A Low Cost, Highly Capable Navigation Flight Test Approach through Industry and University Collaboration

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BIOGRAPHIES

Scott Sorber is a Fellow at Lockheed Martin in Owego, New York. Scott's 30 year career began in hardware design, moved to Navigation and Kalman filter integration, then on to guidance algorithm development. His focus for the last 15 years has been in GPS Navigation Warfare system analysis and design. Scott is currently the technical lead for Lockheed Martin's GSTAR GPS anti jam product line.

Dan Hennessey is the GSTAR product line manager and worked as the program manager for the efforts described in this paper. He has 12 years of experience at Lockheed Martin, the last 6 years with GPS and anti-jam GPS technology. He is a graduate from St. Bonaventure University with a BBA/MBA with concentrations in finance and accounting.

Dr. John Moody is a Principal System Architect at Lockheed Martin in Owego, NY. His work bridges basic technology development and complex system development, performing as both lead investigator for internal and externally-funded research programs and lead engineer for large scale system integration projects. He received his doctorate in electrical engineering from the University of Notre Dame, where he was an Arthur J. Schmitt Fellow. He has been awarded eight patents and is the author of numerous journal and conference papers as well as the book Supervisory Control of Discrete Event Systems Using Petri Nets (Kluwer Academic 1998, with Panos Antsaklis).

Dr. Dean Bruckner is Assistant Professor of Industrial and Systems Engineering in Ohio University’s Russ College of Engineering and Technology. Until January 2013, he was Assistant Director—Technical of Ohio University’s Avionics Engineering Center, a $5M per year research, development, test and evaluation organization serving U.S. government and industry sponsors. He was lead test system integrator for Lockheed Martin’s evaluation of the F-35's electronic navigation sensor suite, and for Lockheed Martin’s proposed reference station for the GPS-based Joint Precision Approach and Landing System (JPALS) for the U.S. Air Force.

Dr. Trent Skidmore is Senior Research Engineer and Adjunct Assistant Professor at the Ohio University Avionics Engineering Center. He is involved in a variety of projects involving applications of GPS, including the use of differential GPS for aircraft precision approach applications. These include JPALS development for the F-35, the Automated Aerial Refueling (AAR) program and the Federal Aviation Administration’s Local Area Augmentation System (LAAS).

ABSTRACT

Lockheed Martin and Ohio University (OU) have jointly built a unique flight test capability. Flight testing aircraft navigation systems can be a costly proposition. Our unique collaborative arrangement enables a very flexible, cost effective flight test capability. The essential elements required to perform flight test of a military navigation system are the following:

- Aircraft as the flight test platform
- Ability to modify the flight test platform
- Navigation truth source
- Secure network environment for collecting and analyzing flight data
- Physical controls for the protection of potentially sensitive equipment
- Access to and license to broadcast on military communications frequencies

Figure 1: Overview of flight test facility.
There are very few places in the world where all these pieces can come together. When they do, it is typically very costly. The collaboration between Lockheed Martin and Ohio University allowed us to modify an aircraft with our unique navigation system, including an external 14-inch, multi-element GPS antenna array, for less than $50,000. The modifications were made to a Piper Saratoga and yielded a system we could fly for less than $400 per flight hour.

INTRODUCTION

Lockheed Martin began collaboration with Ohio University to apply the University’s pioneering work with the FAA in the field of differential GPS navigation to the military domain. As we explored possible avenues of collaboration, we realized that together, we had the potential for a very practical extension of our theoretic work. We could perform flight tests, and that flight testing could include our military GPS navigation system complete with an off-the-shelf 5-10 cm truth system.

Our objective was to perform flight testing of military GPS navigation equipment configured to provide very accurate differential navigation solutions. A block diagram of the basic air/ground system functionality is given in Figure 2. Our system performs the basic differential GPS function similar to existing civil Local Area Augmentation Systems (LAAS) [1], but includes the following additional elements to meet military requirements:

- Anti-jam antenna systems (air and ground)
- Military GPS receivers (air and ground)
- Encrypted datalink in military UHF band

![Figure 2: Functional block diagram of military differential GPS system](image)

Both the air and ground components are protected from extreme levels of interference in the L1 and L2 frequency bands through the use of multi-element phased-array antennas coupled with anti-jam (AJ) antenna electronics.

Our system uses Lockheed Martin’s GPS Spatial-Temporal Anti-jam Receiver (GSTAR) [2], which performs both interference nulling and satellite beam-steering to ensure accuracy and availability of GPS in challenged (i.e., jammed) electronic environments.

