Test Results of a Digital Beamforming GPS Receiver in a Jamming Environment

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BIOGRAPHY

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ABSTRACT

NAVSYS High Gain Advanced GPS Receiver (HAGR) uses a digital beam-steering antenna array to provide additional gain in the direction of the GPS satellite signals. This increases the received signal/noise ratio on the satellites tracked and also improves the accuracy of the pseudo-range and carrier-phase observations. The directivity of the digital beams created from the antenna array also reduces the effect of jamming and interference.

This paper describes the operation of the HAGR digital beam steering array in a jamming environment and includes test data collected from the HAGR at the Electronic Proving Grounds, Fort Huachuca, that demonstrate the performance of a digital, beam-steering receiver against interference sources.

INTRODUCTION

The susceptibility of the GPS signals to interference is of concern to the GPS user community. Because of the low received power of the GPS signals, outages can easily occur due to unintentional interference, and even low power jammers can deny GPS operation over significant areas of operation. Current generation GPS military User Equipment (UE) uses nulling electronics to increase the Jammer/Signal (J/S) margin under which they can operate. These analog electronics use a Controlled Reception Pattern Antenna (CRPA) to create an adaptive pattern which provides nulls in the direction of a detected GPS jammer. With a 7-element antenna array, such as the GAS-1 antenna in use by the DoD, nulls can be placed on up to 6 different jammers.

In this paper, an alternative GPS jammer protection solution is described where digital beam-steering is used to apply gain in the direction of the GPS satellites. This improves the J/S margin for each of the GPS satellites tracked by applying optimized antenna weights on a channel-by-channel basis.

Digital beam-steering has the following advantages for GPS anti-jam applications.

1. **Increases GPS satellite signal power**. The beam-steering provides gain in the direction of the GPS satellites increasing their effective C/N0.
2. **Improved GPS measurement accuracy.** The increase in C/N0 on the GPS satellites reduces the pseudo-range and carrier-phase measurement noise improving the navigation solution accuracy.
3. **Improves satellite coverage factor**. With null-steering electronics, significant segments of the sky are "blanked" out when a jammer (or jammers) are detected. This will cause the GPS UE to lose lock on multiple satellites whenever jammers are detected, reducing the satellite coverage factor. With the beam-steering approach, the antenna pattern is optimized to increase the satellite gain. This improves the amount of time that four or more

satellites will be tracked by the UE in the presence of jamming.

4. **Maintains code and carrier phase precision.** For high accuracy applications, such as Joint Precision Approach Landing System (JPALS), it is essential that the code and carrier phase precision be maintained. The phase shifting applied by the analog null-steering electronics can degrade the measurement accuracy when jammers are detected. With digital beam-steering, the code and carrier measurement accuracy is maintained.

HIGH GAIN ADVANCED GPS RECEIVER

NAVSYS' High-gain Advanced GPS Receiver (HAGR)[1] was used to collect GPS measurements to observe the digital beam-steering performance in the presence of jamming. The HAGR components are illustrated in Figure 1. With the current generation analog CRPA antenna electronics in use by the DoD, a single composite RF signal is generated from the combined antenna inputs, adapted to minimize any detected jammer signals. With the HAGR digital beam-steering implementation, each antenna RF input is converted to a digital signal using a Digital Front-End (DFE). In the current HAGR configuration, up to 16 antenna elements L1 and L2 can be supported. The 16-element phased array used to support the beam-steering tests is shown in Figure 2. Each DFE board in the HAGR can convert signals from four antenna elements (see Figure 3).

The digital signals from the set of the antenna inputs are then provided to the HAGR digital signal processing cards. Each card can handle the processing for six GPS satellites, L1 C/A and L1 and L2 P(Y) when operating in the keyed mode. The digital signal processing is performed in firmware, downloaded from the host computer. Since the digital spatial processing is unique for each satellite channel, the weights can be optimized for the particular satellites being tracked. The digital architecture allows the weights to be computed in the HAGR software and then downloaded to be applied pre-correlation to create a digital adaptive antenna pattern to optimize the signal tracking performance.

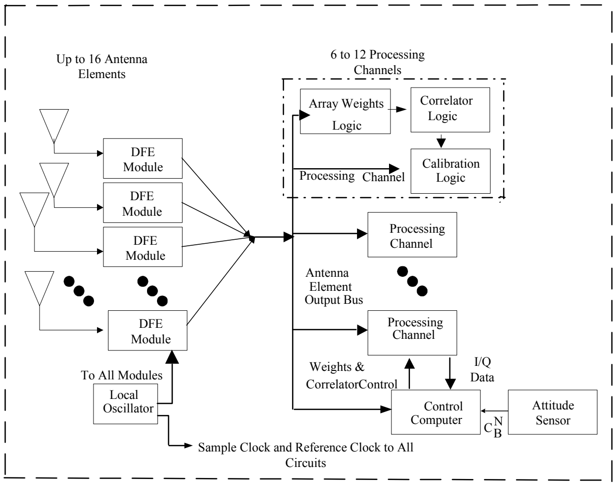

Figure 1 P(Y) HAGR System Block Diagram

Figure 2 Sixteen Element HAGR Antenna Array

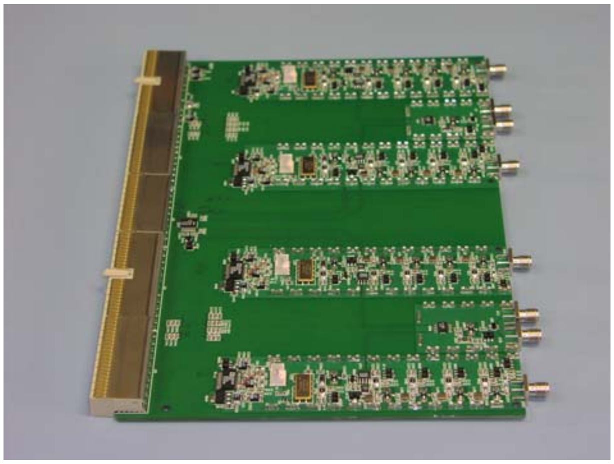

Figure 3 Digital Front End (DFE) Board

DIGITAL BEAM-STEERING

The digital signal from each of the HAGR antenna elements can be described by the following equation.

