HIGH ACCURACY KINEMATIC GPS PERFORMANCE USING A DIGITAL BEAM-STEERING ARRAY

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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 for the USAF and serves on the GPS World editorial advisory board.

Jin Wang has been with NAVSYS Corp. as an Engineer since February 1999. He was a researcher in the Ohio State University Center for Mapping. He holds a Ph.D. in Precision Instrumentation and Control from Tsinghua University and MS in EE from Beijing Institute of Technology. His major area of interest include the kinematic positioning algorithm design, the integration of GPS with INS and other sensors for various applications on land and aviation with respect to navigation and gravity field recovery.

ABSTRACT

In this paper, the performance of a digital beam steering antenna array, developed by NAVSYS Corporation, is presented for high accuracy differential and kinematic GPS applications. The NAVSYS' High Gain Advanced GPS Receiver (HAGR). uses digital beam-steering to combine signals from an antenna array with up to sixteen elements and create a multi-beam antenna for up to eight GPS satellites simultaneously. This has the effect of applying up to 10 dB of additional antenna gain on the GPS satellite signals. The additional gain provided improves the accuracy of the pseudo-range and carrier-phase observations, and the directivity of the digital beam created from the antenna array also reduces multipath errors. In this paper test data taken from the HAGR using NAVSYS' kinematic GPS navigation software is presented.

1 INTRODUCTION

For high performance applications, the limiting performance factor for many GPS receivers suing kinematic GPS (KGPS) methods is the combination of receiver noise and multipath errors. In any environments where strong multipath signals can be received, for example from buildings, vehicle structure or surrounding terrain, the multi-path errors in particular can offset both the pseudo-range and the carrier-phase observations and can even on occasion prevent correct ambiguity resolution, degrading the performance of kinematic GPS navigation.

The solution that NAVSYS has developed to improve the accuracy and robustness of KGPS navigation, leverages a multi-antenna solution. This GPS receiver, the High-gain Advanced GPS Receiver (HAGR) uses digital beam forming to provide dynamic antenna steering to each of the GPS satellites tracked. The directivity of the antenna results in improved measurement accuracy and multipath rejection. As described in the following sections, this approach has been shown to reduce the noise on the pseudo-ranges. More importantly, it also reduced the effect of multipath on the pseudo-range and carrier-phase observations. In this paper, the principle of operation of the HAGR digital beam steering is described and test results are presented to illustrate its performance for precision KGPS applications.

2 HIGH GAIN ADVANCED GPS RECEIVER

The HAGR design is based on NAVSYS' Advanced GPS Receiver (AGR) PC-based digital receiver architecture[1] integrated with a digital beam steering array[2]. Using a proprietary digital signal processing algorithm, the HAGR is able to combine the GPS signals from as many as 16 antennas and create a multi-beam antenna pattern to apply gain to up to eight GPS satellites simultaneously. The 16-element antenna array is shown in Figure 1.

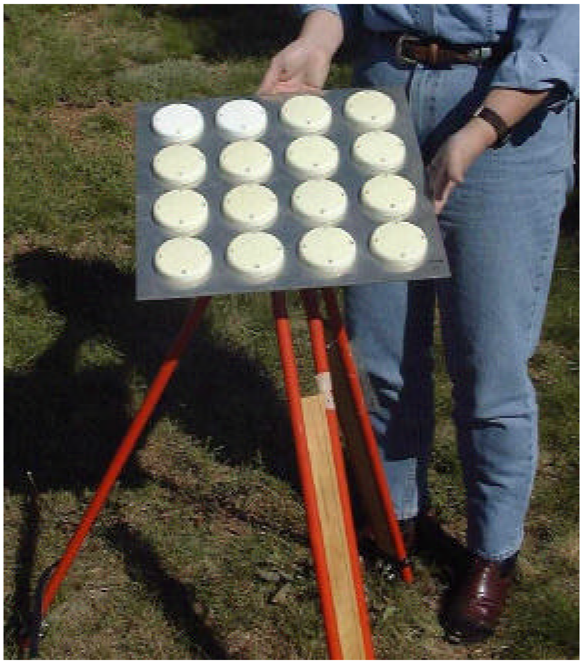

Figure 1 HAGR 16-element antenna array

In Table 1, the performance specifications for the HAGR are shown for a 16-element, L1 C/A code version of this product. Currently an L1/L2 Precise Position System (PPS) version of the HAGR (the HAGR-200) is also in development.

