Miniaturized GPS Antenna Array and Test Results

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BIOGRAPHY

Alison Brown is the President and CEO of NAVSYS Corp. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge Univ. In 1986 she founded NAVSYS. Currently she is a member of the GPS-III Independent Review Team and Science Advisory Board for the USAF and serves on the GPS World editorial advisory board.

Huan-Wan Tseng is an Antenna & RF Engineer at NAVSYS Corporation. He has a PhD from Ohio State University, an ME from University of Florida, and a BS from Tatung Institute of Technology (Taipei, Taiwan), all in Electrical Engineering. He is responsible for the development of novel GPS antenna arrays at NAVSYS.

ABSTRACT

NAVSYS has developed a miniaturized GPS antenna array technology that reduces the size of the antenna elements and the array dimensions. This technology enables GPS controlled reception pattern antenna arrays (CRPAs) with anti-jamming capability to be installed on vehicles where their size has previously prohibited their use. This includes aircraft where size and weight constraints resulted in fixed reception pattern antenna (FRPA) installations instead of CRPAs and munitions where space and surface area are at a premium.

In this paper, the design of the antenna array is presented and test data collected in an instrumented anechoic chamber with the antenna array installed in a Joint Direct Attack Munition (JDAM) tail-kit is included. Test results are also presented from the antenna array installed on an aircraft and integrated with a digital beam-steering antenna electronics package. Commercial aspects of this technology for aircraft navigation and interference rejection will also be presented.

INTRODUCTION

The NAVSYS' Mini-Array antenna was developed under a contract to the Office of Naval Research (ONR). Many of the DoD's aircraft currently use FRPAs instead of CRPAs, due to the size and weight of the current CRPA antenna arrays. The goal of this ONR funded effort is to produce a mini-array that is form-factor compatible with existing FRPA antennas used on the DoD's aircraft, but which can be used to provide GPS anti-jamming protection.

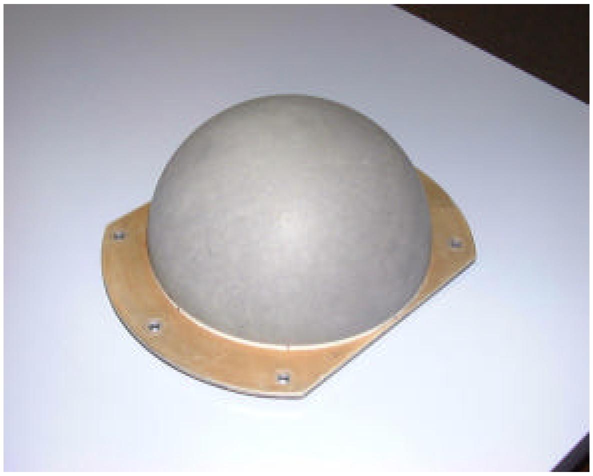


Figure 1 6" diameter 4-element Mini-Array.

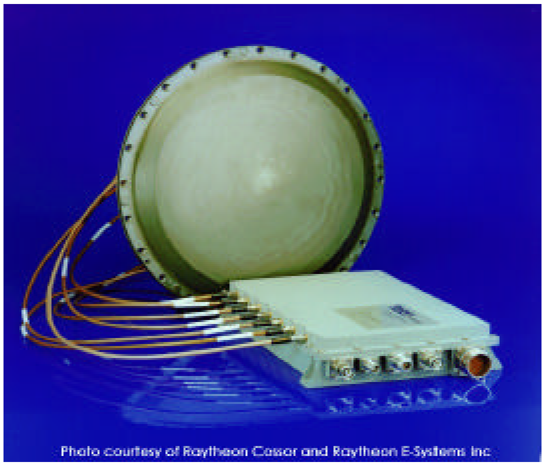


Figure 2 GAS-1 Null-Steering Antenna

The NAVSYS' Mini-Array antenna is shown in Figure 1. This antenna is significantly smaller than the CRPA but provides equivalent performance in terms of null-depth and beam-steering as a full-size antenna array. The Mini-Array has been tested for its null-steering performance by Boeing in their anechoic chamber[1] and has been flight qualified under contract to the Naval Air Warfare Center (NAWC) at Patuxent Rive (see Figure 2). Flight tests are planned in the near future on NAWC's Beechcraft aircraft demonstrate this system's performance in support of the Joint Precision Approach and Landing System (JPALS) program.

JPALS plans to use a similar architecture for precision approach and landing of DoD aircraft as the FAA propose for the Local Area Augmentation System (LAAS). This relies on differential corrections of the GPS code and carrier signals to compute the aircraft's location relative to the landing site. The JPALS system has the additional requirement that it must continue to operate in a jamming environment.

