Four-Element Adaptive Array Evaluation for United States Navy Airborne Applications

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BIOGRAPHIES

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ABSTRACT

This paper provides background on the design methodology of an adaptive GPS antenna system and the testing methodology used to evaluate such a system. The challenge in evaluating multi-element active antenna arrays is that conventional antenna characteristics such as element phase, gain, or sidelobe levels do not easily translate into system level performance measures such as dynamic response time, pattern null width and null depth. The GPS Antenna System (GAS-1N) Foreign Comparative Testing (FCT) program evaluated a four-element, four-channel adaptive antenna system for U.S. Navy airborne applications by using various measures of performance based on the stage of testing. Testing methodologies included anechoic chamber, F/A-18 full-scale model on an outdoor range, modeling and simulation techniques, and dynamic flight testing on a C-12J and F/A-18C. Additionally, side-by-side comparisons were made during flight testing using Fixed Radiation Pattern Antenna (FRPA), GAS-1N (4-element), and GAS-1 (7-element) antenna systems.

INTRODUCTION

The susceptibility of the GPS signal to intentional or unintentional interference is well documented and a major concern for the U.S. Navy's fleet of ships and aircraft currently being outfitted with GPS. The Navy's Navigation Systems Program Office, Space and Naval Warfare (SPAWAR) Systems Command, PMW/PMA-187, has tasked the SPAWAR Systems Center GPS Division with providing technical support to review candidate anti-jam technologies for incorporation into Navy warfighting platforms. Without anti-jam protection, U.S. Navy platforms (mainly aircraft) may not be able to play a significant role during the early days of a conflict, when the deployment of countermeasures is most intense. In June of 2000, the Navy's leadership validated the requirement to provide protection to GPS by signing an Operational Requirements Document (ORD) designed to provide enhancements to GPS User Equipment (UE). U.S.

Naval forces specifically require protection in a GPS jammed environment to meet warfighting requirements to navigate and utilize timing data. The challenge in providing this protection arises not with the cost of anti-jam system procurement, but with the impact of the platform integration and qualification, which are retrofits in most cases. As a result the Navy searched industry for GPS anti-jam solutions that offered a capability upgrade without significantly impacting legacy platform integrations. Ideally, the solution would be a form and fit replacement for the existing, unprotected FRPA GPS antenna.

BACKGROUND

The ongoing research in shrinking antenna array size is centered on the fundamental laws of physics: how do you closely space the many elements of a Controlled Reception Pattern Antenna (CRPA) while avoiding the inherent mutual coupling effect that degrades performance? Industry feedback in this area has concluded that the multiple elements of a CRPA antenna cannot be so closely spaced as to yield a FRPA-sized footprint and yet deliver meaningful anti-jam performance with existing technologies. The current leader in providing robust anti-jam capability in the near term is the GAS-1 manufactured by Raytheon Systems Limited (RSL) of Harlow, England. This system consists of a 7-element antenna array and associated 7-channel antenna electronics (AE) unit that allow the antenna to form null patterns against numerous GPS jamming sources, which is considered 6 degrees of freedom (DOF). This system is currently in production after being chosen in a competitive source selection conducted by the GPS Joint Program Office (JPO) in 1996 and is being used by the U.S. Air Force on a majority of its strategic aircraft (B-52, E-3, B-1B, and C-17). However, the limitation of GAS-1 for many military platforms is its antenna size: a 14.2-inch diameter array, whereas existing military FRPA GPS antenna systems are on the order of 5.25 inches in diameter. The GAS-1 hardware is not suited to many of the compact carrier-borne aircraft operated by the Navy. The dominant factor remains the "real estate" required to accommodate the size of the CRPA array.

Therefore, the CRPA array size is driven by two conflicting requirements:

- a FRPA footprint (5.25 inches diameter)
- large DOF's (total jammer power suppressed)

This led the Navy to ask what magnitude of anti-jam performance was actually needed, i.e., can we get the protection we need with fewer than the seven elements of a GAS-1? What about six, five, or even four elements? Additionally, how much performance can be provided by a smaller array with the elements closely spaced?