Equation 1

$$y_k(t) = \sum_{i=1}^{Ns} s_i(\underline{x}_k,t) + n_k(t) + \sum_{k=1}^{Nj} j_j(\underline{x}_k,t)$$

where $s_i(\underline{x}_k,t)$ is the ith GPS satellite signal received at the kth antenna element

$n_k(t)$ is the noise introduced by the kth DFE

$j_j(\underline{x}_l,t)$ is the filtered jth jammer signal received at the kth antenna element

The GPS satellite signal at each antenna element ($\underline{x}_k$) can be calculated from the following equation.

Equation 2

$$s_i(\underline{x}_k,t) = s_i(0,t)\exp\{-i\frac{2\pi}{\lambda}\underline{1}_i^T\,\underline{x}_k) = s_i(0,t)e_{sik}$$

where $s_i(0,t)$ is the satellite signal at the array center and

$\underline{1}_i$ is the line-of-sight to that satellite

e_{sik} are the elements of a vector of phase angle offsets for satellite i to each element k

The combined digital array signal, z(t), is generated from summing the weighted individual filtered DFE signals. This can be expressed as the following equation.

Equation 3

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

With beam-steering, the optimal weights are selected to maximize the signal/noise ratio to the particular satellite being tracked. These are computed from the satellite phase angle offsets as shown in the following equation.

Equation 4

$$\underline{w}_{BS} = \begin{bmatrix} \exp\{-i\frac{2\pi}{\lambda}\underline{1}_i^T\,\underline{x}_1) \\ . \\ \exp\{-i\frac{2\pi}{\lambda}\underline{1}_i^T\,\underline{x}_M) \end{bmatrix} = \underline{e}_s$$

The HAGR digital signal processing implementation also allows the beam-steering weights to be adapted in software based on the detected jammer signal power to further minimize the Jammer/Signal power after the weights are applied. The cross-correlation matrix, R, can be used to observe the jammer signal power. This is computed from the raw signal digital outputs as shown in the following equation.

Equation 5

$$R = R_J = E[\underline{y}\,\underline{y}^T] = R_S + R_N + R_J$$

The signal-to-jammer gain can be computed based on the following equation for a particular satellite signal[2].

Equation 6

$$S_i/J = \frac{\underline{w}'R_{si}\underline{w}/tr[R_s]}{\underline{w}'R_J\underline{w}/tr[R_J]} \cong \frac{\underline{w}'R_{si}\underline{w}/tr[R_s]}{\underline{w}'R\underline{w}/tr[R]}$$

Since the satellite line-of-sight is known, the numerator of this expression can be calculated.

Equation 7

$$R_{Si}/tr[R_{Si}] = A_i^2\,\underline{e}_{Si}\underline{e}_{Si}'/MA_i^2 = \underline{e}_{Si}\underline{e}_{Si}'/M$$

$$S_i/J = \frac{\underline{w}'\,\underline{e}_{Si}\underline{e}_{Si}'\,\underline{w}/M}{\underline{w}'R_J\underline{w}/tr[R_J]}$$

where M is the number of antenna elements.

GPS JAMMER TESTS AND DATA COLLECTION

Jammer testing, to evaluate the digital beam-forming anti-jam performance, was conducted at the Army's Electronic Proving Ground (EPG) at Ft. Huachuca, Arizona. Live jamming tests were performed using a 10 MHz wide noise jammer centered at L1. A single jammer was used which was located in a mountain canyon roughly NW of the test location (see Figure 8 and Figure 4).

During the tests, GPS tracking loop measurements were recorded from a 16-element HAGR antenna array (see Figure 5). The HAGR was configured to track using the L1 C/A code signals (no P(Y)), using the conventional beam-forming weights derived using mode of operation. The test results collected were compared with a SOLGR GPS receiver at the same location, which was used as a reference throughout the jammer tests.

During the jammer tests, data was also collected using NAVSYS' Digital Storage Receiver (DSR). The DSR can be configured to record data from up to 16 independent antenna elements (see Figure 6). This allows logging of real-world data from a digital phased array, such as the 16-element HAGR array shown in Figure 2. The data recorded from the multiple antenna elements can then be played back as a data library into our Advanced Hybrid GPS Simulator (AGHS)[3] to evaluate the performance of alternative digital spatial signal processing algorithms post-test. During the jammer trials, the DFE data was recorded from four of the antenna elements and post-processed to evaluate the HAGR digital spatial processing effectiveness in different modes of operation.