MINI-ARRAY DESIGN OVERVIEW

The miniature array is composed of a ground plane, a substrate with the antenna elements on its surface, and a superstrate on top of the elements. The dielectric constant of the substrate is increased so that the size of the antenna elements can be reduced. This allows the antenna element spacing to be reduced. By controlling the design of the antenna elements, the efficiency is increased so that they have the same gain as a standard GPS antenna element. By adjusting the dielectric constant and shape of the superstrate, the mutual coupling between the antenna elements is minimized and the reduced antenna spacing is scaled so that it appears to be effectively $\lambda/2$ in its beamforming or null steering performance.

A summary of the mini-array specifications is shown below in Table 1. As can be seen, the array was designed for receiving the GPS L1 frequency with sufficient bandwidth to receive both C/A code and P code versions of GPS data. To provide optimum performance as a CRPA, its elements have been arranged into a square with $\lambda/2$ antenna spacing. Figure 3 displays the top view of the current mini-array configuration. Work is in process for a second version of the Mini-Array with an even smaller footprint.

Table 1 Summary of Mini-Array specification

Center Frequency	1575.42 MHz (at L1)
Bandwidth	20 MHz (1575.42 +/- 10 MHz)
Input Impedance	50 Ohms
VSWR	2.2:1 Maximum
Polarization	Right Hand Circular Polarization (RHCP)
Array Size	6 Inches Diameter
Array Configuration	Square
Number of Elements	4
Element Type	Rectangular
Feed Arrangement	Probe Feed

Details on the Mini-Array and antenna measurement performance are included in reference [1]. This antenna provides the identical phase relationship to a full-size antenna array while reducing the over-all array physical dimensions. A high-dielectric lens is installed over the antenna array plane (patent pending), which allows the separation between elements to be reduced while still maintaining the same phase spatial separation. In Figure 4 actual phase angle measurements are plotted between two of the antenna array elements, showing that the spatial phase separation matches the predicted 0.5 cycles for the Mini-Array although the physical antenna separation is only 0.2236 cycles.

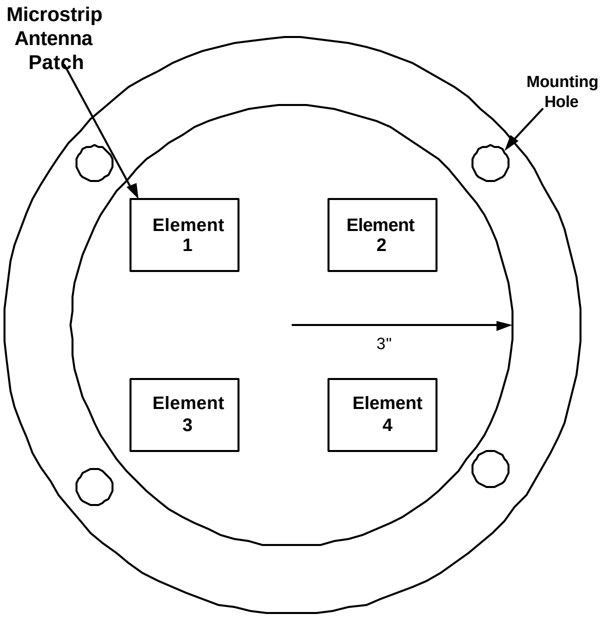


Figure 3 Top view of the 4-element mini-array configuration

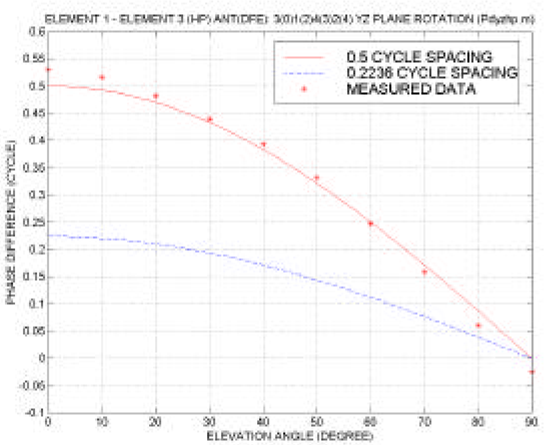


Figure 4 Measured phase difference vs elevation angle

DIGITAL ARRAY ELECTRONICS

The Mini-Array has been designed to be compatible with the existing CRPA and GAS 1 antenna electronics being used by the DoD. Testing of the Mini-Array has been conducted with an all-digital antenna array electronics package developed by NAVSYS. This all-digital approach for antenna array electronics enables precise digital beam-forming and null-forming to enable high accuracy observations to be maintained in the presence of a jamming signal.

