KINEMATIC TEST RESULTS OF A MINIATURIZED GPS ANTENNA ARRAY WITH DIGITAL BEAMSTEERING ELECTRONICS

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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.

Keith Taylor is a Project Manager for NAVSYS Corporation. He is responsible for developing MATLAB based GPS signal simulation tools for user selectable signal environments and jamming scenarios. He holds an MSEE from University of Florida and a BSEE from the University of Louisville.

Randy Kurtz is the Production Manager at NAVSYS Corp. He holds a BS in Electrical Engineering from Colorado Technical University. He has eight years of experience in manufacturing and materials management, and was a key team member on the Kaman Aerospace / Lockheed SDIO Starlab Wavefront Control Experiment.

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 have developed a miniaturized GPS antenna array technology that reduces the size of the antenna elements and the array dimensions. Using this technology, a 4-element GPS antenna array has been developed in a 6-inch diameter footprint. This miniaturized antenna array technology enables GPS controlled radiation pattern antenna arrays (CRPAs) with anti-jamming capability to be installed on vehicles where their size has previously prohibited their use.

Problems have been experienced with previous CRPA electronics that can degrade the accuracy of carrier phase observations derived from the multiple elements. To demonstrate the capability of the Mini-Array for precision applications, such as JPALS, the 4-element miniaturized antenna array has been configured for aircraft installation and integrated with NAVSYS GPS digital beamforming electronics. Test data is presented in this paper, demonstrating the ability of the Mini-Array to generate a precise kinematic GPS solution. Simulation results are also presented of the expected performance of the Mini-Array with NAVSYS beam/null-steering electronics in a jamming environment.

INTRODUCTION

In this paper, the NAVSYS miniature antenna array (Mini-Array) is described with the digital beam-steering electronics used to perform the kinematic GPS testing.

The Mini-Array antenna was developed under a contract to the Office of Naval Research (ONR). Many of the DoD's aircraft currently use fixed radiation pattern antennas (FRPAs), due to the size and weight of the current CRPA antenna arrays. The goal of the 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.

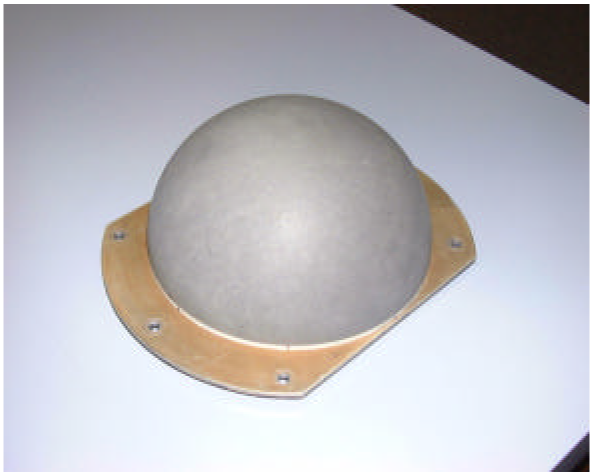

Figure 1 6" diameter 4-element Mini-Array.

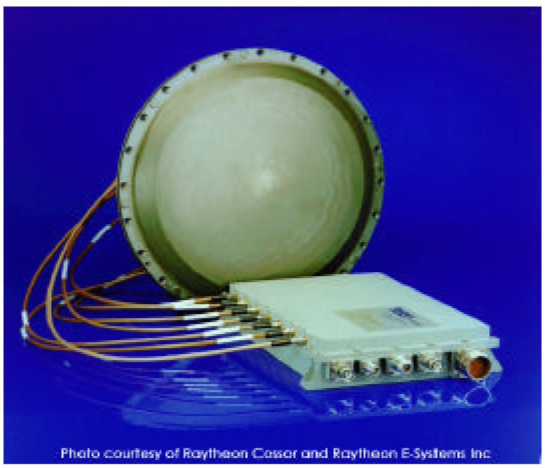

Figure 2 GAS-1 Null-Steering Antenna

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 will be flight qualified under contract to the Naval Air Warfare Center (NAWC) at Patuxent River. 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.

