Test Results from a Digital P(Y) Code Beamsteering Receiver for Multipath Minimization

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BIOGRAPHY

Alison Brown is the President and CEO of NAVSYS Corporation. 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 University. In 1986, she founded NAVSYS Corporation. Currently she is a member of the GPS-III Independent Review Team and Scientific Advisory Board for the USAF and serves on the GPS World editorial advisory board.

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ABSTRACT

When using a digital phased array, it is possible to leverage the adaptive spatial signal processing of the array to minimize the effect of multipath signals arriving from near-by reflective surfaces. NAVSYS has developed a digital phased array that can be used for adaptive spatial processing, the High-gain Advanced GPS Receiver (HAGR). Previous testing using the L1 C/A code have demonstrated the performance improvements possible using spatial processing to increase the accuracy of the code and carrier observations and also to minimize the effect of multipath errors. In this paper, we present test results taken from a P(Y) digital beam-steering GPS receiver, the P(Y) HAGR that demonstrates the performance improvements possible for military GPS User Equipment (UE) when using spatial processing to increase accuracy and also to minimize the effect of multipath from near-by reflective surfaces.

INTRODUCTION

In order to meet the accuracy requirements for precision approach and landing for the Joint Precision Approach and Landing System (JPALS) and Ship-board Relative GPS (SRGPS) programs, specially designed military GPS User Equipment (UE) is needed. Precision approach and landing operations rely on obtaining precise pseudo-range and carrier phase data in a challenging tactical environment. The GPS UE must be able to provide accurate measurements in the presence of GPS jamming. The GPS UE must also be able to provide accurate measurements in the presence of close-in multipath sources, for example in a ship-board landing environment.

To improve the GPS anti-jamming (A/J) performance, current generation GPS UE can be integrated with Controlled Reception Pattern Antennas (CRPAs) that provide null-steering to attenuate the effect of a GPS jammer. The GPS A/J performance can be improved through the use of both beam-forming and null-steering to provide additional jammer protection. The use of digital beamsteering also has advantages for increasing the precision of the GPS observations and reducing the effect of multipath errors.

In this paper, test results are included showing the reduction of multipath errors and measurement noise when using a P(Y) code digital beam-steering receiver. The results collected are compared with a C/A code digital beam-steering receiver and also two Novatel GPS receivers using a conventional large ground plane and choke ring antenna respectively.

DIGITAL BEAMFORMING GPS RECEIVER (HAGR)

NAVSYS has produced a 6-channel L1 P(Y) code version of our commercial HAGR digital beam-steering GPS receiver[1]. The re-programmable digital spatial processing capability inherent in the HAGR allows GPS signals to be combined from as many as 16 antennas and create a multi-beam antenna pattern to apply gain to up to six GPS satellites simultaneously. A 12-channel L1/L2 version of this receiver is also in development and flight tests will be conducted later this year to measure the digital beam/null-steering performance in the presence of GPS jamming.

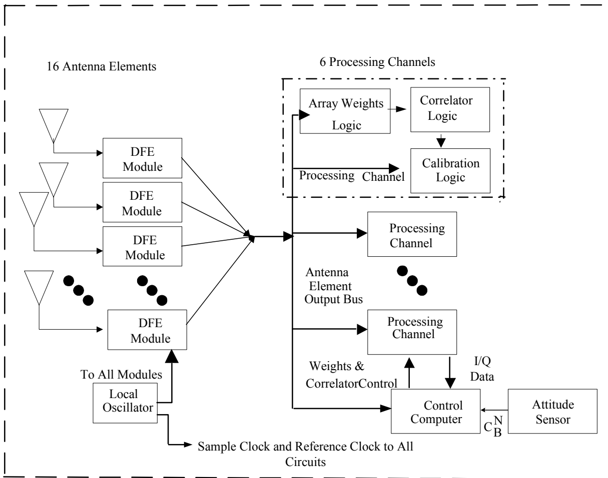

Figure 1 P(Y) HAGR System Block Diagram

The P(Y) HAGR system architecture is shown in Figure 1. The signal from each antenna element is digitized using a Digital Front-End (DFE). The bank of digital signals is then processed by the HAGR digital-beam-steering card to create the composite digital beam-steered signal input for each of the receiver channels. The weights for each channel are dynamically downloaded through software control. The re-programmable digital spatial processing approach adopted by the HAGR also enables adaptive beam and null-forming to be applied which can be used to reduce the effect of multipath errors, improving the GPS performance for high accuracy applications [2,3,4,5]. The correlation card includes a 6-channel Precise Positioning Service Security Module (PPS-SM). A development program is starting later in 2001 to convert this design to be compatible with the Joint Program Office's SAASM security guidelines.