Figure 4 Electronic Proving Grounds Jammer Test Site

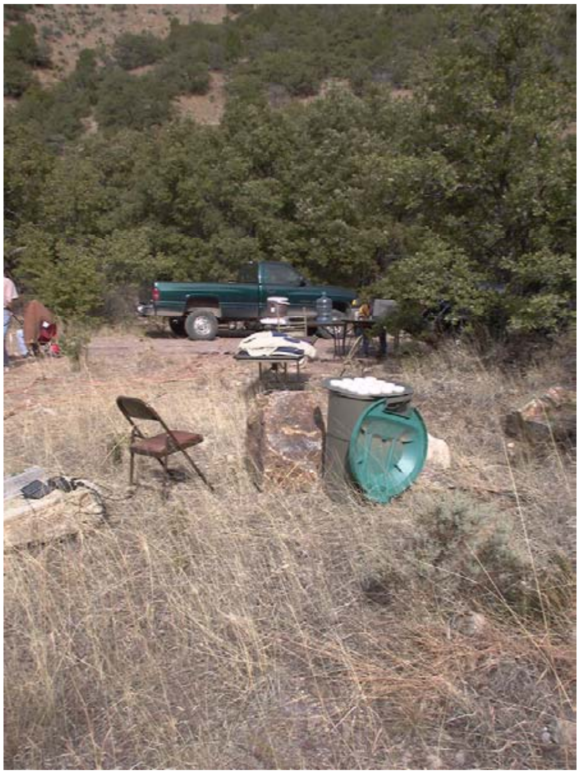

Figure 5 HAGR at test site

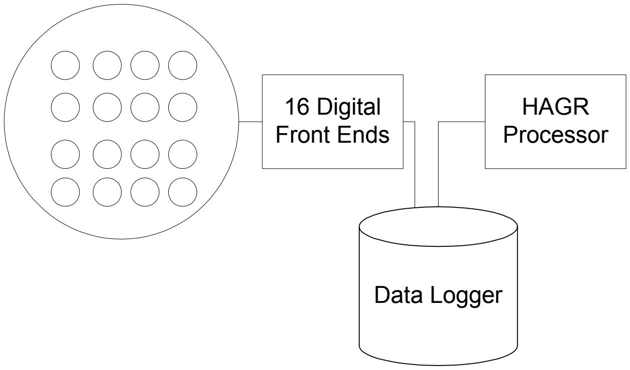

Figure 6 Sixteen Element Digital Storage Receiver

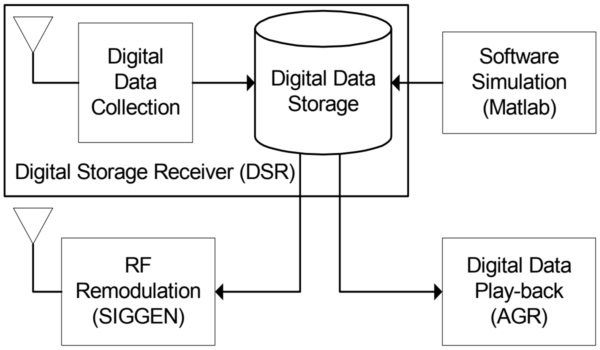

Figure 7 Advanced GPS Hybrid Simulator Architecture

REAL-TIME BEAM-STEERING TEST RESULTS

Figure 8 is a skyplot of the satellite positions during the test, with the relative jammer position indicated by the arrow. The test site was located in a mountain canyon so many of the lower elevation satellites were masked from view. Figure 9 to Figure 20 show the HAGR C/N0 (green), the SOLGR C/N0 (blue), and the jammer to signal ratio reported by the SOLGR (red). During the tests the SOLGR was reporting 40 dB to 45 dB J/S values on L1 P(Y) code. The highest jamming level occurred in the first 10 minutes after the jamming started at 1:00 pm local time. The gain of the digital beams created from the HAGR antenna array improves the performance of the reference receiver. The directivity of the digital beams also provides additional anti-jam capability when the satellites are not in the line of site of the jammer (SV 2 and SV 7). SV 24 was only in view of the receivers at the end of the test sequence.