There are concerns that the analog electronics used in the DoD's current CRPA and GAS 1-N antenna electronics (as shown in Figure 2) will result in unacceptable errors on the pseudo-range and carrier-phase observations when nulling is applied. There is a desire to transition to a more precise digital beam-forming and null-forming antenna electronics to enable high accuracy observations to be maintained in the presence of a jamming signal.

In this paper, the digital beam-steering electronics developed by NAVSYS for use with our High-gain Advanced GPS Receiver (HAGR) are described. This antenna electronics was used to test the Mini-Array performance in computing a kinematic GPS solution. The HAGR electronics provide beam-steering on up to eight GPS satellites simultaneously to enhance the performance of the GPS signals being tracked and to provide spatial filtering to reduce the effect of multipath or interference sources.

MINI-ARRAY

The principle of operation of the Mini-Array and antenna measurement data is described 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 3 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.

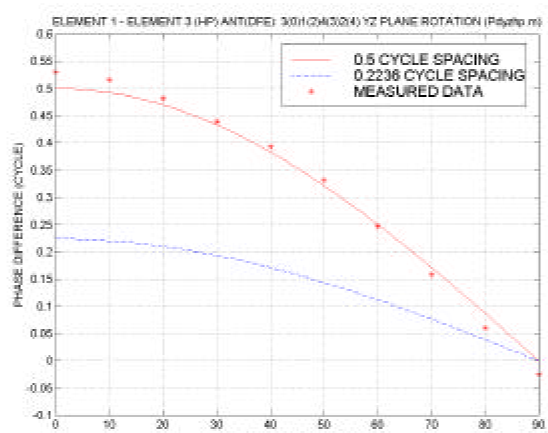

Figure 3 Measured phase difference vs elevation angle

HIGH GAIN ADVANCED GPS RECEIVER

NAVSYS High Gain Advanced GPS Receiver (HAGR) uses a digital beam-steering antenna array to enable up to eight GPS satellites to be tracked, each with up to 10 dB of additional antenna gain over a conventional receiver solution. This digital, PC-based architecture provides a cost-effective solution for commercial applications where more precise GPS measurements 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 corrections generated by the HAGR and the 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.

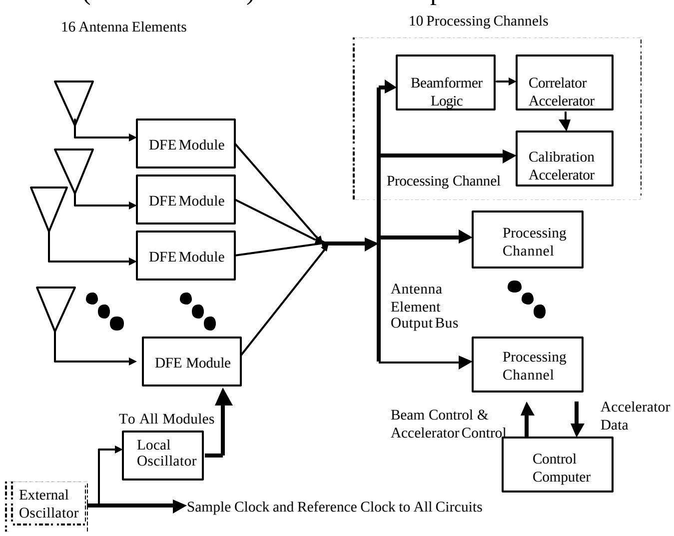

Figure 4 HAGR System Block Diagram

The HAGR system architecture is shown in Figure 4. 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. The pitch, roll and heading of the vehicle while it was driving around the test track are shown in Figure 5 to Figure 7. The attitude rate of change was generally less than 1 deg/sec throughout this test.

The satellites tracked by the Mini-Array are shown in Figure 8 and in Figure 9 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 10.