NAVSYS High Gain Advanced GPS Receiver (HAGR) includes digital electronics to implement a digital beam-steering antenna array which allows up to eight GPS satellites to be tracked, each with up to 10 dB of additional antenna gain over a conventional receiver solution. The PC-based architecture provides a cost-effective solution for commercial or military applications where precise GPS measurements on interference protection are needed. The additional gain provided on the satellite signals by the HAGR enables sub-meter pseudo-ranges to be observed directly on the C/A code and also improves the accuracy of the GPS carrier phase and estimates of the satellite signal strength. The directivity of the digital beams created from the antenna array also reduces multipath errors further improving the accuracy of DGPS, navigation, and timing solution computed.

In a mobile environment, the digital beam-steering must compensate not only for the satellite motion, but also for the vehicle motion as well. The HAGR design has been updated to accept an external input through an RS-232 port of the vehicle's pitch, roll and heading. This can be used to provide real-time correction of the digital beam's direction while the vehicle is in motion.

The performance specifications for the HAGR for a 16-element, L1 C/A code version of this product are included in reference [2]. The design of the mobile beam-former architecture is included in reference [3]. Currently an L1/L2 Precise Position System (PPS) version of the HAGR (the HAGR-200) is also in development.

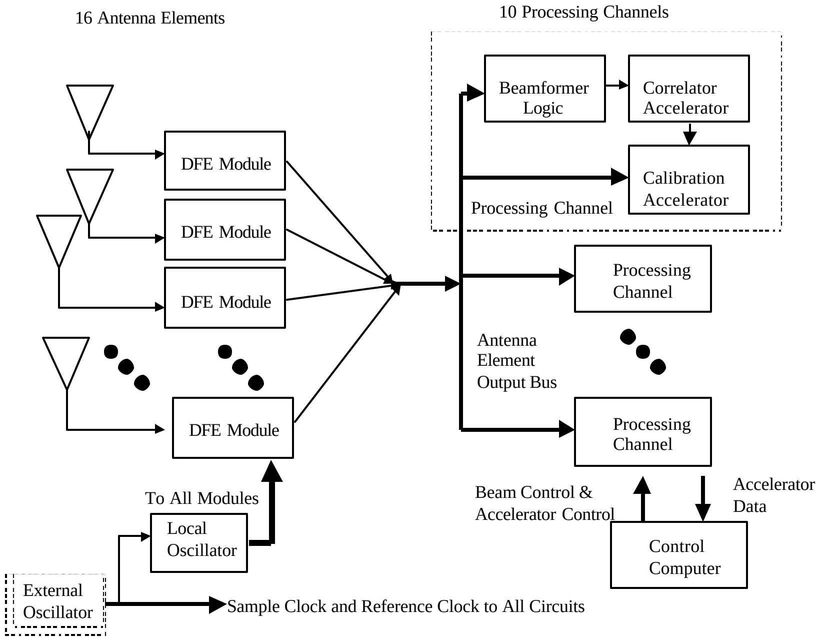


Figure 5 HAGR System Block Diagram

The HAGR system architecture is shown in Figure 5. The signal from each antenna element is digitized using a Digital Front-End (DFE). The combined digital array signal, z(t), is generated from summing the weighted individual DFE signals. This can be expressed as the following equation.

$$z(t) = \underline{w}' \underline{y}(t) = \underline{w}' \left[\sum_{i=1}^{Ns} s_i(t) \underline{e}_{si} + \underline{n}(t) + \sum_{l=1}^{Nj} j_j(t) \underline{e}_{jl} \right]$$

The complex weights (w) applied by the HAGR are computed in software and downloaded to the digital beam-steering card. Through software changes, weights can be applied to implement both digital beam-steering (directing gain in the direction of the desired satellite signal, s(t)) and null-forming on an undesired signal such as a jammer source (j(t)). To implement null-forming, the HAGR must also include the adaptive electronics firmware to identify the direction of any interference or jammer signals[4].

The direction of the digital beam is computed in real-time by the HAGR based on the following equation.

$$\underline{1}_i^{(B)} = (C_B^N)^T \underline{1}_i^{(N)} = (C_B^N)^T (\underline{x}_u - \underline{x}_{svi}) / R_i$$

The user position and satellite position are provided from the HAGR navigation algorithms. The direction cosine matrix to transform from the navigation frame (north, east, down), to the antenna body frame (defined as forward, right, down) is computed in real-time using input pitch, roll and heading data from an external sensor.

MOBILE MINI-ARRAY AND HAGR TESTING

The test was configured with a reference HAGR (16-element) located at a survey point and a 4-element Mini-Array installed in a truck. Two Novatel receivers were also used to collect data, installed equidistant either side of the Mini-Array. The kinematic GPS solutions derived from these reference receivers was used to compare with the kinematic solution computed from the Mini-Array and HAGR. The attitude of the vehicle was provided using a 3-axis digital tilt and compass module. Details of this testing is included in reference [5].