RSL and AIL Systems Inc. initiated an Internal Research and Development (IR&D) effort to develop a four-channel system in a smaller footprint that approached the FRPA size. The GAS-1N has been produced as a smaller alternative to the GAS-1 and offers a potential near-term solution to solving this critical military need for anti-jam GPS protection. The system is comprised of two LRU's: the 4-channel AE and the 4-element CRPA. It was designated 'GAS-1N' by the Navy and made available to SPAWAR for test and evaluation.

The U.S. Navy is taking the lead on evaluating this new system with the support of the Foreign Comparative Testing Program Office and plans to provide the results to all interested military services.

PROGRAMMATICS

The Foreign Comparative Testing Program is authorized by Title 10, United States Code, and is funded under the Defense-Wide Research Development Test and Evaluation (RDT&E) Appropriation at the Office of Under Secretary of Defense.

The principal objective of the FCT Program is to support the warfighter by leveraging nondevelopmental equipment of allied and friendly nations to satisfy U.S. defense requirements more quickly and economically. The FCT process is dependent on a world-class foreign item, U.S. user interest in the item, a valid requirement, and good procurement potential. The goal is to reduce the acquisition cycle time and RDT&E expenditures while enhancing standardization and interoperability, improving cooperative support, promoting competition, and eliminating unnecessary duplication.

Since 1980, OSD has provided funding for 416 FCT projects. Of the 359 projects completed to date, 193 have resulted in successful evaluations. Of these, 110 projects have resulted in procurements worth over $5 billion in FY 2000 dollars. With an FCT investment of approximately $725 million, the FCT Program has realized RDT&E cost avoidance for the Department of Defense (DoD) of approximately $3.8 billion.

The current funding provided by the FCT Program for the Navy's evaluation is being used to accomplish two main objectives: 1) determine if the GAS-1N with four elements is technically feasible to yield sufficient protection over a FRPA in a GPS-denied environment and

2) perform a "quick look" analysis on a tactical aircraft (F/A-18C) in a maneuvering environment similar to what is expected in combat. The question to answer with this test and evaluation is: are four elements enough? This independent government evaluation seeks to answer that question.

SYSTEM DESCRIPTION

The GAS-1N is an anti-jam GPS antenna system that consists of two components: a 4-element antenna array and a 4-channel antenna electronics unit. The antenna system actively steers gain and phase nulls toward jammer energy that has the potential to disrupt the tracking of GPS signals used for platform Position, Velocity, and Timing (PVT).

Antenna Array

The N-100 4-element Controlled Reception Pattern Antenna that is currently being used for the GAS-1N testing developed from a need for smaller CRPA antennas to permit installation on a greater number of platforms (airborne and shipboard) than current 7-element, 14.2 inch diameter CRPA systems. This GAS-1N system is designed to provide a GPS receiver with the ability to counteract interference sources that would deny an operator the capability to accurately determine his position. AIL's objective for the GAS-1N program was to develop an equally capable, yet reduced size CRPA antenna suitable for installation on many platforms. Considering that a maximum size of seven inches square would permit a wide variety of installations, AIL focused on developing a four-element array that would meet all the current electrical and environmental requirements of the present 7 element GAS-1 Antenna. Although the reduction in the number of antenna elements from 7 to 4 would reduce the number of interference sources that could be defeated, a high degree of interference reduction necessary to retain position information is maintained. This antenna incorporates four identical Right Hand Circularly Polarized (RHCP) antenna elements in an array with smaller element-to-element spacing than conventional CRPA designs. A photo of AIL's N-100 4-Element CRPA GPS antenna is shown in Figure 1.