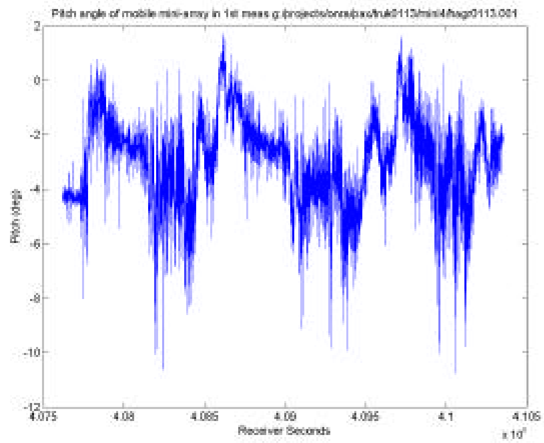

Figure 5 Mobile Mini-Array Testing (Pitch)

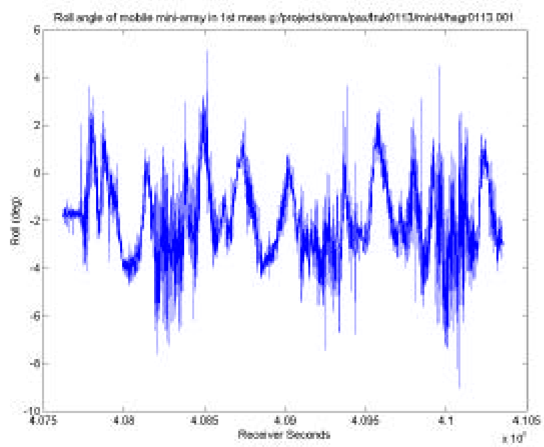

Figure 6 Mobile Mini-Array Testing (Roll)

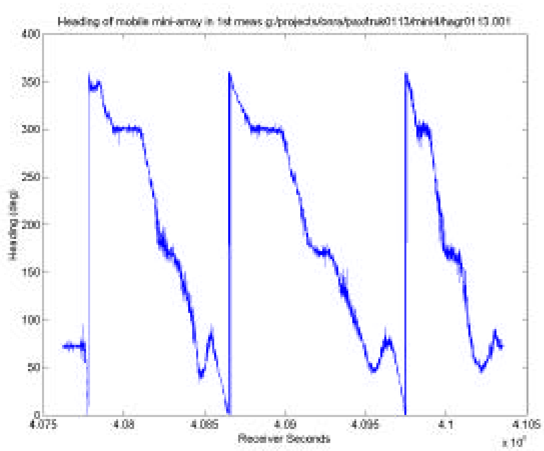

Figure 7 Mobile Mini-Array Testing (Heading)