The 16-element antenna array uses conventional L/L2 antenna elements laid out in the 4x4 grid as shown in Figure 2. This produces the beam pattern shown in Figure 3, which provides up to 12 dB gain in the direction of the GPS satellites and will attenuate signals received from other directions.

Figure 2 Sixteen Element L1/L2 Antenna Array

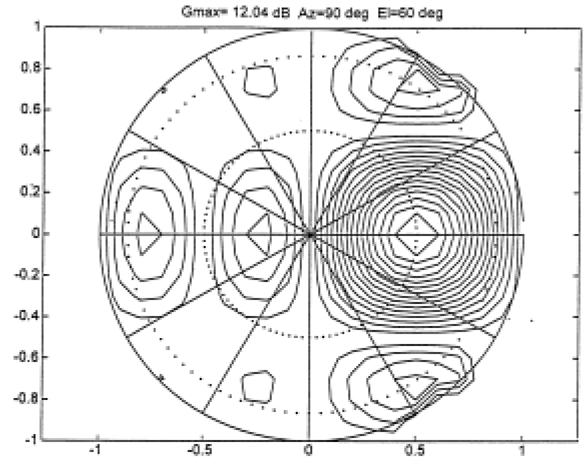

Figure 3 Sixteen Element Digital Beam Forming Gain Pattern

MULTIPATH ERRORS

Multipath errors are caused by the receiver tracking a composite of the direct GPS signals and reflected GPS signals from nearby objects, such as the ground or nearby buildings, as illustrated in Figure 4.

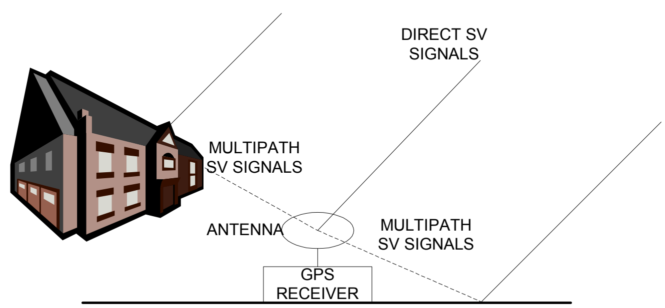

Figure 4 GPS Multipath Errors

Multipath errors can be observed by their effect on the measured signal/noise ratio and the code and carrier observations, as are described below[6].

Signal/Noise Ratio When multipath is present the signal/noise ratio magnitude varies due to the constructive and destructive interference effect. The peak-to-peak variation is an indication of the presence of multipath signals, as shown by the following equation where A is the amplitude of the direct signal, A_M is the amplitude of the reflected multipath signal, θ is the carrier phase offset for the direct signal and θ_M is the carrier phase offset for the multipath signal.

$$\widetilde{A} = \left|A + A_M e^{\Delta\theta}\right| - A$$

$$\widetilde{\theta} = \angle(A + A_M e^{\Delta\theta})$$

$$\Delta\theta = \theta - \theta_M$$

The magnitude of the multipath power can be estimated from the peak-to-peak cyclic observed variation in signal/noise ratio by using the relationship plotted in Figure 5.

Carrier-phase Error The multipath carrier phase error ($\widetilde{\theta}$) is related to the received multipath power level from the above equation. This results in a cyclic carrier phase error as the multipath signals change from constructive to destructive interference that has the peak-to-peak carrier phase error shown in Figure 6.

Pseudo-range Error For close-in multipath, where the additive delay τ_M is small compared with the code chip length, the Dynamic Link Library (DLL) will converge to a value between the correct pseudo-range and the multipath pseudo-range resulting in an error that can be approximated by the following equation.

$$\widetilde{\tau} = \frac{A_M^2}{A^2}\tau_M$$

The pseudo-range error that could be expected for a multipath delay of 15 m is plotted in Figure 7.