The design chosen was a dual frequency, stacked L1 and L2 patch element configuration. This approach was determined by AIL to be the best alternative for the GAS-1N requirements based on frequency, radiation pattern coverage and environmental considerations. Etched on higher K dielectric substrate materials, the approach permitted a reduction in both the physical size of the L1

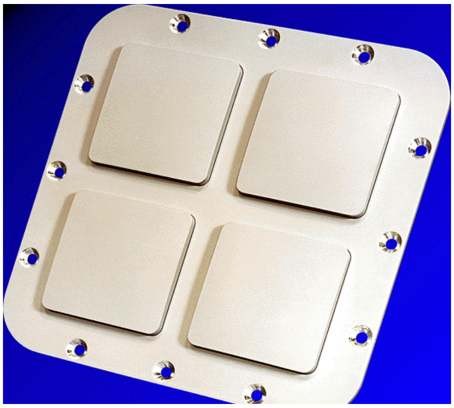

Figure 1. N-100 4-Element Array

and L2 patch antennas and the element-to-element spacing that impacts mutual coupling.

The stacked-patch antenna elements operate over both the L1 and L2 bands, each obtaining bandwidths in excess of 20 MHz over the –50 to +95 degree C temperature range necessary for military aircraft applications. This temperature range is also more than adequate for shipboard and ground usage. A feed concept utilizing a parallel coupled-line 90° coupler was employed which improves bandwidth and introduces the right hand circular polarization desired for GPS signal reception, while retaining axial ratio of less than 2dB at the pattern zenith. Axial ratio of less than 5dB for elevation angles of 0 to 40 degrees from the horizon is also achieved. Most importantly this feed approach yields consistent element-to-element phase and amplitude characteristics over the entire operating band as well as low VSWR.

In order to achieve the maximum system anti-jam capability, AIL focused its antenna design on the following key performance objectives:

- Maximum element-to-element isolation with reduced spacing
- Minimal element-to-element amplitude ripple
- Minimal element-to-element phase ripple
- Maximum L1 and L2 gain and pattern symmetry
- Maximum horizon pattern performance
- Modularity of the design to permit use in multiple element arrays

Typical phase and amplitude ripple between reference and auxiliary elements in the array is shown in Figure 2 and Figure 3.

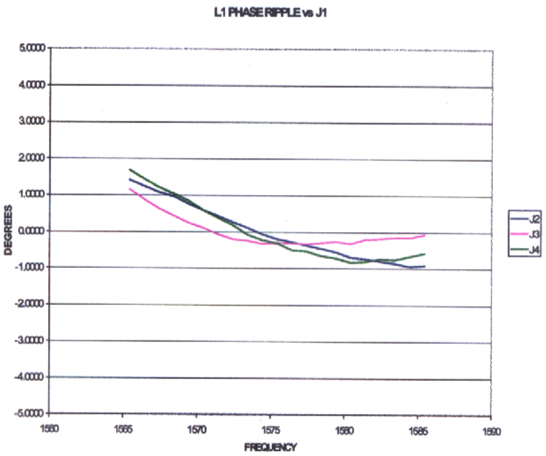

Figure 2. 4-Element Array Relative Phase Ripple

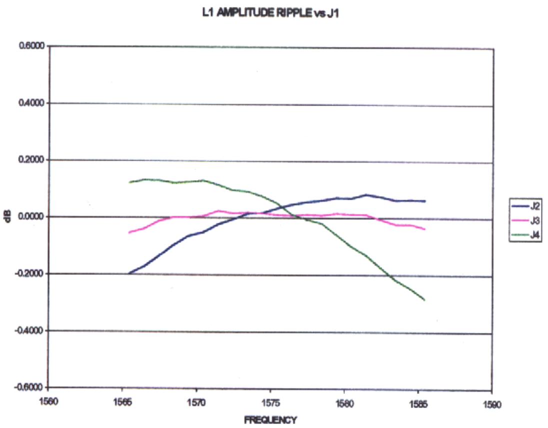

Figure 3. 4-Element Array Amplitude Ripple

The individual radiating element patterns of this reduced size 4-element CRPA antenna maintained very good hemispherical coverage. A typical radiation pattern taken from the CRPA array is shown in Figure 4. Typical peak gains of 2-3dBic were recorded on all elements.