The satellites tracked by the Mini-Array are shown in Figure 6 and in Figure 7 the same plot is shown for the 16-element HAGR that was used as a reference receiver. From these plots, it can be seen that the Mini-Array was able to maintain lock on the satellites tracked throughout the test maneuvers. The carrier phase lock from the Mini-Array data is plotted in Figure 8.

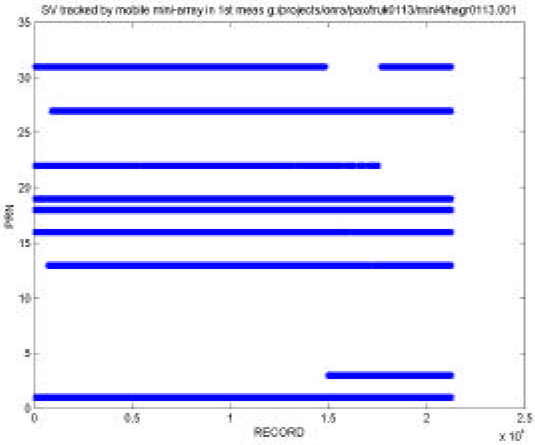


Figure 6 Satellite tracked by Mobile HAGR with a 4-element Mini-Array

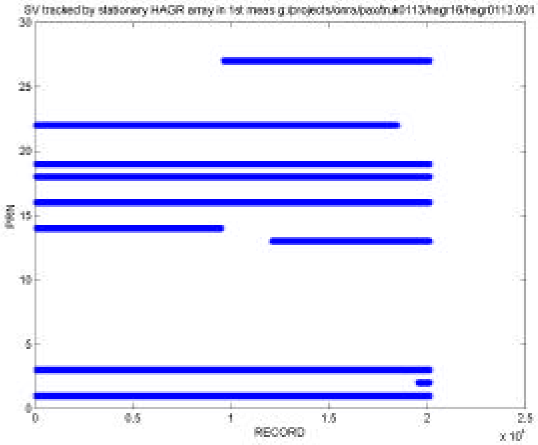


Figure 7 Satellite tracked by Reference HAGR with a 16-element antenna array

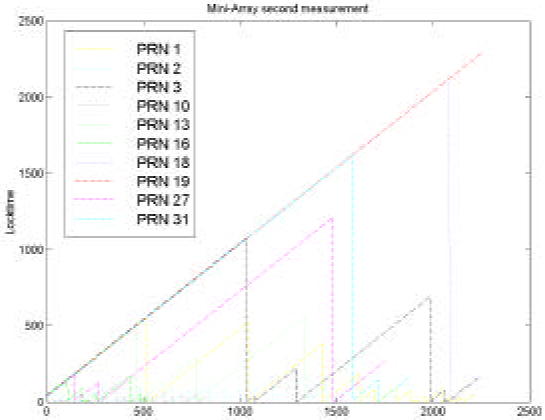


Figure 8 Locktime on all satellites tracked by Mini-Array

In Figure 9 to Figure 15, the recorded C/N0 during the mobile tests is shown for the Mini-Array with beam-steering and a Novatel receiver on-board the same test vehicle, as a point of comparison. These results show that the Mini-Array C/N0 was consistently higher than the Novatel C/N0 and moreover, the variation in C/N0 was much less during the testing. This effect is attributed to the reduction in multipath that is observed when using digital beam-steering [2].