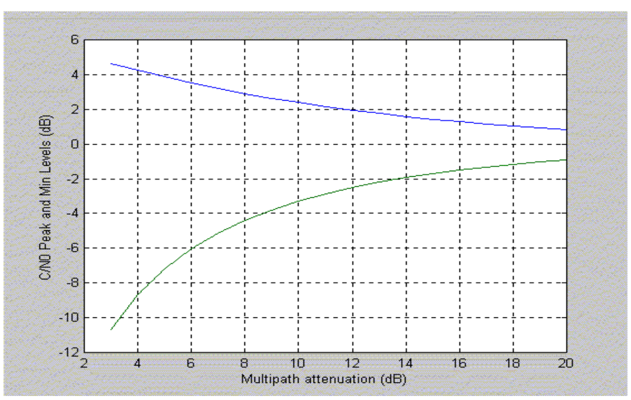

Figure 5 Multipath Amplitude Effect

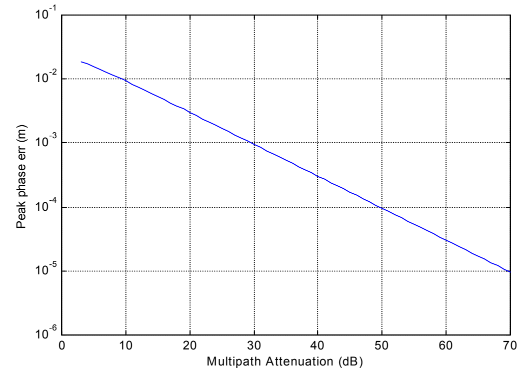

Figure 6 Multipath Peak Phase error vs. Attenuation (dB)

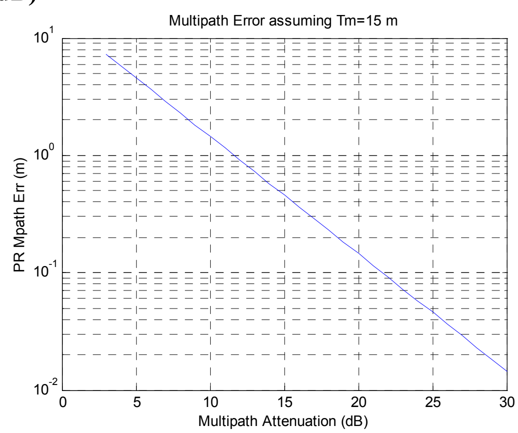

Figure 7 Peak Multipath Pseudo-Range Error

P(Y) HAGR COMPARISON TESTING

The performance of the P(Y) HAGR was compared with a C/A code HAGR and also from data collected from two Novatel GPS receivers operating with the multipath rejection antennas shown in Figure 8 and Figure 9. These antennas were installed on the roof of NAVSYS' facility and raw measurements were recorded over a 12-hour test window.

Figure 8 Antenna # 1 (provided by NGS)

Figure 9 Choke Ring Antenna (provided by NGS)

The signal/noise ratio from each of the receivers under test for four of the satellites tracking is shown in Figure 16 through Figure 19. When these figures are zoomed in the cyclic variation caused by the multipath constructive and destructive interference is clear (see Figure 10). The highest signal/noise ratio is observed from the C/A code measurements of the HAGR. The P(Y) code carrier-to-noise ratio (C/N0) is approximately 3 dB below this value due to the lower power of the P(Y) code signals. From Figure 10, the HAGR is applying around 11 dB of gain towards the satellite.

The peak-to-peak variation in signal/noise was computed and used to estimate the level of multipath-signal (M/S) power attenuation which is plotted in Figure 20 through Figure 23. The mean multipath-signal power levels for all of the satellites tracked are shown in Figure 11. Both the C/A and P(Y) HAGR show significant attenuation of the average multipath power levels due to the beam-steering antenna pattern which gives around 10-11 dB additional multipath rejection. This will result in significantly lower carrier phase errors on the HAGR than using the conventional antennas. With an average M/S level of –6 dB the carrier phase peak multipath would be around 14 mm. With an average M/S level of –16 dB the carrier phase peak multipath error will be less than 5 mm (see Figure 6).