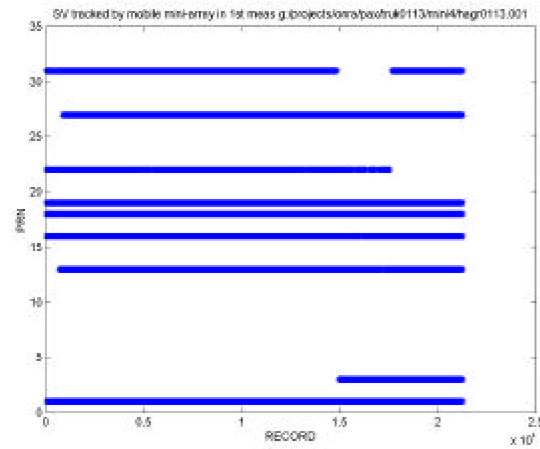

Figure 8 Satellite tracked by Mobile HAGR with a 4-element Mini-Array

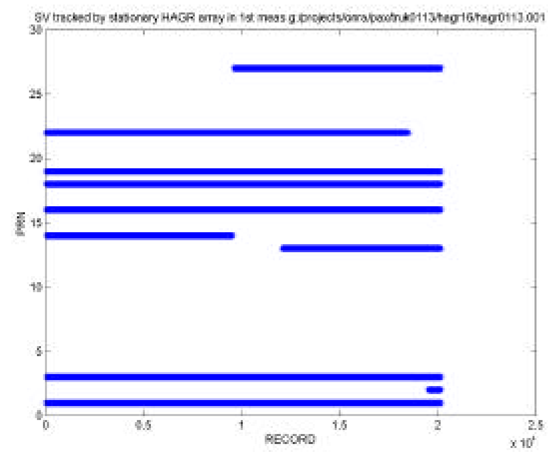

Figure 9 Satellite tracked by Reference HAGR with a 16-element antenna array

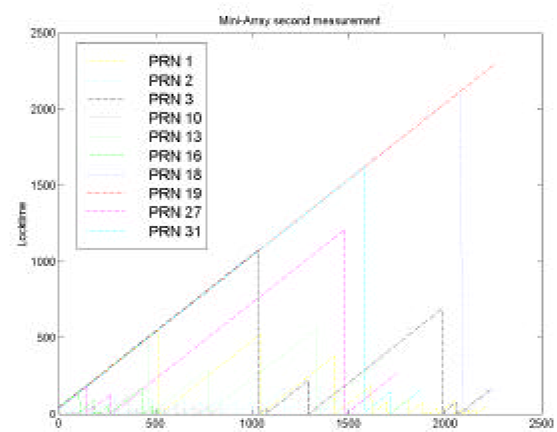

Figure 10 Locktime on all satellites tracked by Mini-Array

In Figure 11 to Figure 17, 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].