Following laboratory tests at the AIL facility, the antenna and overall GAS-1N system was evaluated by U.S. Navy test lab personnel in both indoor anechoic chamber and outdoor test range scenarios.

Preplanned product improvements for the array include:

- Frequency bandwidth increase to accommodate a future M-code
- Optional inclusion of an integrated LNA's for individual antenna elements
- Operation in a conformal cavity and in the presence of FSS (frequency selective surfaces) for Military Low Observable applications.

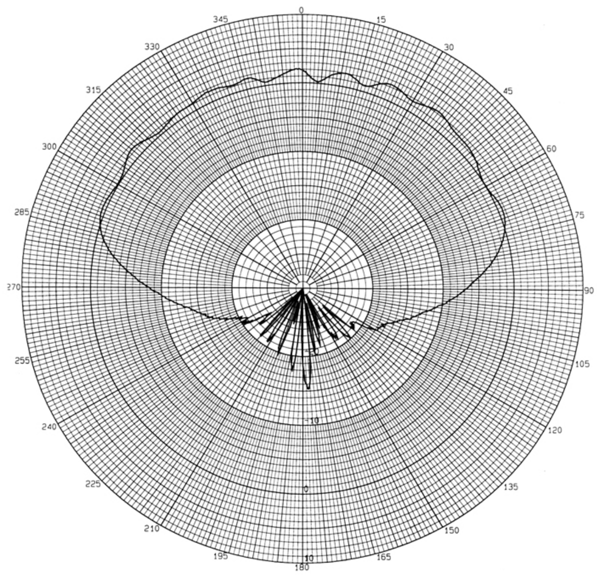

Figure 4. Fore/Aft Elevation Pattern

Antenna Electronics

GPS anti-jam systems have been around for a number of years and generally utilize either temporal nulling, or spatial nulling. Temporal nulling is an architecture that can be implemented in the analogue domain, but has capitalized on the advances in digital processing power over recent years. These architectures are very efficient against narrow band jammers, but inherently weak against the more stressful multiple broadband jammer scenarios. Spatial nulling can be implemented in the analogue or digital domain and has the potential to counter these more stressing scenarios.

GAS-1N is a spatial nulling adaptive array consisting of a four element CRPA and the AE unit. The architecture of the GAS-1N AE is similar in function to the larger GAS-1 system in full-scale production for the USAF, but opportunity has been taken to introduce a high degree of RF hybridization to achieve a compact form factor. The generalized architecture for adaptive arrays is shown in Figure 5.

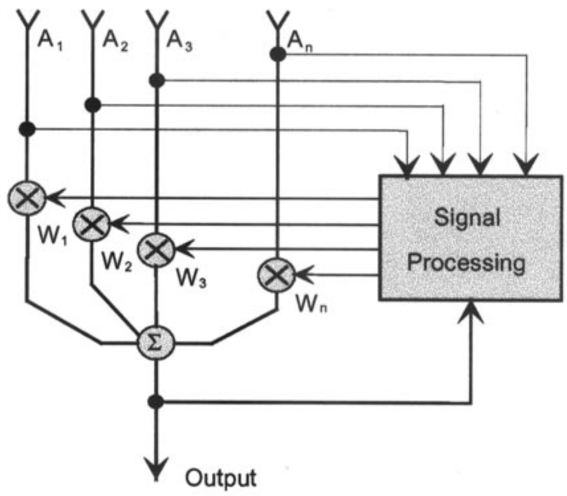

Figure 5. Generalized Adaptive Array

The signals from the four antenna elements are weighted and summed to form the composite reception gain pattern. The optimum algorithm for controlling the array is to maximize the signal-to-noise ratio at the output of the beam forming network, but this is not practical in GPS without feedback from the receiver due to the low power spread spectrum signals from the satellites which are below thermal noise until de-spread. Hence a sub-optimal solution of minimizing the output power from the beamformer is generally employed. This approach requires that one of the elements (designated the reference element) has a fixed (or clamped) weight to ensure that the array defaults to an omni-directional pattern in the absence of jamming. It was an operational prerequisite that any CRPA solution should contribute no degradation to the navigation solution when no jamming is present when compared to the capability provided by the original FRPA. There are two alternative architectures, which have been utilized for control of this type of GPS adaptive array, either