Table 1 HAGR –100 Version Specifications

Technical Specifications GPS Frequency Source Channels	 L1, 1575.42 MHz C/A code (SPS) 8 channels
Operating Specifications Signal Acquisition Signal Tracking Time To First Fix Re-Acquisition	 32 dB-Hz (single element) 34 dB-Hz (single element) 24 dB-Hz (16 element array) 40 secs (cold – no time or position) 10 secs to valid position
DFE Input Signals Center Frequency Nominal Signal Level Signal Bandwidth	 1575.42 MHz -136 to-86 dBm 20 MHz
CW or Noise Interference Levels at DFE Input Center Frequency ± 10 MHz 1200 to 1600 MHz Outband Interference	 10 dB above weakest <-80 dBm <-20 dBm
Built-in Modules	DGPS, KGPS (reference and remote) Timing Reference Beam steering
User Configuration	Vehicle Dynamics
Parameters Selectable through configuration file or user interface	Track Thresholds DLL and PLL or FLL bandwidths and Thresholds DFE characteristics Correlator spacing Data logging rates Satellite selection methods

The HAGR system consists of the components shown in Figure 2. The 16-element antenna array is shown in Figure 1. The antenna outputs are fed to multiple Digital Front End (DFE) custom RF-boards that digitize each of the received L1 signals. The digital output from the DFE boards is then passed to a custom Digital Beam Steering (DBS) board that performs the digital signal processing required to implement the digital beam steering operations. The Correlator Accelerator card (CAC) performs the C/A code correlation and carrier mixing on each satellite channel.

The HAGR is built on a modular architecture using a Personal Computer (PC) as the host for the components. This allows GPS receivers to be configured to meet a customer's individual requirements in terms of numbers of antenna elements, tracking channels and SPS or PPS capability. The HAGR is available in desktop or rack-mounted configurations and a Compact PCI version is also in production.

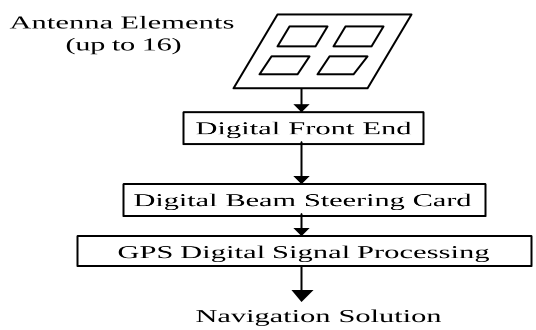

Figure 2 High Gain Advanced GPS Receiver Design

In the current HAGR configuration, the sampled data from up to 16 DFE outputs is processed by the digital beam-steering (DBS) card to provide a composite signal output for each satellite being tracked. This card applies the array digital signal processing (DSP) operations under control of the HAGR-PC software. The normal mode is to compute the satellite beam-forming equations based on the line-of-sight to the satellite, as illustrated in Figure 3.

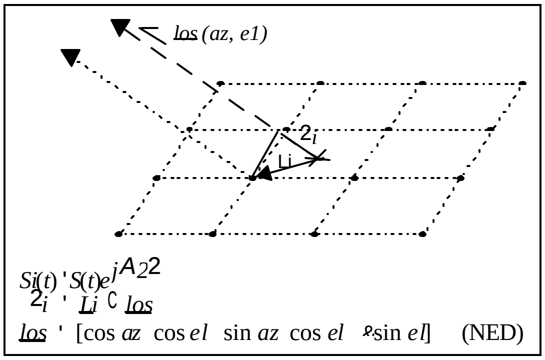

Figure 3 Beam forming satellite geometry

An individual beam is created optimized for each satellite tracked under software control of the DBS. If attitude data (pitch, roll, yaw) is provided from an inertial navigation system or attitude sensor, the HAGR will operate while the antenna is in motion. The default mode, for static operation, is to align the array pointing north.

As is discussed in the following section, the digital beam forming provides significant benefit in improving the measurement accuracy due to the narrow beam antenna pattern directed at each satellite tracked. The antenna gain pattern is shown in Figure 4 for a 16-element array and the directivity is illustrated in Figure 5 for a 1, 4, 9 and 16-element antenna pattern.