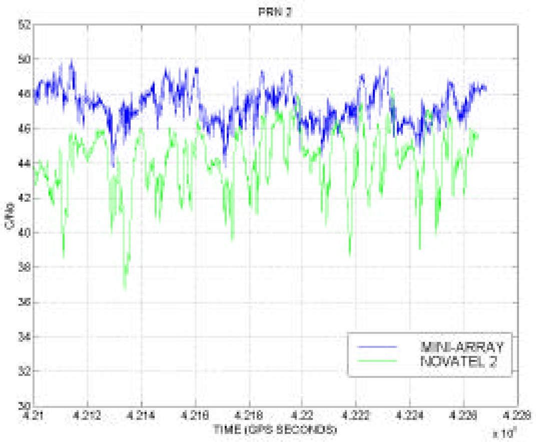


Figure 9 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 2

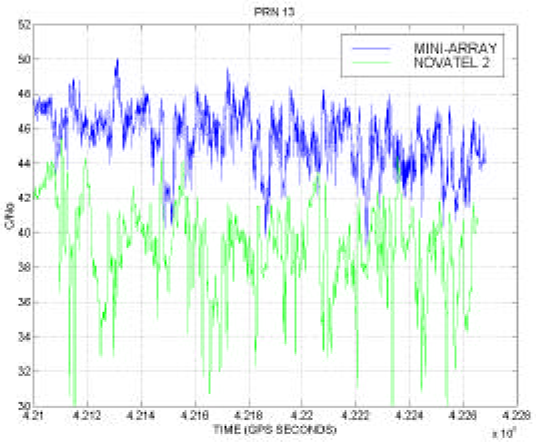


Figure 11 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 13

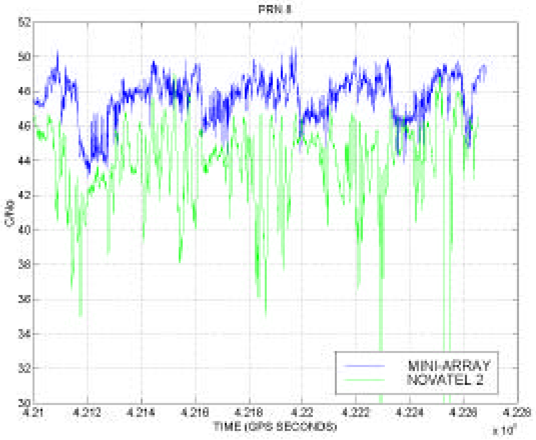


Figure 10 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 8

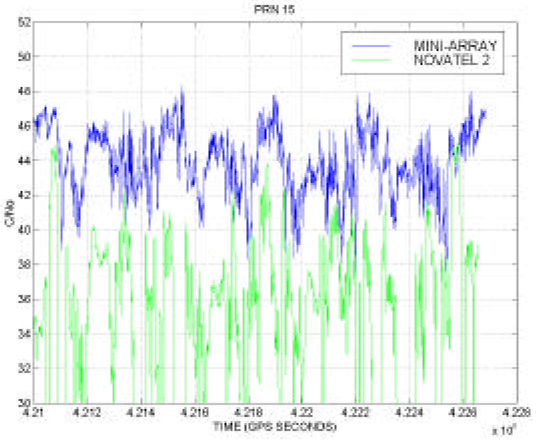


Figure 12 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 15

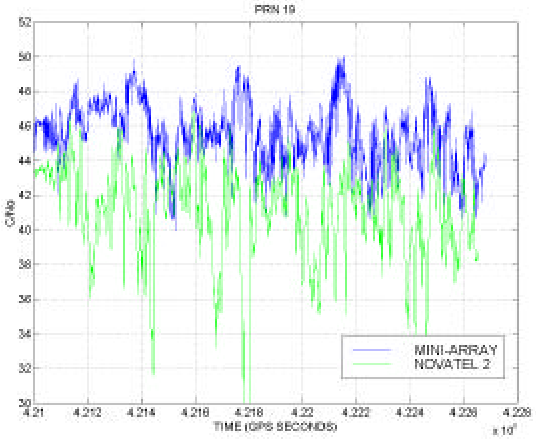


Figure 13 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 19

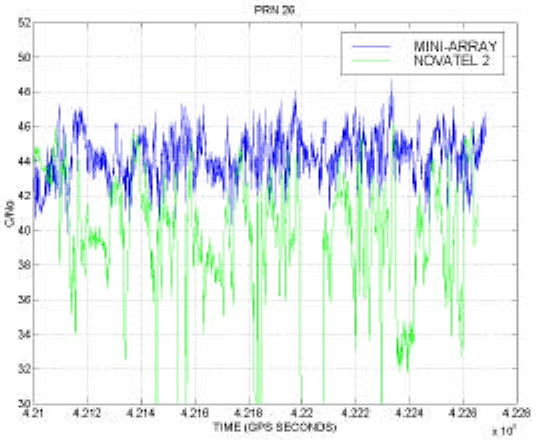


Figure 14 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 26

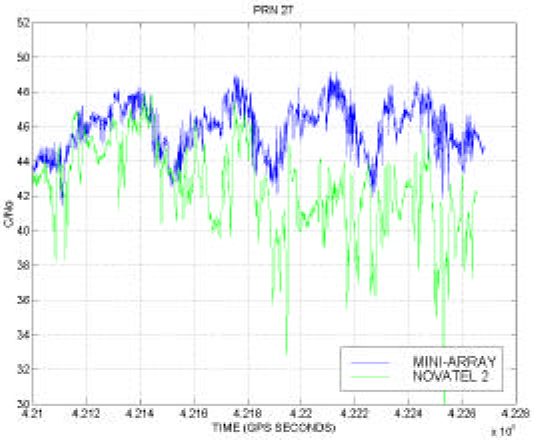


Figure 15 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 27

BEAM-STEERING/NULL STEERING PERFORMANCE

The test data presented above demonstrates the beam-steering performance of the Mini-Array and HAGR electronics. As discussed previously, for applications such as the Joint Precision Approach Landing System (JPALS), both beam-steering and null-steering are desired to provide anti-jamming GPS protection during precision approach and landing.