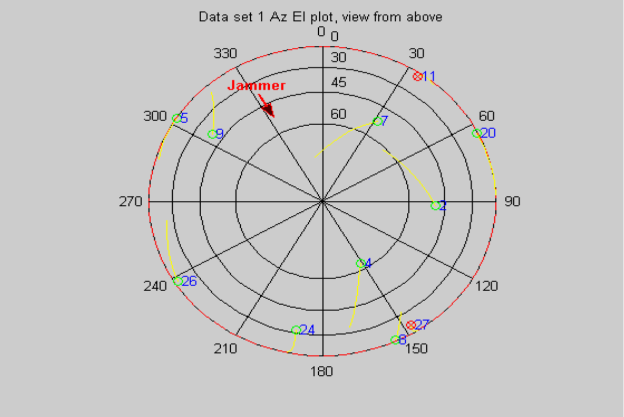

Figure 8 Satellite positions during jamming tests

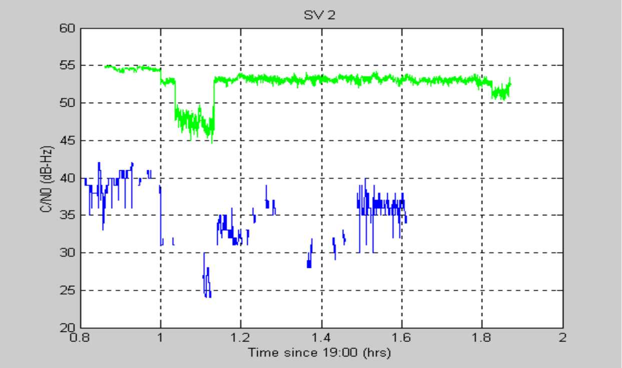

Figure 9 SV 2 C/N0

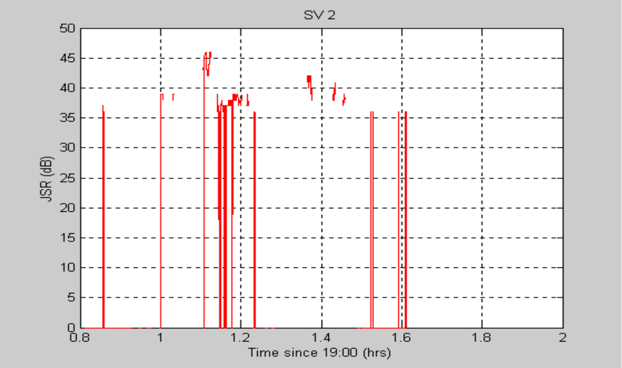

Figure 10 SV 2 SOLGR L1 P(Y) JSR

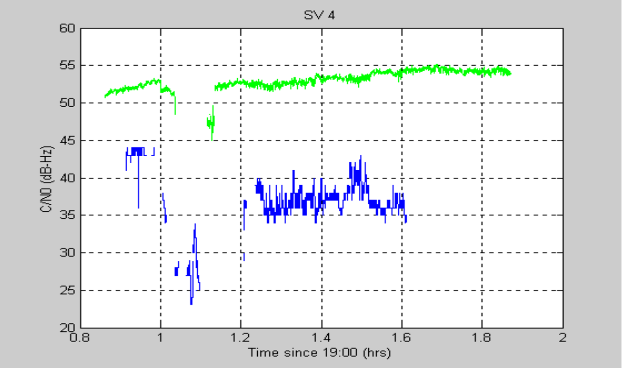

Figure 11 SV 4 C/N0

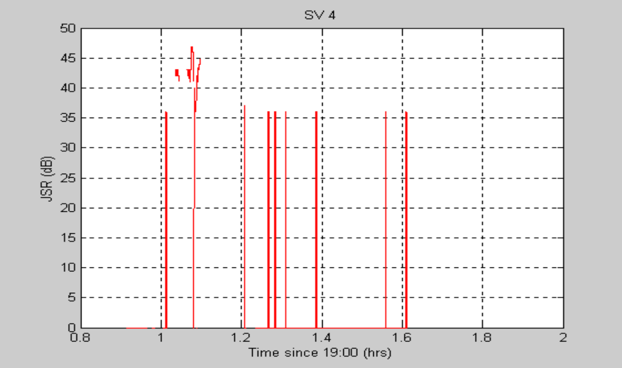

Figure 12 SV 4 SOLGR L1 P(Y) JSR

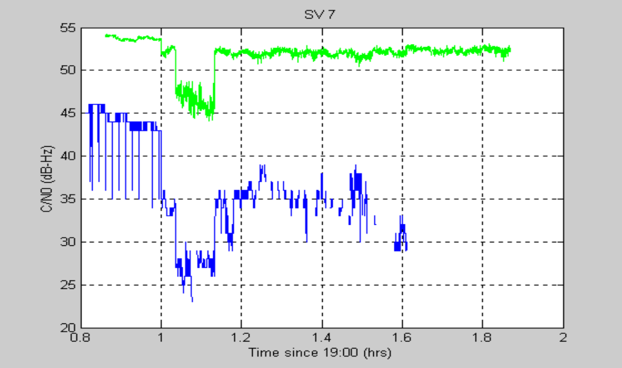

Figure 13 SV 7 C/N0

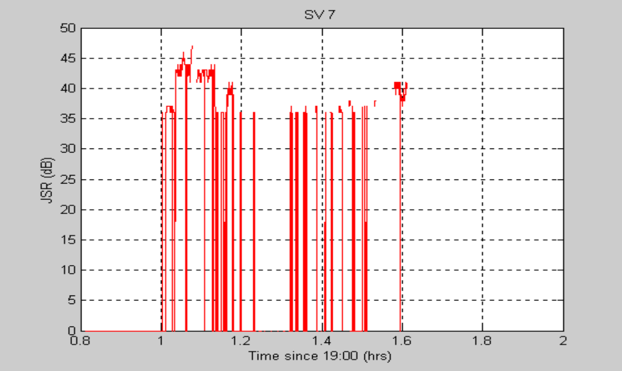

Figure 14 SV 7 SOLGR L1 P(Y) JSR

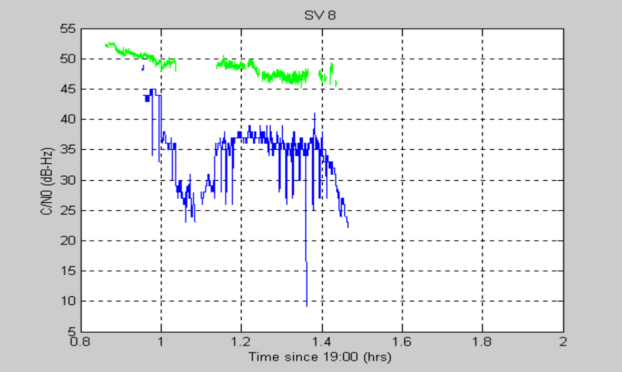

Figure 15 SV 8 C/N0

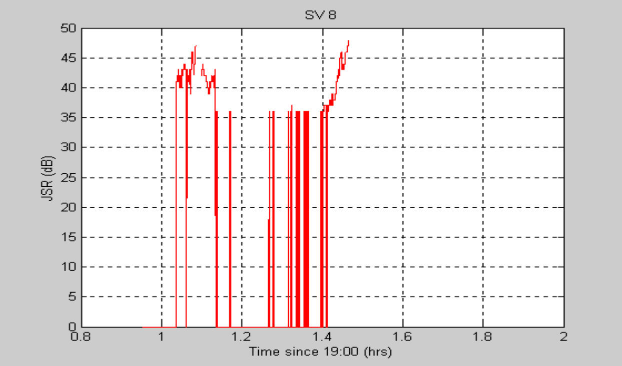

Figure 16 SV 8 SOLGR L1 P(Y) JSR

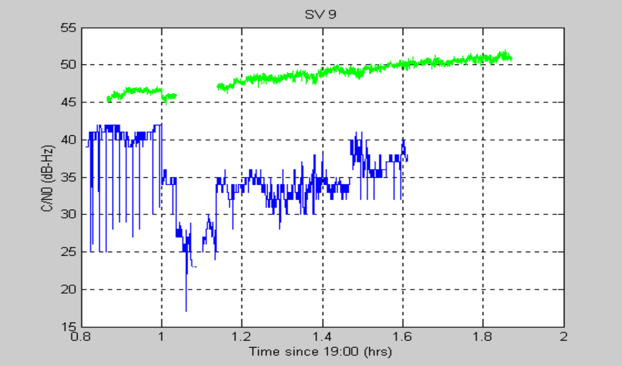

Figure 17 SV 9 C/N0

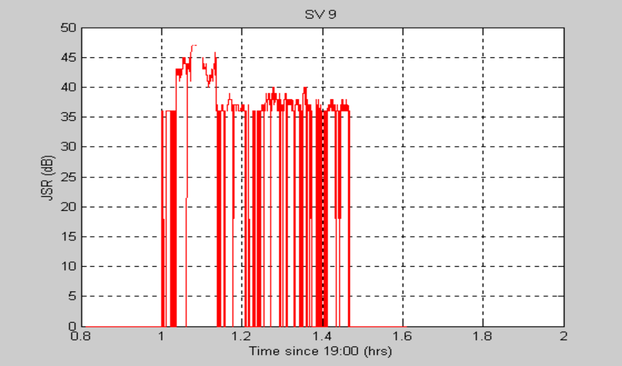

Figure 18 SV 9 SOLGR L1 P(Y) JSR

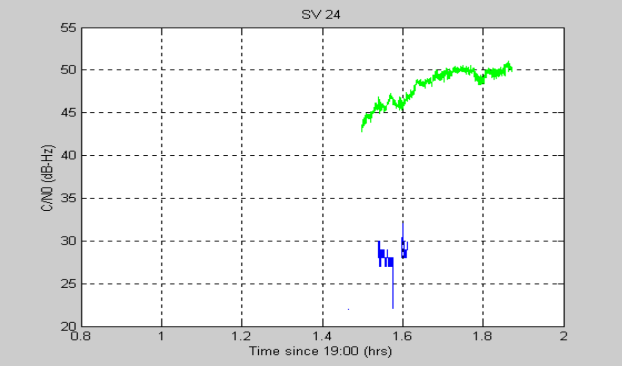

Figure 19 SV 24 C/N0

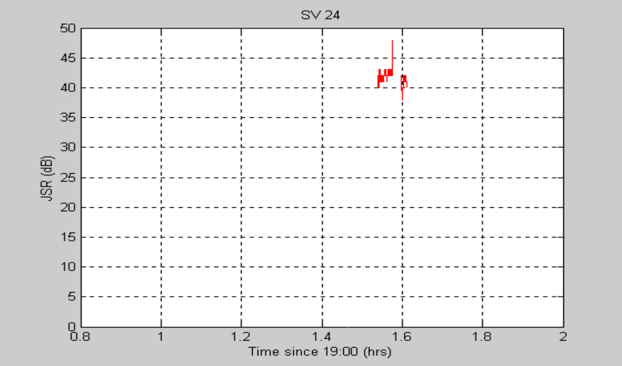

Figure 20 SV 24 SOLGR L1 P(Y) JSR

POST-TEST JAMMING ANALYSIS

The recorded DSR data from four of the antenna array elements was played back post-test to evaluate the digital beam-steering performance and to analyze the detected jammer signal power. A data set recorded on February 6 was analyzed. This was collected immediately following the HAGR beam-forming test data shown in Figure 21. During this testing, the SOLGR was not tracking any satellites.

The data was post-processed as a 4-element phased array. This provides 6 dB of gain over the individual element data which was also analyzed (see Figure 22). The digital beam-forming antenna gain patterns for each of the satellite observations are