Weight Perturbation Feedback (dotted connections not fitted)

or

Correlation Feedback (dotted connections fitted)

In the first case the signal processor makes a small change to the weight and observes the effect on the output. If the output signal power is reduced, then further changes are made in the same direction until a minimum is found. The weighting networks for each channel are vector functions, hence require two control inputs (I and Q) for each element. For a multi-element adaptive array, multiple weights must be sequentially varied to find the minimum. Once the minimum is found, the weights must continue to be perturbed to follow changes in the environment.

In the second case the signal processor derives the weights by performing a correlation between each antenna element input and the beamformer output. This is a very efficient approach, which has been used by a large variety of RF receiving systems and has the advantage that any non-linearity in analogue components is compensated by the feedback loop.

The weight perturbation architecture is less complex in hardware terms than the correlation approach, but is inefficient because it uses a scalar measurement (output amplitude) to determine a vector signal (the weight). This makes the architecture weak against scenarios where the jamming is changing rapidly due to amplitude modulation or platform motion. Weight perturbation was employed by the first systems fielded by the USAF as predecessors to the GAS-1 AE and GAS-1N AE.

The GAS-1N AE architecture uses the correlation feedback technique to derive the weight vectors. Figure 6 shows a simplified block diagram of the main control loop.

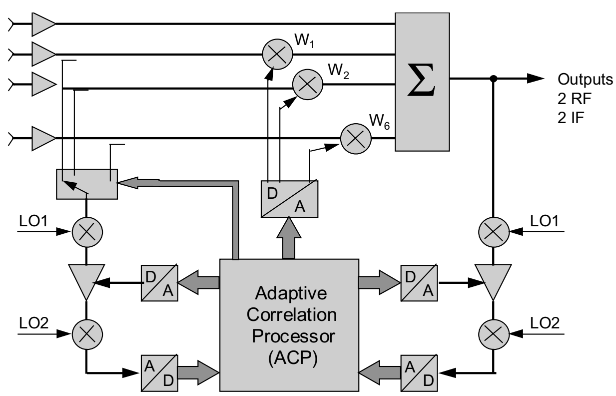

Figure 6. GAS-1N AE Architecture

Each Antenna signal is amplified by one of four Low Noise Amplifiers that define the system noise figure. One channel is designated the reference channel and is associated with a particular element on the antenna array, and the remaining three elements are the auxiliary channels. Each auxiliary channel contains a vector modulator which varies the amplitude and phase of the RF input signal according to its I & Q control inputs. The reference channel contains an identical vector modulator circuit, but has fixed value I & Q inputs to produce the clamped weight. The four vector modulator outputs are summed to derive the composite signal. The summed RF output is mixed down to IF where AGC is applied, then further mixed down to baseband and converted to digital I & Q.

Prior to the vector modulators, a sample of the RF output from each of the auxiliary channels is coupled off and used by the correlation processor. These samples are sequentially selected by a multiplexing network prior to down-conversion to baseband and digital conversion in an identical chain to the sum channel.

Correlation Algorithm

The digital processing at the heart of the GAS-1N AE is the Adaptive Correlation Processor (ACP), which is hosted in an ASIC. The ACP derives the weight updates by correlation between the unweighted element input signal $x_i(k)$ and the output from the summing network $y(k)$. The correlator is time shared between the three auxiliary outputs that are selected in random order by the digital processor. The ACP also determines the AGC levels independently for both the Sum and Element channels.