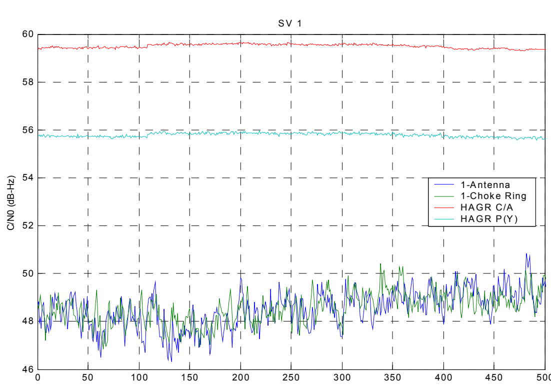

Figure 10 Signal/Noise Variation - SV 1

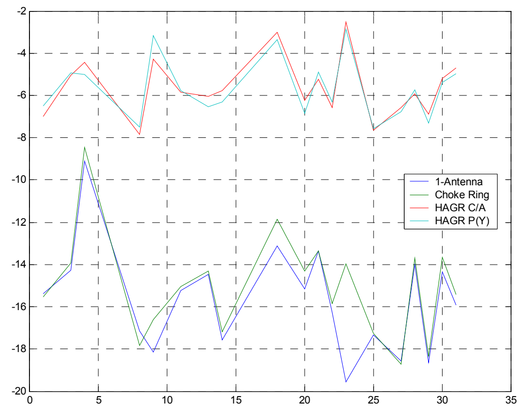

Figure 11 Mean M-S Level versus SVID

The pseudo-range + carrier phase sum cancels out the effect of the range to the satellite and observed the following parameters.

$$PR + \lambda\theta = n_{PR} + n_{cph} + \lambda\theta_o + \tau_M + 2\Delta_{Iono} \quad \text{(m)}$$

where

n_{PR} is the pseudo-range measurement noise

n_{cph} is the carrier phase noise (m)

τ_M is the multipath PR error (m)

Δ_{Iono} is the change in the ionosphere from start (m)

θ_0 is the starting carrier phase offset

The PR+CPH is plotted in Figure 12 for each of the receiver data sets. The short term (<100 sec) white receiver noise was removed by passing the PR+CPH observation through a linear filter. The drift caused by the ionosphere on each observation was removed using a polynomial estimator. The remaining cyclic error is an estimate of the multipath pseudo-range errors. The peak-to-peak cyclic PR variation for each of the receiver data sets was calculated and is plotted in Figure 24 to Figure 27. The maximum PR errors observed for each satellite attributed to the multipath errors are listed in Table 1 for each of the receiver data sets.

The RMS white noise on the pseudo-range observations was computed by differencing the PR+CPH measurement. This is shown in Figure 13 and Figure 14 for all of the satellites tracked for the C/A and P(Y) code observations. The observed PR RMS noise is shown in the bottom figure. The predicted PR noise, based on the observed C/N0 for each satellite, is also plotted (top figure). The observed PR noise shows good correspondence with the predicted values. In Figure 15, the PR RMS errors for the C/A code and P(Y) code HAGR observations are plotted as a function of the C/N0 observed. For C/N0 values above 52 dB-Hz, the P(Y) code HAGR provided pseudo-range accuracies of 5 cm (1-sigma) while for C/N0 values above 55 dB-Hz the C/A code observations were accurate to 15 cm. These values are for 1-Hz observations without any carrier smoothing applied. The mean observed RMS accuracies are summarized below in Table 1 with the average peak multipath PR errors observed.