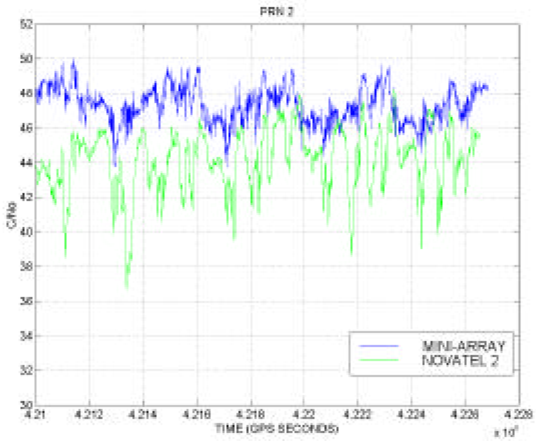

Figure 11 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 2

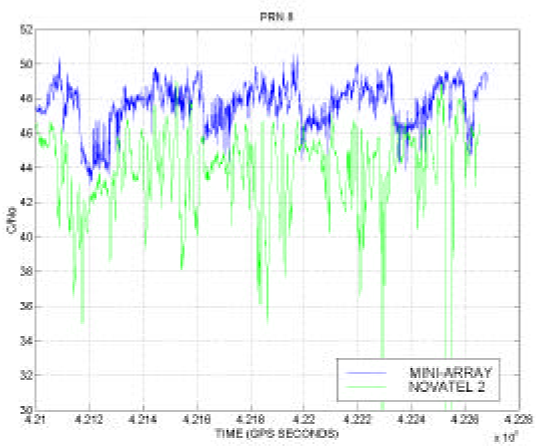

Figure 12 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 8

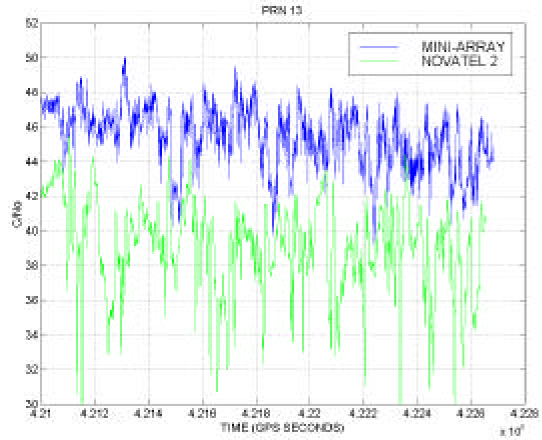

Figure 13 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 13

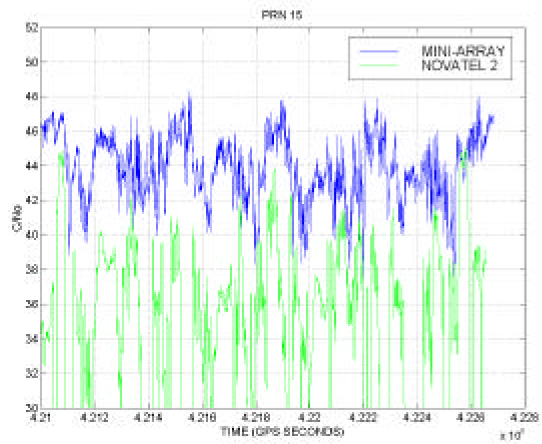

Figure 14 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 15

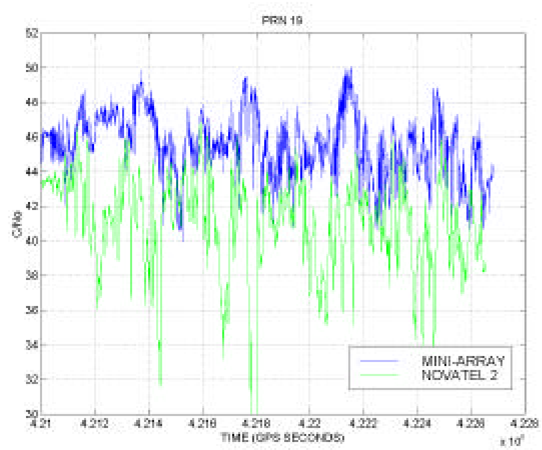

Figure 15 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 19

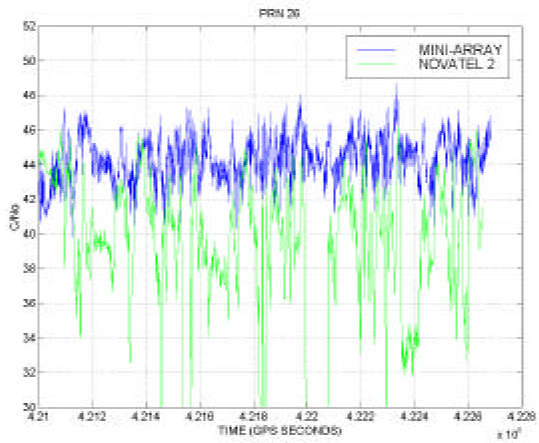

Figure 16 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 26

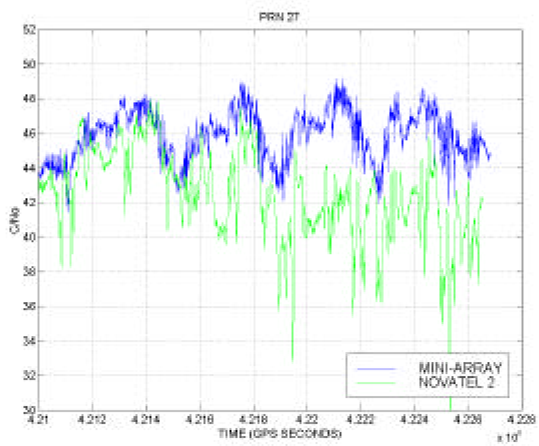

Figure 17 Mobile Mini-Array and Novatel C/N0 (dB-Hz) PRN 27

The carrier phase accuracy of the Mini-Array was measured by double-differencing the observed carrier phase data with the carrier phase observations from two reference GPS receivers, spaced equidistant about the Mini-Array during the mobile testing. The observed phase differences are shown in Figure 18 and Figure 19 for two of the satellites tracked, and the statistics (mean and standard deviation) for each satellite are shown in Table 1.