The overall system includes military GPS receivers that operate at both L1 and L2 bands (as opposed to L1-only civil GPS receivers as in LAAS) and employ keys that require special security procedures for their use, handling, and storage. The system is also capable of broadcasting the differential corrections over an encrypted datalink in the military UHF communications band, as opposed to the unencrypted VHF datalink used in LAAS. Ohio University obtained an experimental license from the FCC in order to support this UHF transmit capability.

Finally, as would be required for any navigation test environment, the system is combined with a navigation truth system to allow us to measure our performance.

In the remainder of this paper, we describe the flight test facilities, aircraft modifications, ground station construction, secure processing requirements, telemetry and visualization, truth system, and an overview of the flight test results.

THE OHIO UNIVERSITY FACILITIES

Our work was centered at the Ohio University Airport (UNI) located in Albany, Ohio. This facility offers an avionics hangar with over 14,500 square feet including offices, labs, and aircraft storage. This airport offers Instrument Landing System (ILS) Approaches, Microwave Landing System (MLS) approaches with Distance Measuring Equipment (DME), and Local Area Augmentation System (LAAS) Differential GPS (DGPS) approaches.

![Figure 3: The Ohio University Airport (UNI)](image)
office and laboratory space with easy access to the nearby test hangar and DGPS ground stations. This 8000 square foot building also provided conference room space for team meetings and collaboration.

Another unique feature of Ohio University Avionics is the ability to work with both classified and sensitive data. This was necessary for the testing we were doing with military GPS receivers.

AIRCRAFT MODIFICATIONS

The OU facility’s aircraft can be quickly transitioned between the FAA’s standard category and the experimental category that is often used for temporary modifications that conceivably could alter the designed capabilities of the aircraft in ways that are not completely predictable. OU has six experimental aircraft to choose from for flight test activities and a small number of unmanned aerial vehicles (UAVs). We chose the Piper Saratoga single-engine, 6-person aircraft because it was the most economical to fly and could easily accommodate our equipment, including:

- Military GPS receiver
- GSTAR Digital Antenna Electronics
- Controlled Reception Pattern Antenna (CRPA)
- Survey-grade civil GPS receivers for truth reference
- Small commercial Inertial Measurement Unit (IMU)
- IP-based wireless secure data link for telemetry
- Two test laptops

The Saratoga with test rack installed has room for a pilot, a co-pilot, and two flight test engineers. Most flights were accomplished with just a pilot and a single flight test engineer.

We were able to limit modifications to the aircraft skin to six mounting screw holes for an aluminum collar onto which the CRPA was fastened. The CRPA cables were fed through an existing inspection port.
GROUND STATION

We set up multiple ground reference stations to allow us to process real time differential GPS based on either civil or military GPS measurements. Our military equipment racks included the following:

- GPS receiver
- GSTAR Digital Antenna Electronics with beamsteering and nulling capability
- Seven Element Controlled Reception Pattern Antenna (CRPA), same as in the aircraft
- Control computer for IP based communication and data logging

![Figure 8: Ground system flight test block diagram](image8.png)

Figure 9: Exterior view of reference receiver in all-weather enclosure (it required manual ice removal, however).

![Figure 10: Reference receiver electronic components](image10.png)
SECURE PROCESSING

In order to meet the information security requirements associated with the project and the use of military equipment, the team established a networking and data environment isolated from the general OU campus network. Our team established a certificate-based, secure, encrypted virtual private network (VPN) for data handling and visualization in these tests. The team accessed the network from on-site workstations, but in the future could access the various elements of the network and data storage remotely. This setup can allow remote logging and processing of sensor data and display of visualizations, whether in real-time or in playback mode, for future flight test events.

REAL TIME VISUALIZATION

The IP-based telemetry system installed in the aircraft allowed real-time visualization of key flight parameters while the flight test was in process. This capability was a valuable engineering tool allowing real-time “quick look” supervision of equipment and datalink performance from the ground-based integration laboratory while the platform flew [3, 4]. This computer graphics engine and its adaptation for this application was a key feature of the collaboration between Lockheed Martin and Ohio University.

Figure 11: The flight test aircraft outfitted with real-time telemetry enabling the in-test visualization of the flight path, glide slope, and GPS constellation

Two datalinks exist in this configuration and are represented in the picture above as a single green line of bearing. One transmits processed differential data to the aircraft from the reference station (located in a shelter near the runway), while the other is a two-way network connection from aircraft to shelter that enables data analysis and visualization at both ends and at any other location with secure VPN access. The blue lines represent lines of bearing to the GPS satellites currently in view from the aircraft CRPA. This allowed the analysis team to view and model the effects of body and terrain masking as well as intentional or unintentional jamming, and to present that visually to test engineers and prospective customers as appropriate.