Table 1 Mean PR Noise and M-path Peak Errors (m)

SVID	C/A HAGR RMS PR	C/A Mean Mpath PR	P(Y) HAGR RMS PR	P(Y) Mean Mpath PR
1	0.239	0.259	0.054	0.202
3	0.284	0.494	0.056	0.337
8	0.200	0.278	0.045	0.202
11	0.278	0.535	0.059	0.287
13	0.252	0.321	0.059	0.260
14	0.214	0.359	0.049	0.350
20	0.222	0.267	0.050	0.164
21	0.252	0.261	0.058	0.133
22	0.248	0.318	0.047	0.217
25	0.202	0.362	0.044	0.265
27	0.183	0.270	0.044	0.178
28	0.236	0.366	0.055	0.272
29	0.225	0.312	0.050	0.217
30	0.477	0.791	0.089	0.624
31	0.325	0.266	0.055	0.135

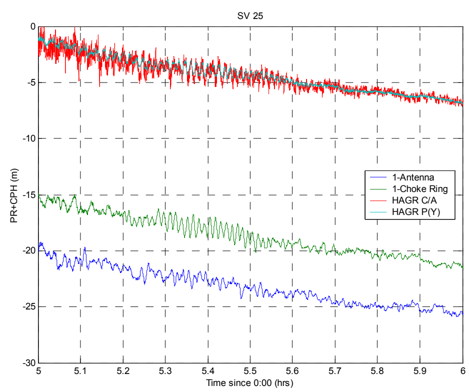

Figure 12 PR+CPH (m) - SV 25

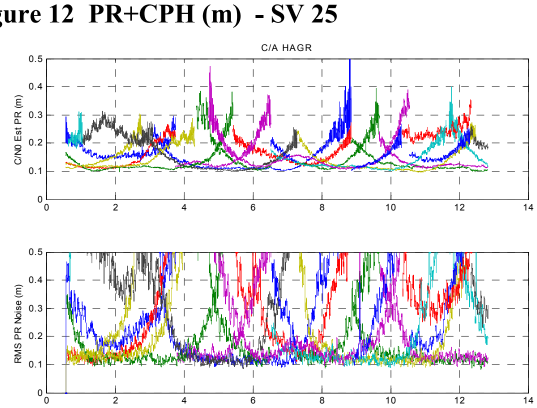

Figure 13 C/A HAGR RMS Pseudo-Range Noise (m)

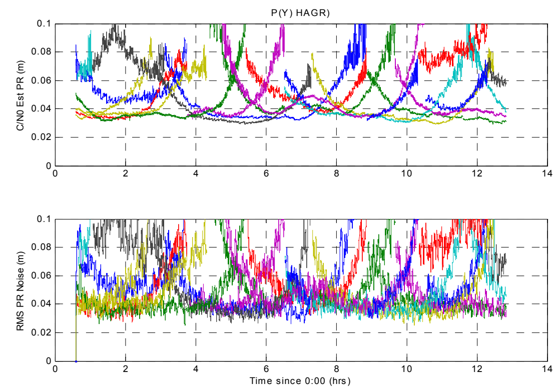

Figure 14 P(Y) HAGR RMS Pseudo-Range Noise (m)