The nulling performance of the mini-array antenna element was measured inside the Microwave Anechoic Chamber at the Boeing Military Aircraft And Missile Systems Group Facility in St. Louis, Missouri. The array was attached to the tail end of Boeing PGM tailkit mockup with “NORTH” (between elements 1 and 2) aligned with the “fixed fin” or +x axis. A photo of this setup is shown in Figure 16. To generate the antenna patterns, a set of antenna data was collected at the L1 frequency for horizontal polarization, vertical polarization, and circular polarization at 216 angular points which is approximately a 15° spacing.

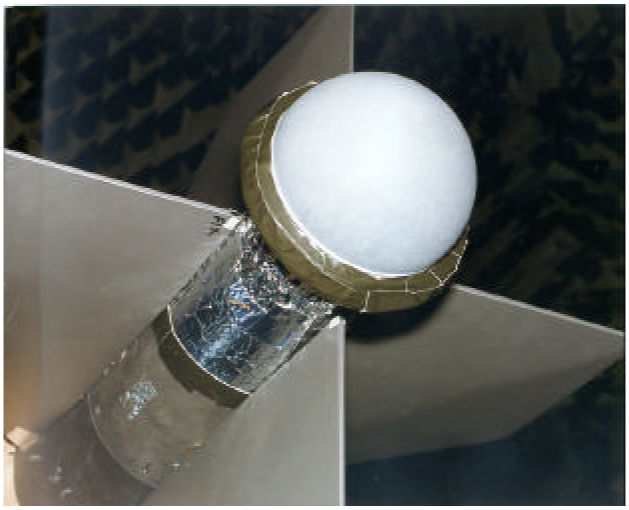


Figure 16 Mini-array mounted on Boeing PGM tailkit.

The nulling performance of the Mini-Array was generated from this data using AGHAST™ (Another GPS High Anti-jam Simulation Tool), which allows the anti-jam performance under different jamming scenarios to be predicted. This showed that the nulling performance provided by the Mini-Array was similar to that of a conventional CRPA [1]. Figure 17 shows the relative nulling performance of the mini-array.

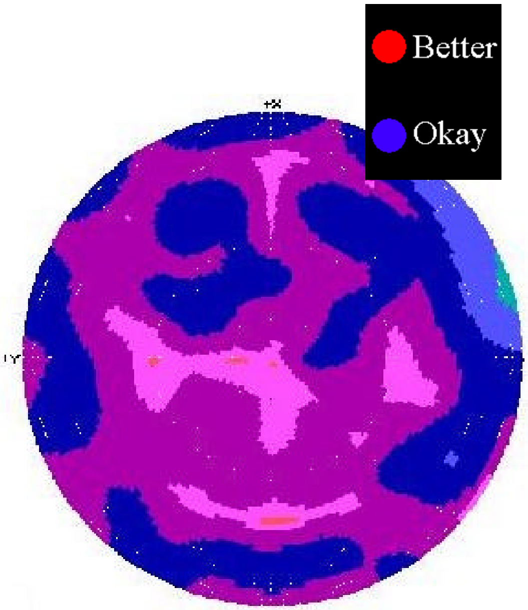


Figure 17 Relative nulling performance of the mini-array, zenith hemisphere

As described previously, the HAGR digital electronics can be programmed to provide both beam-steering in the direction of a satellite signal and null-steering in the direction of an interference source or a source of multipath reflections. In Figure 18 to Figure 21 simulation results are shown of the effect of the HAGR digital beam-steering and null-forming algorithms in the presence of a jammer. A key feature of the HAGR digital weight computation is that it provides no distortion of the GPS pseudo-range and carrier-phase observations. The resulting degradation for JPALS operation in a jamming environment is therefore only a function of the signal loss shown in from the jammer signals.