shown in Figure 24 to Figure 33. The detected jammer power was also computed from the cross-correlation matrix (R) and is shown in Figure 23. The power in the top left corner of Figure 23 is from the jammer. The power in the bottom left corner is a secondary return that may have been caused by a slight tilt in the antenna array or a reflection off a nearby object. The post-correlation detected satellite power was also computed and is shown in Figure 34 to Figure 37. For the satellites 2 and 24, which were at too low a power level to be tracked, the power shown is only from the jammer. For the remaining satellites, the detected satellite signal power is shown post-correlation.

In Figure 38 and Figure 39 the estimated J/S margin from the digital beam-steering gain is shown, for a 4-element and a 16-element beam-steering array calculated based on the satellite locations over 24 hours and the estimated jammer location from Figure 23. The worst case J/S value over a set of N satellites was computed. To navigate, at least four GPS satellites (N=4) are required. The worst case J/S level over the 24 hour period is cataloged in Table 1. With a 4-element array, the phased array always provided a jammer attenuation of 12 dB on at least one satellite. On average, the array provided 13 dB of attenuation on at least four satellites. For a 16 element, the jammer attenuation for one satellite was always at least 28 dB. On average the 16-element array provided at least 27 dB of attenuation on four satellites and the worst case attenuation over 24 hours for four satellites was 13 dB.