Figure 12: Datalink and GPS signal lines of bearing

Figure 13: Visualization of final approach

Figure 13 shows the virtual world’s display of the aircraft on a final approach. The dashed blue line represents the traditional three-degree glideslope used in ILS approaches. The inset figure in the bottom right approximates a pilot’s display so that analysts and customers can see what the pilot sees, either in real-time or in simulation (in the latter case, without the expense of flying). The data displayed on the bottom left is the core data of range, heading and the distance to the glideslope and localizer. Having this real-time visualization and analysis to couple with GPS post processing data proved to be a key low-cost development, integration and test tool for our team.

Figure 14: Ground system visualization with GPS signal lines of bearing
Another benefit we found was the ability to engage our customers and leadership teams in the flight test. Any individual with an interest could observe the progress of the flight on a large monitor in the laboratory as it displayed the visualization using telemetry data. This was a highly effective means of explaining the workings of our system and the benefits to end users.

Using this real-time visualization capability, we were able to observe in the virtual world our flights from a wide range of perspectives. We could populate the display with a number of pieces of useful information such as position, velocity, attitude, glide slope, desired guidance path, and actual aircraft path. These capabilities proved to be highly useful. Coupled with the voice radio link, the whole development team could watch the flight test activities, view real time “quick look” data for analysis, and communicate with the pilot and flight test engineer to adjust the flight to meet the objectives of the day.

**TRUTH SYSTEM**

Our position and velocity truth system is based on NovaTel’s GrafNav software from NovAtel’s Waypoint® Product Group [5]. This Real Time Kinematic (RTK)-based differential truth tool uses forward and backward filtering to achieve centimeter-level dynamic accuracies. Typical accuracy for our flights fell between 5 and 10 centimeters. Code and Carrier measurements were logged using NovAtel OEM-4 and OEM-V survey-grade GPS receiver models that supported nearly twenty years of LAAS development and testing at Ohio University. The standard post processing could be comfortably completed within one to two hours following the flight.

**SAMPLE TEST RESULTS**

Table 1 below provides sample DGPS accuracy results for a short flight. A Trimble military receiver with GSTAR connected to a FRPA was operating on the aircraft, while two reference stations were in operation on the ground, one with a FRPA configuration similar to that on the aircraft and the other with a full CRPA configuration operating in beam-on-satellite mode but with no known interfering signals. The results were obtained in post processing. The DGPS Navigation System Error (NSE) values are $\mu + 2\sigma$ quantities given in cm, measured against the NovAtel GrafNav ambiguity-resolved RTK truth trajectory described above. In this flight, the truth accuracy was $\pm 7$ cm, per the GrafNav specification applied to this flight’s parameters. Two separate horizontal and vertical error sets are given, one unsmoothed for both air and ground, and the other using an air-only position-domain smoothing algorithm developed by Ohio University [6].

In this data set, the differential baseline that included the Trimble/GSTAR/CRPA operating in full beam-forming and nulling mode (although in a benign RF interference environment) produced the better accuracy results.

<table>
<thead>
<tr>
<th>Error measure (cm)</th>
<th>Trimble A ground (FRPA)</th>
<th>Trimble B ground (CRPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal, unsmoothed</td>
<td>47.3</td>
<td>50.3</td>
</tr>
<tr>
<td>Horizontal, air-only pos’n smoothed</td>
<td>39.2</td>
<td>33.5</td>
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<tr>
<td>Vertical, unsmoothed</td>
<td>86.7</td>
<td>72.3</td>
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<tr>
<td>Vertical, air-only pos’n smoothed</td>
<td>74.0</td>
<td>53.3</td>
</tr>
</tbody>
</table>

**STUDENT COLLABORATION**

This project provided an opportunity for interaction between bright, highly motivated students and industry professionals. Our industry team was further energized by the vigor, enthusiasm and expertise of talented U.S. graduate students. The students enjoyed confronting and solving the day to day challenges of the flight test program side by side with the industry team members. They were able to see up close the team’s thought process applied to problem solving, design trades, working with constrained funds, and working the early stages of a proposal to win new business. They also brought new perspectives and new visualization products [3]. Together, these produced a real and vital synergy that made the team more than merely the sum of its parts.

**SUMMARY**

The collaboration between Industry and Ohio University has yielded a navigation flight test capability with the following highly desirable attributes: low cost of platform modification, low cost for flight test time, relatively simple flight test platform update process, proven and accurate truth system, the ability for real time (and playback) visualization of key flight parameters, a secure and encrypted telemetry system, and a secure network approach.
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