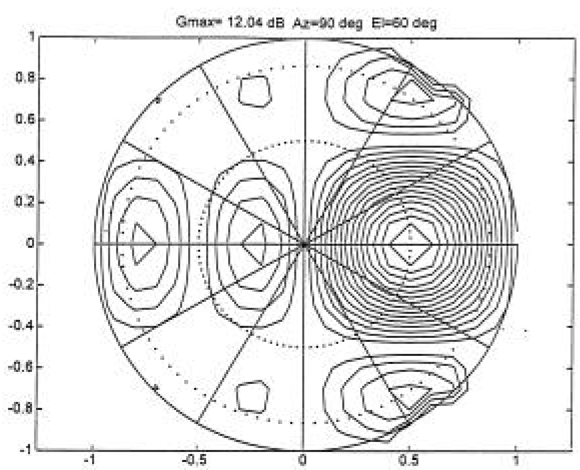

Figure 4 16-element array composite beam pattern

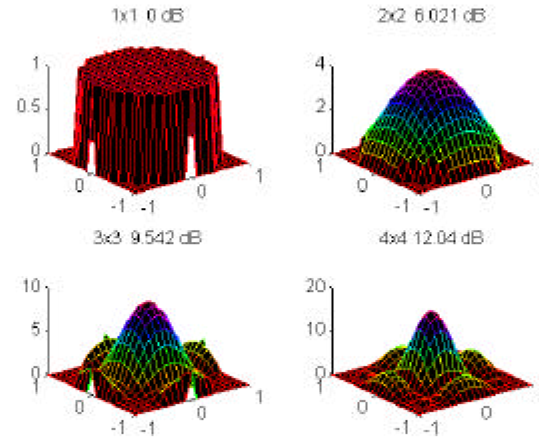

Figure 5 HAGR Beam Patterns

3 DGPS AND KGPS NAVIGATION ACCURACY

The accuracy of a differential GPS (DGPS) solution is a function of the solution geometry and the accuracy of the raw pseudo-range measurements as shown in Equation 1 and Equation 2. A similar equation also exists for a Kinematic GPS (KGPS) solution which is derived from carrier phase observations and a solution of the integer carrier cycle ambiguities.

Equation 1

$$G = (H^T H)^{-1}$$

$$H = \begin{bmatrix} 1_1^T & 1 \\ 1_2^T & 1 \\ . & . \\ . & . \\ 1_n^T & 1 \end{bmatrix}$$

$$PDOP = \sqrt{G_{11} + G_{22} + G_{33}}$$

Equation 2

$$E[\tilde{x}_{DGPS}^T \tilde{x}_{DGPS}] = PDOP^2 s_{DGPS}^2 \approx PDOP^2 (s_{PR}^2 + s_{Mpr}^2)$$

Equation 3

$$E[\tilde{x}_{kGPS}^T \tilde{x}_{kGPS}] = PDOP^2 s_{kGPS}^2 \approx PDOP^2 (s_{cph}^2 + s_{Mcph}^2) l^2$$

The major benefits of the HAGR digital beam forming for DGPS and KGPS navigation applications are the increase in accuracy of the pseudo-range and carrier-phase observations and the reduction in multipath errors due to the antenna directivity. These benefits are discussed in this section.

The differentially corrected pseudo-range accuracy is dominated by two error sources as illustrated in Equation 2. The first is receiver noise and the second is the multipath error. The receiver noise is a function of the effective delay-lock-loop bandwidth after carrier smoothing is applied. This can be computed from the following equation where T_C is the C/A code chip length (293 meters), d is the correlator chip spacing and C/N_0 is the received signal-to-noise ratio in dB-Hz.

Equation 4

$$\sigma_{PR} = T_c \sqrt{\frac{d\, B_{DLL}}{2\, 10^{CNo/10}}} \left(1 + \frac{2 B_{IF}}{(2-d) 10^{CNo/10}} \right)$$

This is plotted in Figure 6 against C/N_0 assuming a 0.1 Hz carrier smoothed bandwidth, a code chip separation of 1 and an accumulation frequency of 1-kHz.

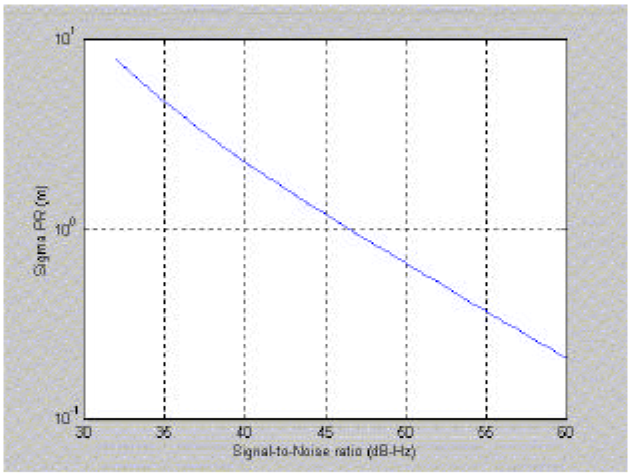

Figure 6 Sigma PR Noise vs C/N0 (Bdll=1, d=1)

From Figure 6, a 10 dB increase in signal power will have the affect of reducing the pseudo-range noise by a factor of 0.3. The HAGR routinely receives satellite signals with C/N_0 of 54 to 58 dB-Hz which reduces the pseudo-range noise level to below 10 cm with carrier smoothing.