The control algorithm implemented in the ACP is the iterative Steepest Descent Algorithm, which continuously updates the auxiliary channel weights to minimize the power output from the summing network. The main features of this algorithm are:

- The magnitude of the weight update decreases as null depth increases ensuring smooth convergence to the optimum solution
- Convergence rate is fast, and is independent of input jammer power.
- Correlation is instantaneous, therefore not significantly affected by jammer modulation.

The algorithm is implemented in an ASIC for high speed (1 weight update per microsecond) and low power (<0.25 Watts), but retains the flexibility of having several programmable parameters such as, antenna array size, loop gain, and Power Threshold (input power at which nulls begin to form). These parameters are loaded at power-up from a simple micro controller, which then plays only a supervisory roll, handling communications with the receiver and conducting health checks.

Host Platform Integration

Host platform integration was a prime consideration of the GAS-1N development, which entailed demonstrating compatibility with the wide range of receivers currently in service. The GAS-1N demonstrators have a single RF output for compatibility with RF receivers such as RF MAGR, EGI, GEM III. The RF output has fixed gain of approximately 19dB, which for the purpose of the evaluation was well suited to the two primary trials platforms, namely the F/A-18C and the C-12J.

The GAS-1N AE does not require an externally provided local oscillator (LO) to protect RF Receivers.

Mechanically, the GAS-1N AE emulates the form factor of the AE-4 antenna amplifier (8.8"x4.25"x1.9") used for some FRPA installations to down-convert RF to IF ahead of the GPS receiver. While this is not a critical factor for the evaluation program, it satisfies 'drop in' criteria that are likely to be important in any future procurement plans.

Preplanned product improvements for the AE include:

- Multiple RF outputs to support three individual GPS receivers
- 'Fail Safe' FRPA reversionary mode
- Qualification to full Military Specifications.

TESTING METHODOLOGY

The testing and evaluation effort focused on determining whether the four-element GAS-1N system provides enough protection against GPS interference sources to justify the pursuit of a near-term DoD acquisition effort for Naval Aviation. Each phase of testing that will be described combines together in the end analysis to lead the Navy to a clearer understanding of what can be expected from a smaller anti-jam GPS antenna system and what factors are critical when specifying such a system for future procurements. Since GPS performance during flight testing is dependent on many variables, such as jammer laydown, assigned mission area, flight scenario, GPS receiver type, GPS/Inertial Navigation System (INS) integration (or lack of), etc., the results from modeling and simulation will be critical in understanding the full impact in a validated threat environment.

Ground Testing

The technical feasibility of utilizing a smaller adaptive array was in question at the outset of this program due to the concerns over mutual coupling between the closely spaced elements. Common adaptive array design has used the well-known half-wavelength spacing between elements to avoid inter-element interference, or mutual coupling, which can degrade null depths. The GAS-1N array departed from the standard 0.5-wavelength spacing to a 0.38-wavelength spacing to achieve a smaller footprint. This design configuration introduced risk to the potential performance expected from the GAS-1N system and therefore became the focus of the first phase of system testing in the anechoic chamber at Naval Air Station (NAS) Patuxent River, MD.

The engineers at the Naval Air Warfare Center-Aircraft Division (NAWC-AD) performed over 400 hours of testing on the GAS-1N array and antenna electronics unit. The array was mounted on a 12-foot ground plane simulating a large-body aircraft fuselage. See Figure 7.

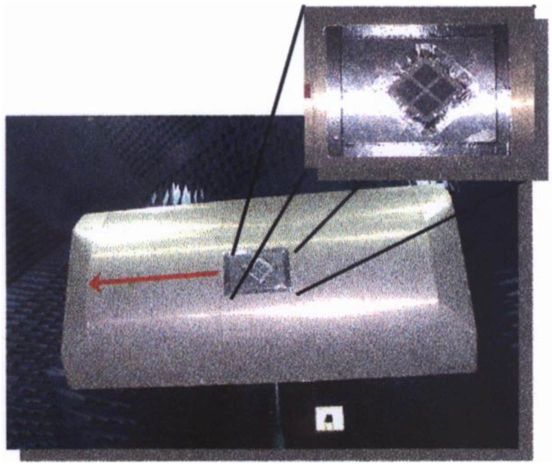

Figure 7. Anechoic Chamber Set-up

The tests performed on L1 and L2 frequencies were:

- Axial Ratios per Element
- Gain Patterns per Element
- VSWR per Element
- Null Convergence Time
- Null Convergence Depth
- AE Gain from 1-2 GHz

This data was used to update the 4-element antenna model at Wright-Patterson AFB at the Air Force Research Lab (AFRL) in Dayton, OH. Additionally, a Coverage Improvement Factor (CIF), an evaluation criteria developed by the GPS JPO for assessing anti-jam antenna performance, was calculated. This provided insight into the system's ability to steer nulls toward jammers while maintaining gain in the direction of satellites being tracked. The measured results were exceptional and met desired performance levels. Therefore the GAS-1N FCT evaluation team agreed to continue on to the next phase of testing which involved mounting the system on a Full-Scale fuselage of the F/A-18 to conduct Outdoor Range measurements. See Figure 8.

Figure 8. Full-Scale F/A-18 on Pedestal

Since ground planes have a significant impact on antenna performance, this phase of testing was concerned with multipath effects of jammer signals and the importance of antenna siting on the aircraft. There is great value added to the evaluation by understanding how "installed" performance differs from laboratory performance. Note in Figure 9 how close the GAS-1N array is located to the UHF blade antenna. This siting was based on replacing the existing FRPA with the GAS-1N in the same location.

Tests performed on the pedestal were similar to the anechoic chamber phase. It was desirable to replicate similar test geometries and power levels to establish test result traceability. This will increase confidence in the results as we move from one testing phase to the next. Additional testing in this area is required to better understand the effects of body masking and quantify it for antenna model refinement to enhance the performance of the antenna wavefront simulator.

Figure 9. GAS-1N on F/A-18 for Pedestal Testing

Modeling and Simulation

The Virtual Flight Test (VFT) capability at the Air Force Research Lab (AFRL/SNAR) is very valuable for predicting GPS performance in a jammed environment. This unique Hardware-in-the-Loop (HITL) capability is the result of interfacing an Antenna WaveFront Simulator (AWFS) and the GPS Interference and Navigation Tool (GIANT) together to provide a realistic environment in simulation space to evaluate anti-jam antenna systems. An excellent description of the process involved can be found in Reference [1] and will not be duplicated here. The real benefit to this phase of testing came when the planned flight test scenarios were run through the VFT and confirmation of proper jammer placement and power levels along with aircraft altitudes and airspeeds were predicted prior to launching any aircraft for live flight test. Additionally, with HITL, the GAS-1N AE and MAGR GPS receiver planned for integration and flight onboard the C-12J were able to be tested as similar units under test. The value added to the analysis was seeing the performance of the FRPA and a 7-element GAS-1 AE HITL flown through the same scenarios used for GAS-1N evaluation. This matched the flight test configuration for the C-12J test bed where the GAS-1N, FRPA, and GAS-1 were flown side-by-side. After flight testing is complete, we will revisit this phase of analysis to validate what was predicted and refine the models if required. At that point validated threat scenarios can be selected from the previous NAVWAR analysis performed for the GPS JPO and the GAS-1N, FRPA, and GAS-1 can be “flown” through these challenging threat scenarios. This will provide data to assist in answering the question: are four elements enough?

Flight Testing

The thrust of the test program is in the flight tests conducted by the 746th Test Squadron on the White Sands Missile Range (WSMR) involving the C-12J from Holloman AFB, NM, and the F/A-18C from the Naval Air Warfare Center-Weapons Division (NAWC-WD) of China Lake, CA. Each aircraft will fly similar profiles in the same GPS-denied environment. In addition, the F/A-18C will fly more tactically realistic profiles to provide an operational "snapshot" of GAS-1N performance. This involves maneuvering and attack profiles to see what affect the jammers have when body masking is not providing added protection to the antenna.

