVs) by the GPS RPU.

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via signals received from the GPS antenna and antenna electronic units. These measurements are used to calculate the GPS Position, Velocity, and Time (PVT) solution.

The GPS receiver interfaces with the launch platform or the CMGS via a MK-82 serial interface. The launch platform sends to the receiver the GFS and satellite almanac information, and sends to the CMGS the GPS cryptographic keys. The CMGS sends crypto keys, initialization data, 8 Hz velocity aiding data, CMGS Kalman Filter reset data, and barometric altitude data to the TLAX receiver. The receiver sends the Built-In Test (BIT) status, and a solution block every thirty-two seconds consisting of position, velocity, and satellite tracking data to the CMGS.

Upon missile power-up or new GFS load the receiver will perform initial BIT and report the results to the CMGS. The launch platform then sends the almanac to the receiver and crypto keys to the CMGS, completing the GPS pre-launch activity. At launch, the missile goes through a boost phase and then transitions to cruise. Once in the cruise phase, the CMGS sends one initialization data block containing the crypto keys and time to the receiver and declassifies itself. Then the CMGS commences the 8 Hz aiding data, and commands the GPS Receiver into the navigation mode. The receiver searches first for the highest two SV’s out of the best four visible SV’s. The receiver is required to track four SV’s and generate a solution to specified accuracies within 5 minutes after being commanded into the navigation mode.

During normal track the receiver has access to a masking algorithm and an antenna switching algorithm. The masking algorithm increases the allowable direct P-code reacquisition time of SV’s lost due to masking during missile turns. The antenna switching algorithm commands the fixed forward null antenna in the presence of jamming. The antenna switching algorithm compares the noise levels of the omni antenna to the fixed forward null antenna once every thirty seconds after the receiver has transitioned to state 3 tracking. The antenna mode with the lower noise level is used for the next thirty seconds.

The missile’s MK-82 interface must be shared by both GPS and DSMAC. Therefore, when DSMAC is activated the GPS will lose the 8 Hz aiding data and the ability to perform state 3 tracking. The probability of encountering a jamming environment during a DSMAC scene required the development of idle mode. The idle mode will stop the receiver from developing high error estimates by halting all SV tracking and navigation processing. On
transition out of idle mode the Kalman Filter error states, except clock bias, are zeroed and the new CMGS position and velocity values are used for direct P-code reacquisitions. After the last DSMAC scene and just prior to the target, the CMGS sends the receiver a command to zeroize.

The receiver has additional data output capabilities to support the test environment. For laboratory and captive carry testing the receiver has an instrumentation port with all the common User Equipment (UE) data blocks of the JPO Phase III receivers plus TLAM unique data blocks. For missile test flights telemetry data from the receiver is provided over the MK-82 at 1 Hz to the CMGS. This data consists of position, velocity, time, SV status, and error estimates.

The TLAM GPS IV&V test effort was performed from January through June 1991, at the NAVAIRDEVCEN CEA Facility. The primary objective of the IV&V test effort was the verification that TLAM GPS requirements specified in the various GPS design and requirement documents were met. An Engineering Development Model (EDM) RPU containing GFS version 0201 was received by NAVAIRDEVCEN on 13 January 1991, and was used to validate MK-82 Serial Data Bus interface requirements and perform GPS/Almanac load testing. The remaining tests were performed using a Pilot Production Unit (PPU) RPU with GPS version 0301 installed. This RPU was received on 14 March 1991. The final TLAM GPS IV&V test was conducted on 13 June 1991.

TEST FACILITIES

For a number of years, NAVAIRDEVCEN has maintained and developed facilities for testing GPS receivers in both aided and unaided configurations. These facilities (Figure 2) collectively comprise the GPS CEA and include a real-time segment for the generation of GPS RF environments, a real-time segment for the generation of host vehicle sensor environments and an off-line (non-real-time) segment providing data reduction and analysis tools. Each facility has its own complement of investigative tools which can be employed individually or as an integrated whole, providing a complete and comprehensive GPS test and evaluation suite.

Real Time Segments

In the real time segments, all timing signals are synchronized to a one second pulse output from the laboratory's master Cesium clock and all frequencies used in RF generation are derived from the master clock's 5 MHz output.

GPS satellite signals are generated in real-time by the Integrated Satellite Signal Generator (ISSG). Each cycle (once every 100ms), mathematical models of the host vehicle's dynamics, antenna effects and jamming effects are updated by the ISSG VAX minicomputer and extracted for post test analysis. Each update generates control information for the coordinated simulation.
of the host vehicle sensor environment, GPS RF (including the effects of SA/A-S), and jammer RF. The GPS RF control data is transmitted to the Satellite Signal Generator (SSG) which uses it to determine the currently visible satellite constellation and to adjust each satellite's range and doppler. Jammer controls are used directly to adjust signal generator outputs which are summed with the SSG's output and input to the GPS receiver being tested.