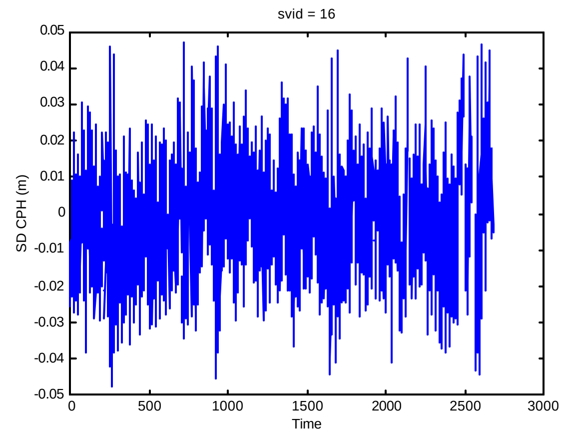

Figure 18 SVID 16 Double Difference Carrier Phase Observations

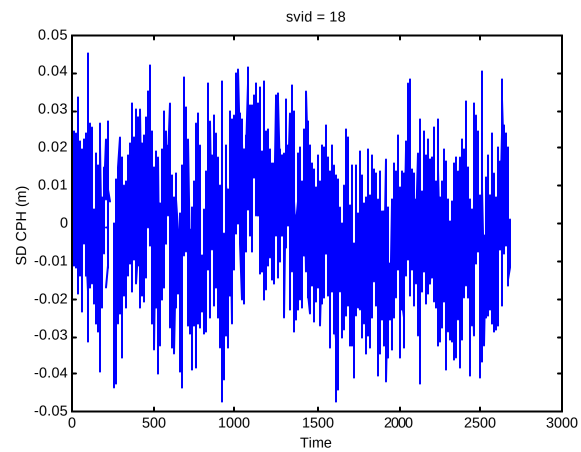

Figure 19 SVID 18 Double Differenced Carrier Phase Observations

Table 1 Double Differences Computed

SVID	1	3	13	16	18	19	22	27	31
Mean (mm)	-	6.4	0.5	-03	-2.4	-1.3	-3.0	-4.1	-0.6
Std (mm)	-	18	18	17	15	15	17	18	16

Since the double-differences increase the noise on the observations by a factor of two, the test data shows that the Mini-Array provides better than 1-cm accuracy KGPS carrier phase observations. This error level is consistent with the expected multipath errors on the reference receivers during the testing.

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 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 was tested by Boeing in their anechoic chamber, using AGHAST™ (Another GPS High Anti-jam Simulation Tool), which allows the anti-jam performance of CRPAs and their null-steering electronics to be predicted. This showed that the nulling performance provided by the Mini-Array was similar to that of a conventional CRPA (see Figure 20 [1]). Figure 20 shows the relative nulling performance of the mini-array.

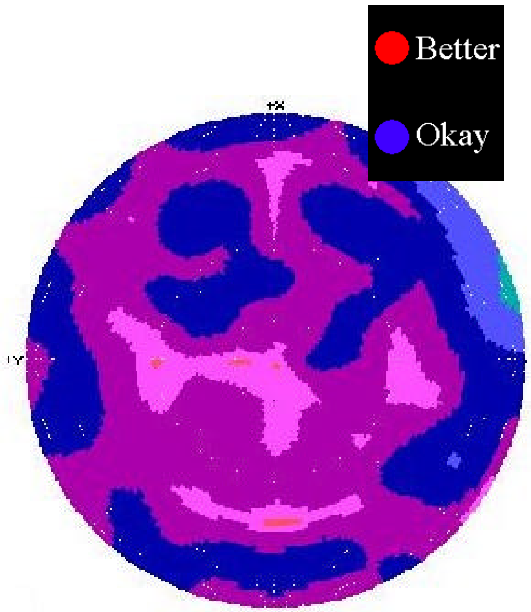

Figure 20 Relative nulling performance of the mini-array, zenith hemisphere

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 21 to Figure 24 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.