Table 1 J/S Attenuation (dB) Satellites over 24 hrs

#SVs	1	2	3	4	5	6
4-element average	-35	-23	-17	-13	-10	-8
4-element worst case	-12	-9	-5	-3	-3	-1
16-element average	-47	-37	-31	-27	-23	-19
16-element worst case	-28	-24	-20	-13	-12	-4

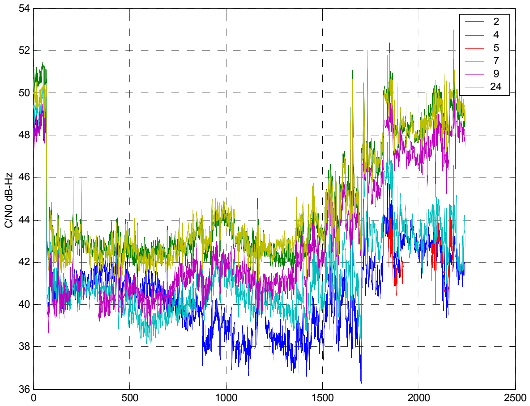

Figure 21 HAGR Observed Beam-steering C/N0 (Feb 6th)

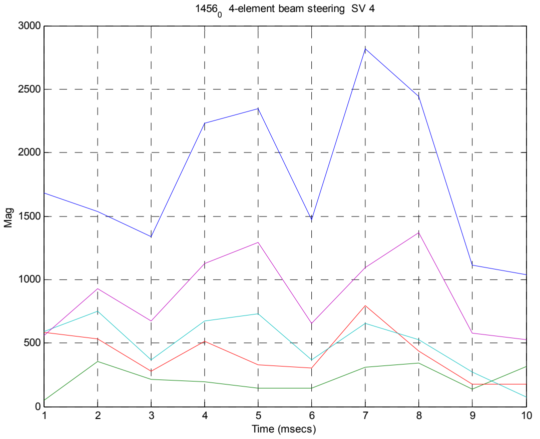

Figure 22 Individual Element and Composite Signal Power

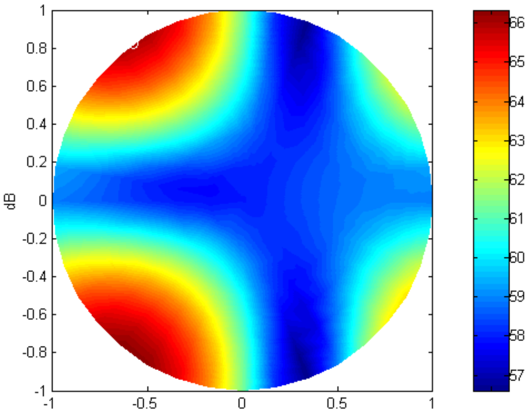

Figure 23 Detected Jammer Power

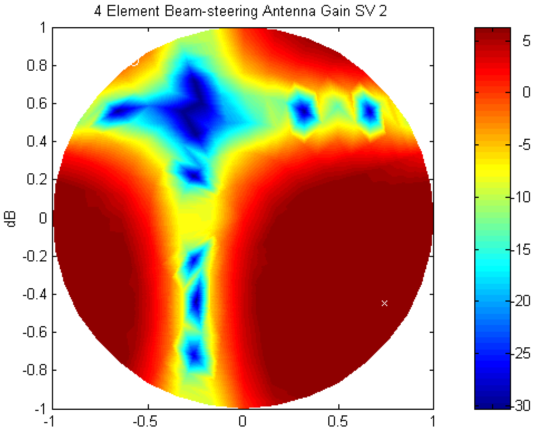

Figure 24 4-Element Pattern - SV 2

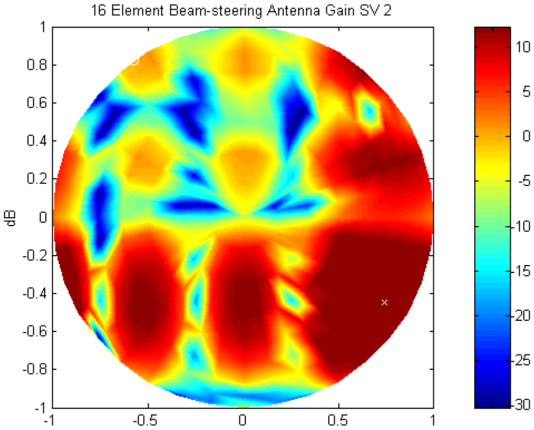

Figure 25 16-Element Pattern - SV 2

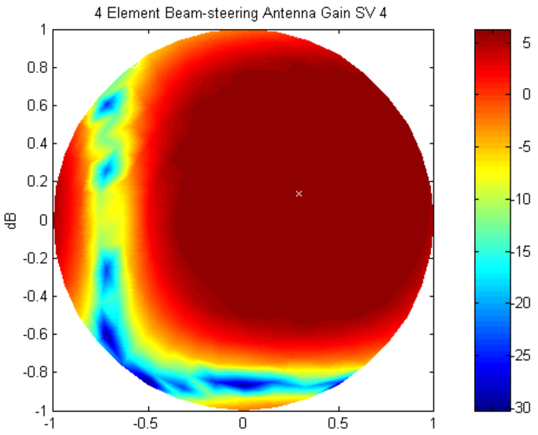

Figure 26 4-Element Pattern - SV 4

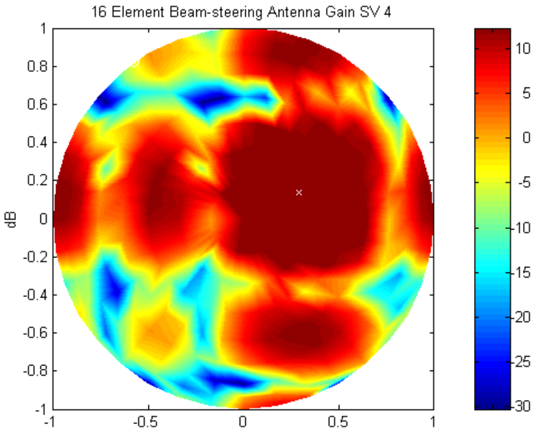

Figure 27 16-Element Pattern - SV 4

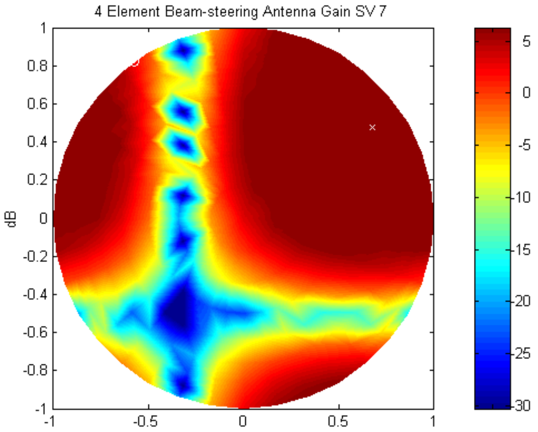