Host vehicle inputs to GPS are generated in real-time by the User Equipment Test Facility (UETF). Once every 100ms, information is transferred to the UETF VAX minicomputer from the ISSG VAX through shared memory. The UETF updates host vehicle sensor models (e.g., inertial measurement units, barometric altimeter, etc.) based on ISSG inputs and transmits its output to peripheral hardware which produces the specific data and digital signals required to interface to the GPS receiver under test. All outputs are extracted for post test analysis.

Off-Line Segments

The primary component of the off-line segment of the CEA facilities is the Data Processing and Software Simulation Facility (DPSSF). It provides data reduction and analysis oftruth data extracted from the real-time segments, data collected from the GPS receiver's Instrumentation Port and MK-82 interface data. The DPSSF provides off-line emulations of various GPS receiver functions and a scenario generation capability used to manufacture high level controls for real-time testing.

Laboratory Changes Required for TLAM

The most significant changes to the CEA in support of TLAM GPS IV&V were those required to implement the MK-82 communications interface to the TLAM RPU. Initially an IBM PC interface board and firmware were developed to generate the signal protocols specified in the TLAM interface control documents. Then the various pre-launch functions were programmed into the PC to support those functions provided by the host vehicle prior to launch (e.g., GPS program load and GPS almanac load). Finally, a real-time interface was implemented to allow VAX control of the TLAM RPU navigation modes and to provide the various aiding inputs used in flight. Changes to inertial model parameters, various damping gains and barometric parameters were required to accurately simulate the error characteristics of the real TLAM navigation system.

The addition of the MK-82 interfaces required changes to the data reduction and analysis software to accommodate processing of new messages unique to TLAM generated by the UETF and collected from the TLAM instrumentation port. Modification of the scenario generator was required in order to provide TLAM specific events and controls in the real-time segments of the CEA.

GPS IV&V Approach

The GPS IV&V effort utilized requirements set forth in MDMSC's CIDS for the TLAM GPS RPU, and further amplified in the SRS for the TLAM GPS RPU as baseline requirements to test the GPS RPU. These requirements stood as the benchmarks in a comprehensive program designed to fully test the TLAM GPS RPU's ability to function as a navigation sensor.

Due to schedule constraints and equipment availability the IV&V test effort was broken into two separate activities. The first effort (Mini IV&V) incorporated government witnessing of the contractor testing required to validate the GPS RPU's capability to be utilized in developmental test flights. This effort was highlighted by the successful completion of GPS Formal Qualification Testing (FQT), GPS Performance Qualification Testing (PQT), Integrated GPS, DM5AC, and CMGS Testing and culminated with captive carry King Air flights. The government (NAVAIRDEVCEN) provided test witnesses and aided in the analysis of test data. In this role, the government was assured access to all unedited test results. The second activity (Formal IV&V) involved Hardware In The Loop (HWIL) testing in which an actual TLAM GPS receiver was subjected to various laboratory testing scenarios. NAVAIRDEVCEN utilized the modified CEA to simulate a wide range of TLAM functional scenarios representing a broad cross section of operational environments. These environments included, but were not limited to, the TLAM GPS Receivers ability to acquire and track satellites, provide position, velocity and time data to the CMGS, reacquire lost satellites, operate under a jamming environment, built-in-test functionality, and interface operations.

Test data during both segments of the IV&V effort was collected via the MK-82 interface and instrumentation port and analyzed to ascertain complete requirement adherence. To further evaluate the GPS RPU performance, during the second phase of IV&V testing, a Rockwell Collins GPS receiver J3A was operated in parallel with the TLAM GPS receiver. This process enabled direct comparison with a proven GPS asset. All problems encountered during receiver testing were documented and are under review by the contractor and NAVAIRDEVCEN.

NAVAIRDEVCEN Laboratory IV&V Testing

The NAVAIRDEVCEN HWIL IV&V test effort was designed to fully test the GPS RPU ability to function as a navigation sensor. The tests that were developed to evaluate the receivers overall capability are listed below:
These tests were conducted using a combination of nine test procedures and scenarios which effectively emulated typical missile dynamics. The testing utilized the KK-82 data bus to provide data communications with the GPS receiver. Outputs were monitored via the MK-82 and the GPS Instrumentation Port. Specific output information was available via the GPS receiver output data blocks. Analysis of the receiver performance was accomplished utilizing software reduction programs and techniques developed for the NAVAIRDEVCEN’s DPSSF.

TEST RESULTS

The entire TLAM GFS IV&V test effort was performed from March 1990 to June 1991. The receiver successfully passed all portions of the IV&V effort listed below:

Test Readiness Review
Integration Testing
King Air Testing
NAVAIRDEVCEN HNIL Testing
Documentation Review

Formal Qualification Testing
Performance Qualification Testing
Developmental Test Flight Physical Configuration Audit

While eventually the receiver was able to successfully complete this extensive validation process, four software releases were required to complete the testing.