The C-12J will be modified to test and record data from three separate GPS antenna systems mounted side-by-side and individually palletized to their own GPS receivers. See Figure 10. Collecting comparative data in a similarly stressed environment provides insight into the benefits of seven elements (GAS-1) versus four elements (GAS-1N) versus one element (FRPA) to aid the decision makers on the merits of anti-jam antennas relative to degrees of freedom (DOF) and array size. It should be noted that the main comparison of interest remains GAS-1N versus FRPA performance. It must be established that GAS-1N, i.e. four element adaptive arrays, can provide a level of protection to a platform well above that of a FRPA to make the investment worthwhile for the DoD. Yet, having the comparison available for the GAS-1N and the GAS-1 systems will provide substantive data on whether the Navy should readdress the trade-off between array size and anti-jam performance for platforms that may be able to incorporate the larger 14-inch array.

Figure 10. C-12J Flying GPS Antenna Test Bed

The data to be collected on the C-12J are:

- MAGR Block 3 Data
- J/S level (FRPA on bottom of fuselage)
- Body masking (FRPA on top of fuselage)
- AE output
- Truth plots of ground track

The F/A-18C has been integrated with a GAS-1N system as shown in Figures 11 and 12. The antenna electronics is mounted directly under the array. The integration can be configured with an in-line L2 filter between the antenna electronics and the GPS receiver to enable L1-only tracking (used to reduce jammer requirements), or a fully capable L1/L2 configuration. Verification of this test configuration was confirmed prior to flight test in the SPAWAR Systems Center GPS Central Engineering Activity (CEA) laboratory shown in Figure 13.

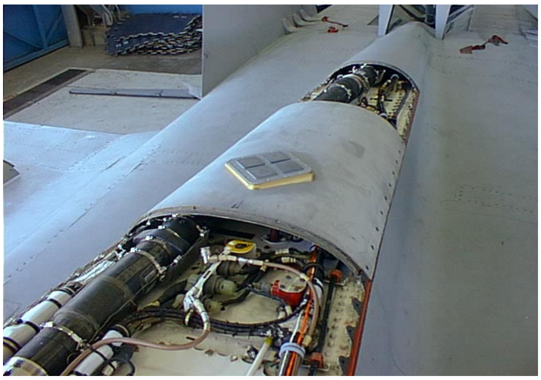

Figure 11. GAS-1N Array on F/A-18C Mounted on Panel #40

The data to be collected on the F/A-18C are:

- MAGR Block 3 Data
- Truth plots of ground track

This data will "close the loop" on the modeling and simulation to validate what was predicted.

Figure 12. GAS-1N AE Mounted below Panel #40

Figure 13. SSC-SD GPS CEA Laboratory

Conclusion

Since the start of the U.S. Navy's FCT evaluation program, the GAS-1N AE and matching four-element antenna have been selected as the GPS Anti-Jam solution for the EMD phase of the U.S. Army's Comanche helicopter (RAH-66). Whether the Navy concludes that four elements are enough, the GAS-1N demonstrator has offered us a route towards a practical solution that proved difficult to reach from a theoretical standpoint. The GAS-1N system, or something like it, may provide a viable upgrade path for many current military GPS platforms.

SPAWAR Systems Center-San Diego has taken the lead on developing a testing methodology that has sought to combine laboratory tests, modeling and simulation, and live flight testing in a comprehensive, end-to-end process designed to provide the answer to the question: are four elements enough?

The GAS-1N FCT project is a work in progress at the time of this writing (September 2000) and the final report is due to be published in 2QFY01. It will be made available for DoD-wide dissemination.

ACKNOWLEDGEMENTS

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- SAIC
- Raytheon Systems Limited
- AIL Systems Incorporated
- SSC-SD Codes D312, D313, D315
- OPNAV N880G2, N633

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