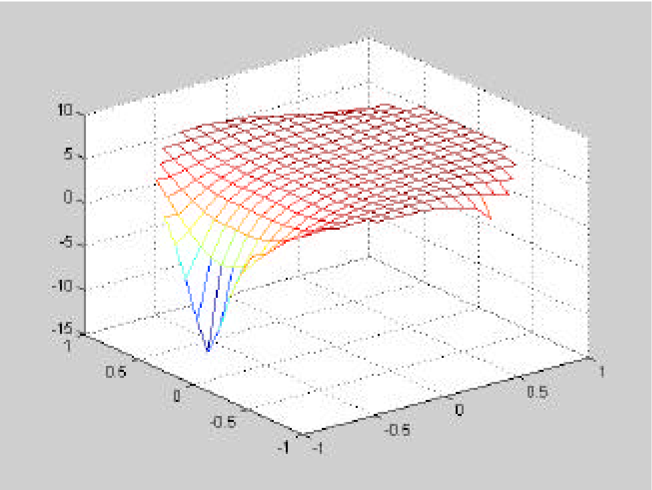


Figure 18 4-element mini-array S/J with beam/null-forming and 1 jammer present

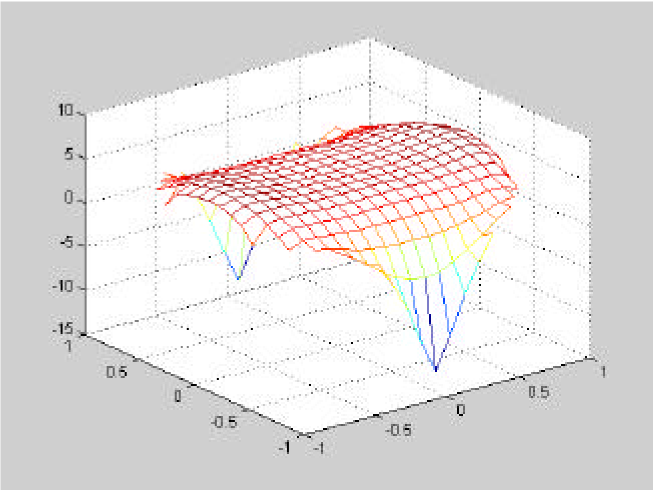


Figure 19 4-element mini-array S/J with 2 jammers

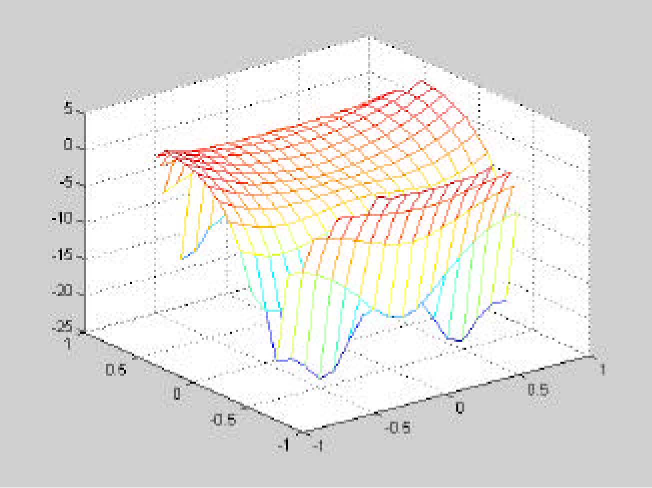


Figure 20 4-element mini-array S/J with 3 jammers

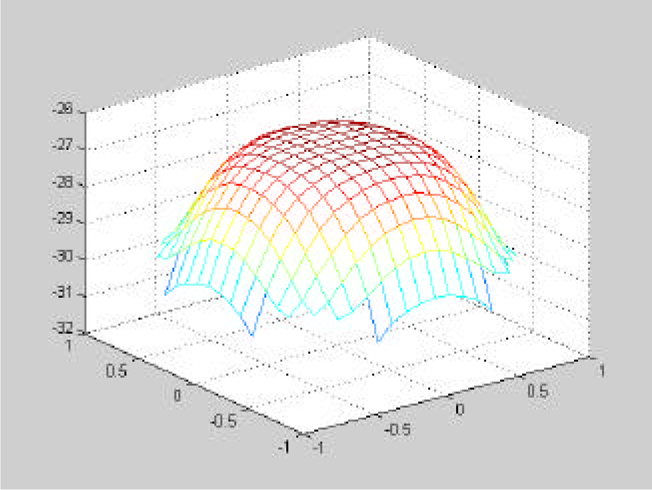
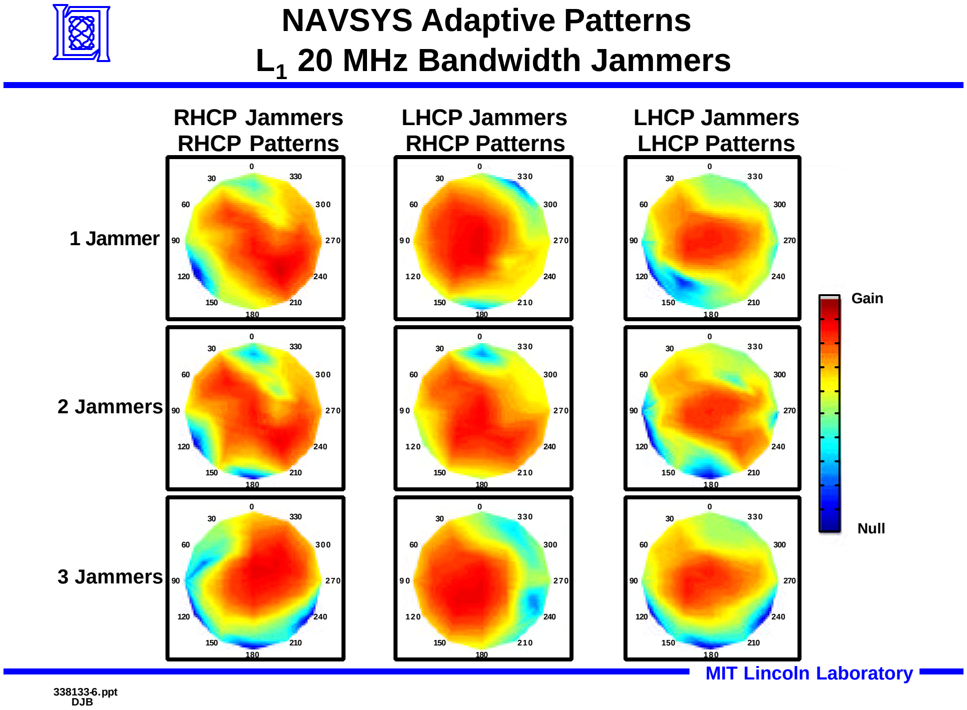