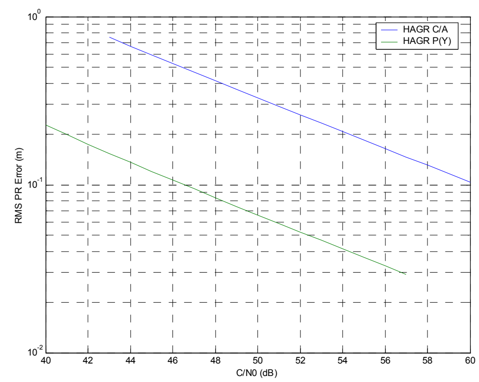

Figure 15 C/A and P(Y) HAGR RMS PR error versus C/N0

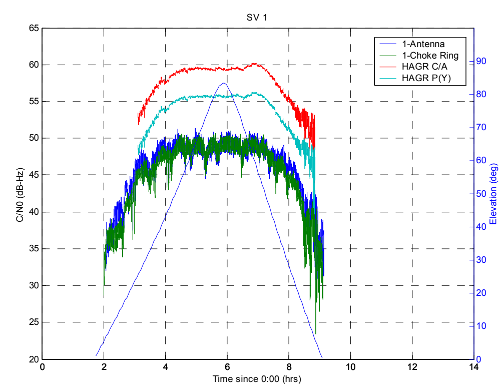

Figure 16 Signal/Noise Ratio - SV 1

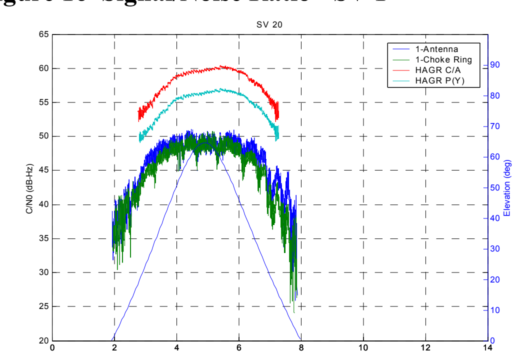

Figure 17 Signal/Noise Ratio SV 20

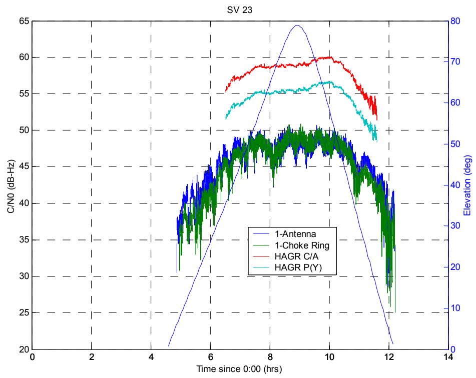

Figure 18 Signal/Noise Ratio SV 23

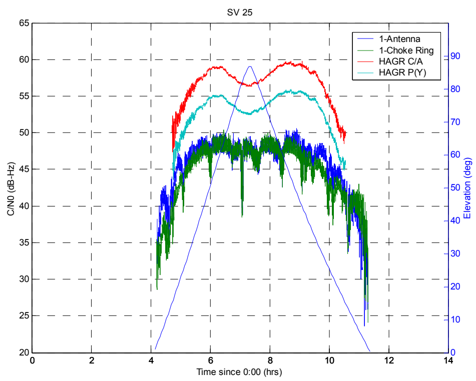

Figure 19 Signal/Noise ratio SV 25

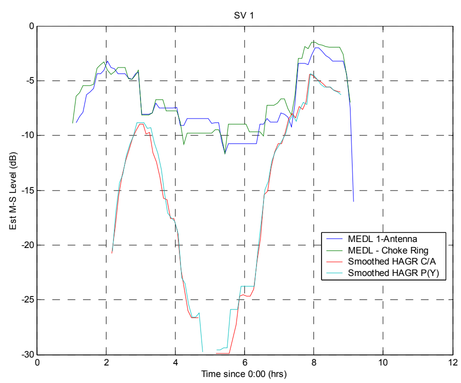

Figure 20 Multipath/Signal Estimated Power - SV 1

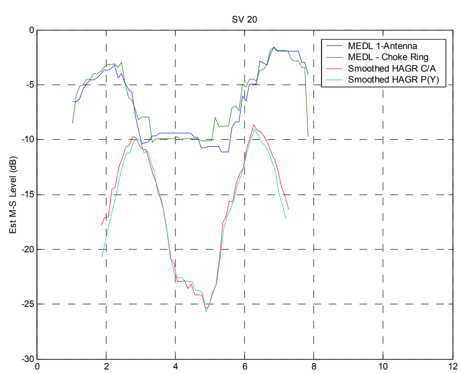

Figure 21 Multipath/Signal Estimated Power - SV 20

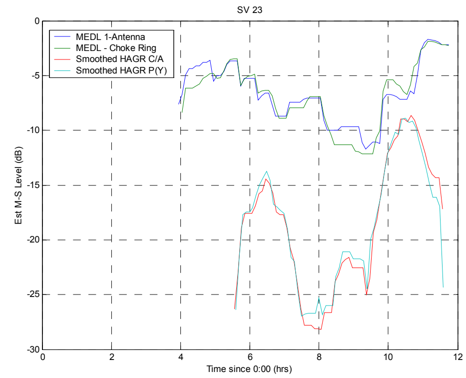

Figure 22 Multipath/Signal Estimated Power - SV 23

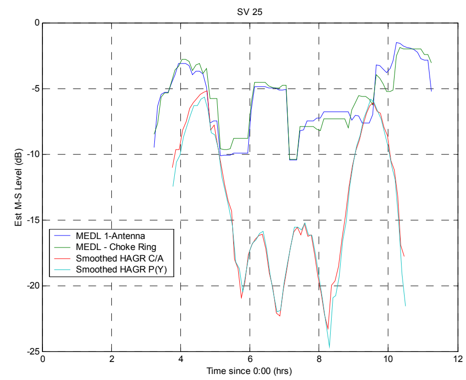

Figure 23 Multipath/Signal Estimated Power - SV 25

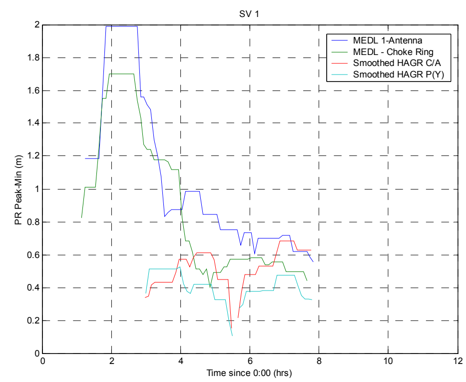

Figure 24 PR Peak-Min Variation- SV 1

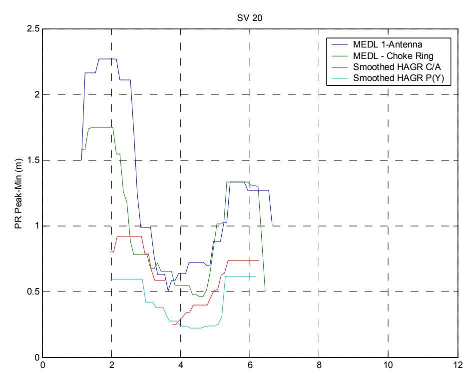

Figure 25 PR Peak-Min Variation - SV 20

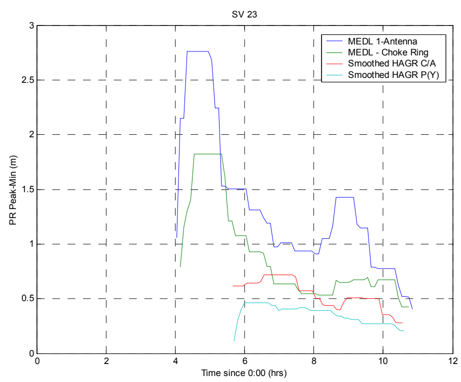

Figure 26 PR Peak-Min Variation - SV 23

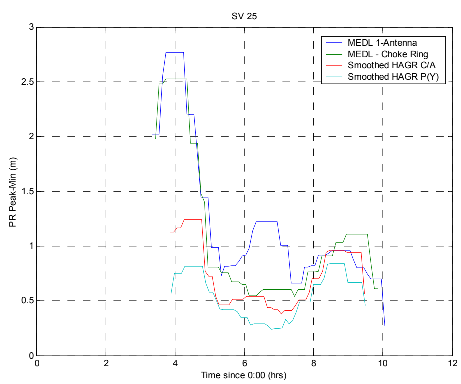

Figure 27 PR Peak-Min Variation - SV 25

CONCLUSION

The test results have demonstrated the following advantages of the P(Y) code digital beam-steering GPS receiver for high accuracy applications.

1) Low PR Observation Noise. The digital beam-steering increases the observed C/N0 by over 10 dB which results in extremely accurate P(Y) pseudo-range observations. The test results showed that the P(Y) HAGR provided pseudo-range measurements with an RMS error of less than 5 cm when the C/N0 was above 52 dB-Hz.
2) Reduced Multipath Errors. The additional gain of the beam-steering array reduced the multipath errors on the pseudo-range and carrier phase observations. The test results showed that the peak PR error from multipath was generally less than 0.3 m and the carrier-phase peak multipath error should be below 5 mm, based on the observed C/N0 power variations from multipath constructive and destructive interference.

The P(Y) code HAGR development activity is continuing and the following improvements will be available shortly. A 12 channel L1/L2 P(Y) HAGR is currently under-going test and evaluation. Digital spatial filtering to further attenuate the multipath errors is also planned to be added in the next year [5]. A SAASM compliant version of the P(Y) HAGR will start development this year under contract to the USAF. Flight-testing is also planned later this year of the HAGR performance in a jamming environment while operating in a digital beam/null-steering mode of operation.

ACKOWLEDGEMENTS

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