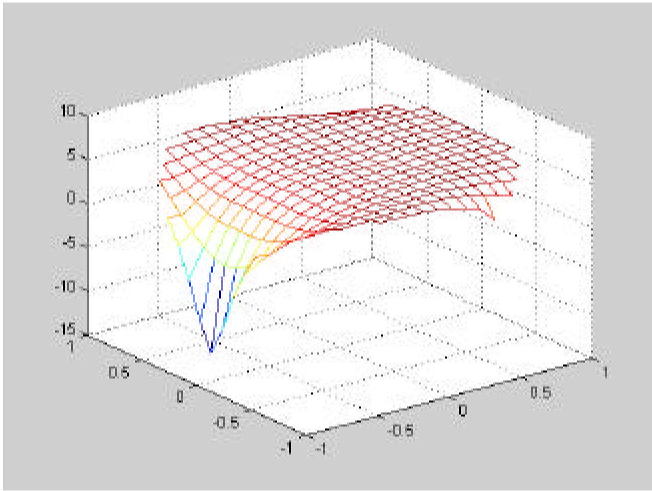

Figure 21 4-element mini-array S/J with beam/null-forming and 1 jammer present

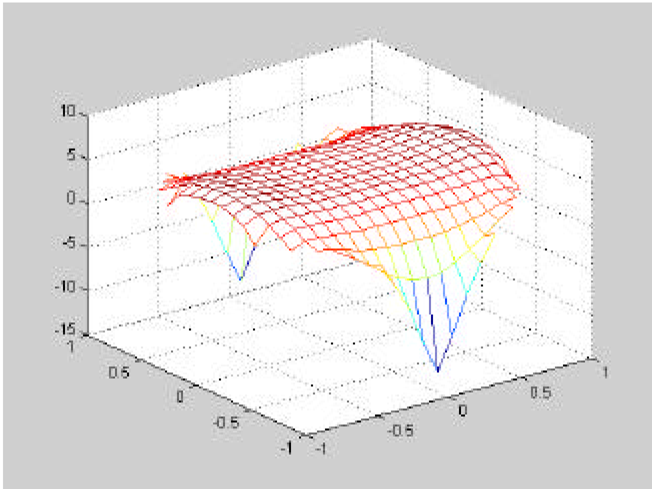

Figure 22 4-element mini-array S/J with 2 jammers

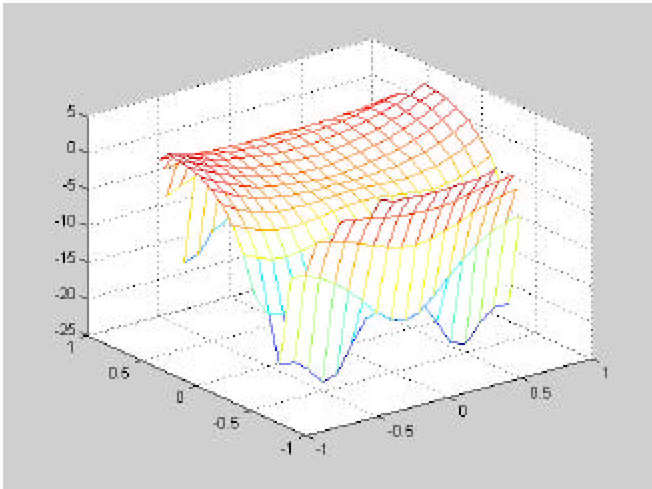

Figure 23 4-element mini-array S/J with 3 jammers

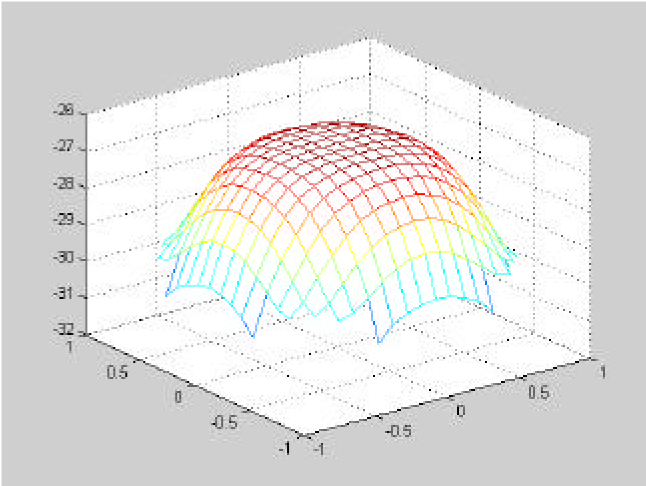

Figure 24 4-element mini-array S/J with 4 jammers

CONCLUSION

These tests successfully demonstrated the ability of the Mini-Array to operate in a mobile environment, using beam-steering to increase the C/N0 and maintain high accuracy carrier phase observations to assure a reliable kinematic GPS solution with centimeter level accuracy.

The test results showed that the Mini-Array with beam-steering performed better than a conventional receiver in maintaining lock on the GPS satellites. This is essential to maximize the lock-time for each satellite tracked and minimize the number of times that ambiguity resolution must be performed.

The benefits of the Mini-Array and digital beam-steering electronics are summarized below for precision applications such as the LAAS or JPALS programs.

- Multipath minimization from the digital beam antenna pattern
- Ability to null out interference sources(currently in development)
- 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

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[1] D. Reynolds, A. Brown and 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