Figure 21 4-element mini-array S/J with 4 jammers

Test data was also collected on the Mini-Array by Lincoln Labs to evaluate its beam-steering and null-steering performance. These results are illustrated in Figure 22, which includes a matrix of RH/LH polarized jammers and patterns.. The Mini-Array was able to null up to three jammers while still providing gain across much of the field of view on the GPS satellites tracked.



NAVSYS Adaptive Patterns

L_1 20 MHz Bandwidth Jammers

MIT Lincoln Laboratory

338133-6.ppt
DJB

Figure 22 Beam-Steering/Null-Steering Testing at Lincoln Labs

MILITARY AND COMMERCIAL APLICATIONS

Many of the smaller munitions in operation or in development do not have a form factor that allows for a conventional CRPA to be installed. Because of size and weight constraints, some host aircraft within the Air Force and Navy have also elected to install FRPA antennas which cannot provide the A/J protection needed in many tactical environments. The GPS mini-array will enable A/J capability to be provided on many small munitions, aircraft and other host vehicles where the size and weight of the conventional CRPA array has previously been prohibitive. For example, current programs, such as the Joint Direct Attack Munition (JDAM), Joint Air-to- Surface Standoff Missile (JASSM), and the Joint Standoff Weapon (JSOW), will be able to benefit from the reduced size but full performance of the mini-array technology.

Commercial applications also exist for the Mini-Array. The digital beam-forming has been proven to give performance advantages for precision GPS applications[6]. The small size of the Mini-Array enables antenna arrays to be used for many precision GPS applications, including surveying, precision vehicle guidance and kinematic GPS applications.[3]

CONCLUSION

The benefits of the Mini-Array and digital beam-steering electronics are summarized below.

- Small antenna array footprint reduces installation costs
- Size and weight of antenna array are reduced
- Mini-array is compatible with existing GPS anti-jam electronics
- Digital antenna array electronics provide beam-steering for high accuracy applications
- Antenna gain increases C/N0 on all satellites tracked
- High accuracy pseudo-range observations facilitate rapid ambiguity solutions
- High accuracy carrier phase observations maintained from beam-forming composite observations
- Multipath errors are minimized by the digital beam antenna pattern

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[1] D. Reynolds, A. Brown, A. Reynolds, “Miniaturized GPS Antenna Array Technology And Predicted Anti-Jam Performance,” Proceedings of ION GPS ’99, Nashville, TN, September, 1999

[2] A. Brown and J. Wang, “High Accuracy Kinematic GPS Performance Using A Digital Beam-Steering Array,” Proceedings of ION GPS-99, Nashville, TN, September 1999

[3] A. Brown, H. Tseng, and R. Kurtz, “Test Results Of A Digital Beamforming GPS Receiver For Mobile Applications”, ION National Technical Meeting, Anaheim CA, January 2000

[4] A. Brown et al, “Jammer and Interference Location System - Design and Test Results”, ION National Meeting, Anaheim, CA, January 2000

[5] A. Brown, K. Taylor, R. Kurtz and H. Tseng, “Kinematic Test Results Of A Miniaturized GPS Antenna Array With Digital Beamsteering Electronics,” Proceedings of ION National Technical Meeting, Anaheim, CA, January, 2000

[6] A. Brown, R. Silva, E. Powers, “High-Gain Advanced GPS Receiver for Precision GPS Applications,” Proceedings of GNSS 2000, Edinburgh, Scotland, May 2000.