Figure 28 4-Element Pattern - SV 7

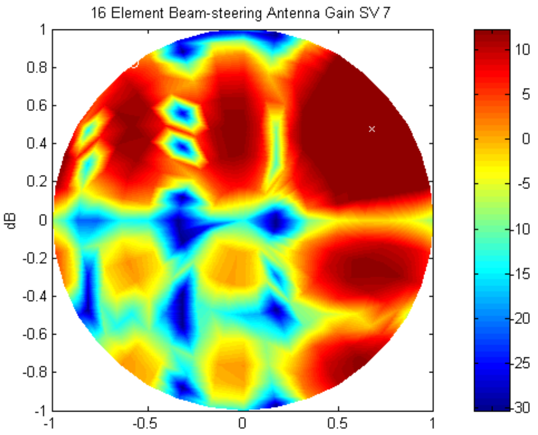

Figure 29 16-Element Pattern - SV 7

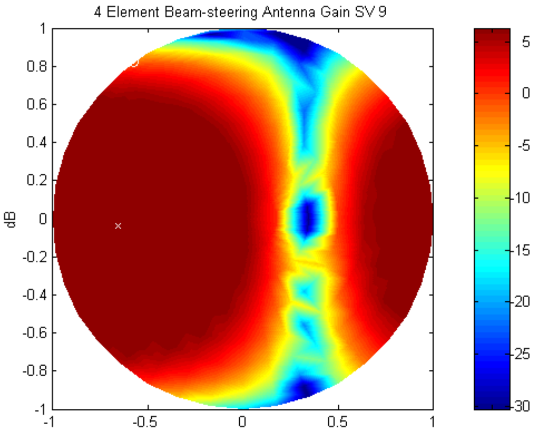

Figure 30 4-Element Pattern - SV 9

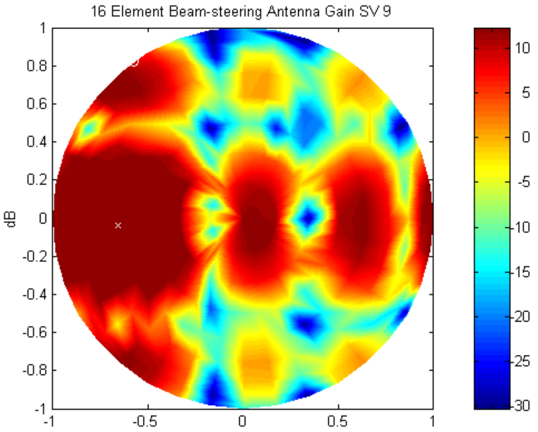

Figure 31 16-Element Pattern - SV 9

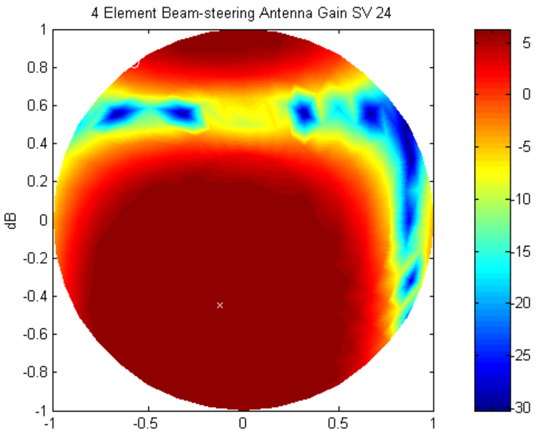

Figure 32 4-Element Pattern - SV 24

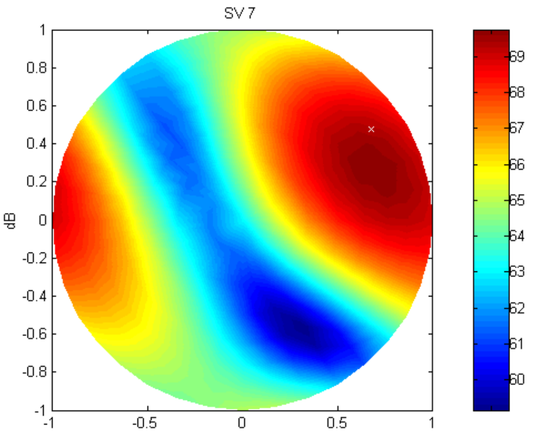

Figure 35 Post-Correlation Power - SV 7

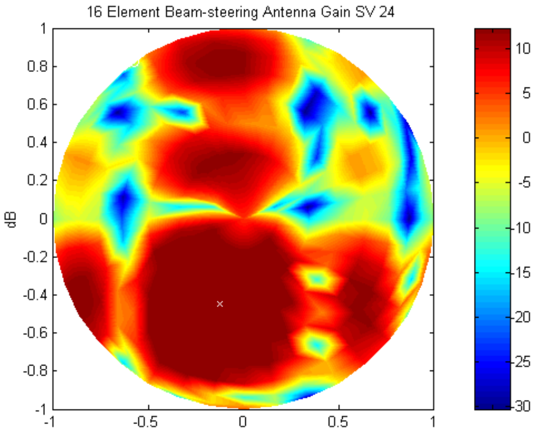

Figure 33 16-Element Pattern - SV 24

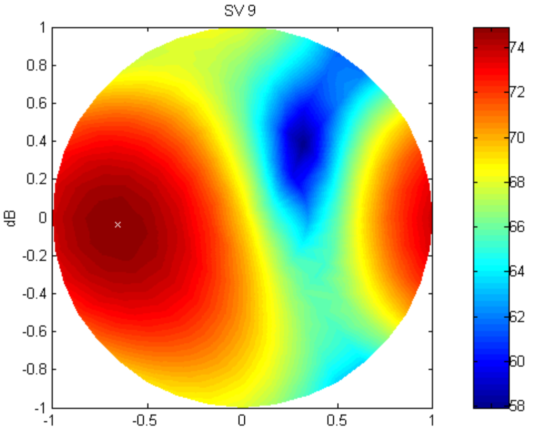

Figure 36 Post-Correlation Power - SV 9

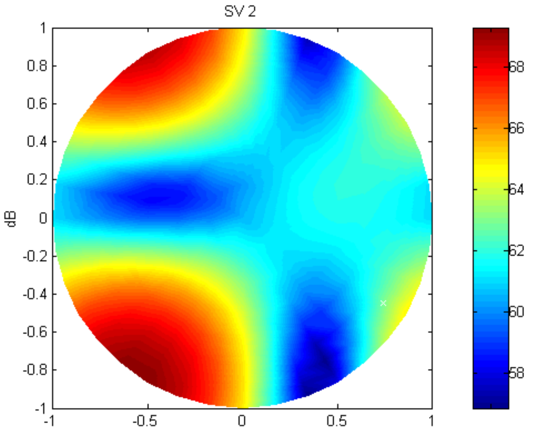

Figure 34 Post-Correlation Power - SV 2

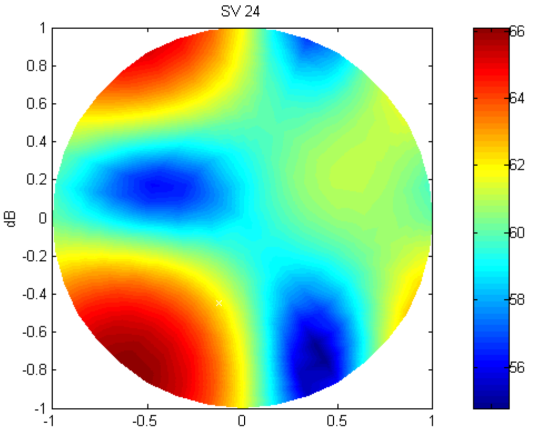

Figure 37 Post-Correlation Power - SV 24

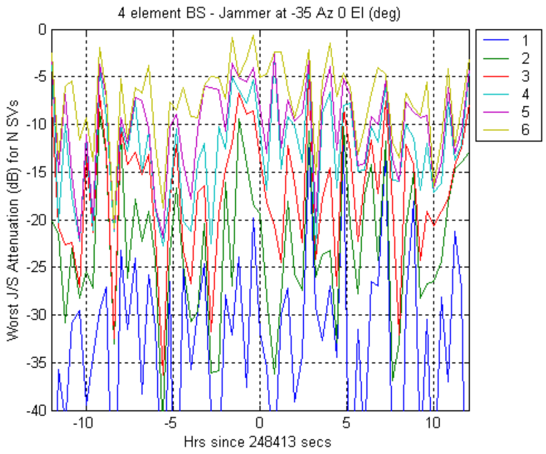