During NAVAIRDEVCEN Laboratory Testing the government independently validated the receivers ability to perform as designed. Figures 3 and 4 represent sample plots of the GPS RPU’s navigation position and velocity accuracies for states 3 and 6, respectively. Following initial laboratory checkout, NAVAIRDEVCEN conducted over 100 hours of actual IV&V testing. NAVAIRDEVCEN’s IV&V efforts, documented in the Software Test Report (dated 14 August 1991), identified a total of 18 problems associated with the last two versions of GPS software (0201 and 0301). These problems ranged from performance limitations to deficiencies in the documentation. Change proposals and problem reports, that address these deficiencies are being evaluated.

The IV&V was a thorough investigation into the GPS receiver’s overall ability to function as a navigation sensor to support the TLAM guidance function. As a result of the IV&V test effort NAVAIRDEVCEN has identified performance areas that warrant further investigation and possible improvement. These areas include but are not limited to the following:

- Performance under multipath conditions.
- Effects of almanac age on Time-To-First-Fix.
- Acquisition and Tracking under adverse dynamics.

GPS REQUIREMENTS FOR FUTURE CRUISE MISSILES

Testing of the TLAM Block III GPS unit, both under laboratory and field conditions, has not only demonstrated exceptional performance, but also has identified potential enhancements made possible by the newer advanced GPS receiver designs which can significantly contribute to improving the overall TLAM responsiveness, flexibility and effectiveness of any future TLAM upgrade. Enhanced GPS receivers coupled with selective improvements of the TLAM sensors and improvements in TLAM processing capabilities will enable these improvements. Enhanced AJ GPS receivers coupled with INS improvements will lessen the dependency on geophysical or scene matching systems and allow for inflight alignment of the INS; thus increasing TLAM responsiveness and flexibility.

Taking advantage of the recent advances in electronics, microprocessors and navigation technology, which have resulted in great strides in the reduction of size, weight, power consumption and cost, the future TLAM GPS functions will be performed by a tightly integrated or embedded navigation system. This type of system will provide cost savings due to the sharing of equipment and/or processing load with other systems (i.e., common chassis, power supply, processors, etc.).
Enhanced anti-jamming performance of the GPS system is a critical area in which technology advancements have significantly contributed to performance improvements. Not only have advancements in receiver designs contributed to improved receiver anti-jamming performance, but advancements in IMU technology, development of new integration algorithms, and use of varying antenna configurations have increased the potential system level anti-jamming performance. The next generation TLAM GPS receiver will be tightly integrated with an Inertial Measurement Unit (IMU) to provide a high performance navigation capability and improved anti-jamming performance. In these systems, the GPS signal tracking processes will be aided by the IMU velocity, thus supporting rapid acquisition, and extending signal tracking under high dynamics and poor signal-to-noise environments. In addition to using the inertial velocity and carrier loop data to aid the code loop, the inertial velocity is used to aid the carrier loop providing extended anti-jamming. In this tightly integrated configuration, GPS measurements (pseudo-range and delta-range) will be processed by a single Kalman Filter which estimates errors in a single, nominal navigation solution, GPS clock errors, and, if desired, IMU instrument errors. Estimation of these errors will greatly reduce error growth during periods of GPS signal loss compared to when the GPS-inertial solution is determined through integrating of IMU data alone. In addition to code/carryer loop aiding, adaptive tracking techniques will allow the signal processing and correlation processes to adjust to varying levels of GPS signal dynamics and jamming threat environments. The number of channels will probably increase from the conventional five for high dynamics, to six to ten channels, where the additional channels perform concurrent L1/L2 tracking, integrity monitoring and alternate satellite processing (e.g., all in view). Large numbers of correlators per channel will also allow for faster acquisition and reacquisition times. The enhanced GPS receiver coupled with a Controlled Reception Pattern Antenna (CRPA), the use of a tightly integrated IMU/GPS design, and advanced signal processing/correlation techniques are expected to enable typical J/S improvements of 90 to 120 dB.

CONCLUSIONS

The TLAM Block III GPS receiver satisfies all of its performance requirements. The use of GPS on TLAM Block III now enables GPS only missions. Advances in technology should enable for future TLAM Block upgrades (use of advanced GPS receiver designs, tightly coupled GPS/IMU systems, and CRPA antenna) which will greatly increase the GPS system anti-jamming, acquisition, and reacquisition capabilities. The employment of GPS throughout a battle force and the use of its accuracy, common coordinate system, and coordinated universal time will improve target handovers or third party targeting and coordinated missile/tactical air operations. The use of an enhanced AJ GPS system in future TLAM Block upgrades will increase the overall responsiveness, flexibility, and survivability of the TLAM weapon system.