Figure 38 Four-Element Beam-Steering worst case J/S

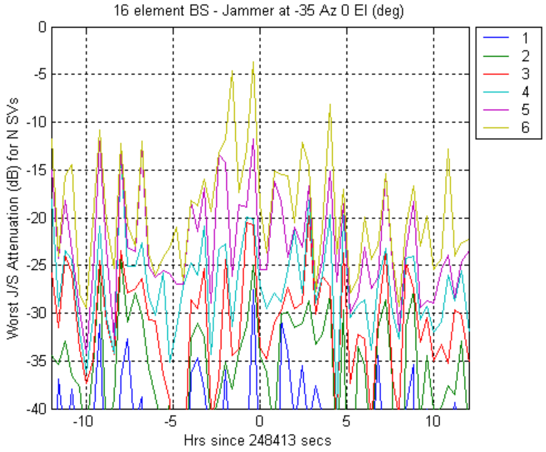

Figure 39 Sixteen element Beam-Steering worst case J/S

CONCLUSION

The test data collected demonstrated the ability of the HAGR digital beam-steering GPS receiver to operate in the presence of a jammer and provide improved J/S margin over a GPS receiver using a single antenna element. The test data recorded was also used to demonstrate how the digital antenna array could detect the jammer spatial profile. This data can be used to create an adaptive beam/null-steering digital array pattern that would further improve the A/J performance. Currently an adaptive digital beam/null-steering HAGR receiver is being developed by NAVSYS that will be flight-tested under contract to the Air Force next year.

ACKNOWLEDGMENTS

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