Multipath errors are caused by the receiver tracking a composite of the direct GPS signals and reflected GPS signals from nearby objects. The resulting pseudo-range error and carrier-phase error is a function of the phase offset between the direct and multipath signals and the relative signal strength. For a fixed installation, these errors appear as biases, changing only as the line-of-sight to the satellite changes due to the satellite motion. Multipath mitigation techniques have been developed using multi-correlator techniques that improve the performance of the code tracking loops in the presence of multipath. However, these have little effect against carrier-phase errors introduced by the multipath signals. The HAGR digital beam-former has the advantage that the multipath is reduced on both the pseudo-range and the carrier-phase errors through the directivity of the antenna pattern towards the satellite which reduces the effect of the multipath signal.

The effect of multipath on the GPS signals can be modeled through the following equations.

Equation 5

$$s(t) = AC(t+\tau)\sin(\omega t+\theta) + A_M C(t+\tau_M)\sin(\omega t+\theta_M)$$
$$s(t)\hat{s}(t) = AR(\tau-\hat{\tau})\sin(\omega t+\theta) + A_M R(\tau_M-\hat{\tau})\sin(\omega t+\theta_M)$$
$$= (A+\tilde{A})\sin(\omega t+\theta+\tilde{\theta})$$

The above equation can be solved for the pseudo-range error that will be observed with the DLL tracking loops and the phase error that will be observed by the PLL tracking loops. This simplifies to the following expression, if it is assumed that the multipath reflections are relatively close to the antenna (compared with the C/A code chip length of 293 m) and that $R(\tau)$ from the DLL is approximately equal to one for both the direct and multipath signals.

Equation 6

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

Which is the approximate maximum error for a 1-chip Early/Late correlator assuming that the multipath delays are less than ½ chip. If the multipath errors are 10 dB down from the satellite signal power, then the multipath error will be approximately 10% of the multipath delay. For example, if signals are received with a delay of 20 meters, then the multipath error will be less than 2 meters on the pseudo-range observation. Since the beam-forming antenna provides 10 dB gain in the direction of the satellite signal, the multipath signals are received with at 1east 10 dB lower power than the direct satellite signals.

Equation 7

$$\tilde{A}/A = \left| A + A_M e^{\Delta\theta} \right| / A$$
$$\tilde{\theta} = \angle(A + A_M e^{\Delta\theta})$$
$$\Delta\theta = \theta - \theta_M$$

In Figure 7 the effect of the multipath signal on the C/N0 envelope is shown as a function of the multipath signal power. In Figure 8 the multipath phase angle errors and signal amplitude are shown versus the multipath phase angle offset ($\Delta\theta$) for the cases when A_M=A (0 dB), $A_M=A/\sqrt{2}$ (-3dB down), A_M=A/2 (-6dB down), and $A_M=A/\sqrt{10}$ (-10 dB down). This figure illustrates the benefit of the beam former in also limiting multipath errors on the phase observations – a key area of concern for kinematic GPS applications.

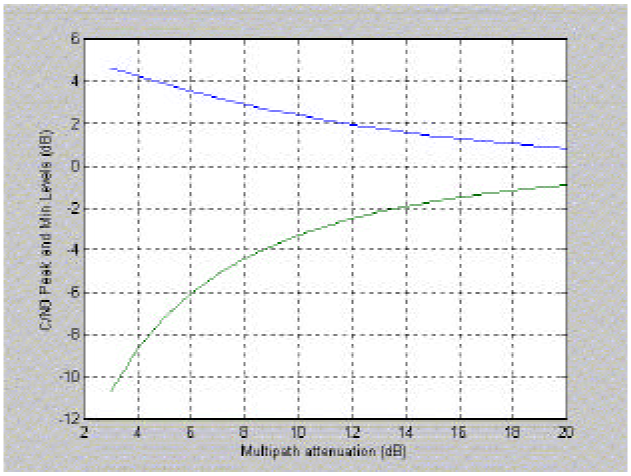

Figure 7 Multipath Amplitude Effect

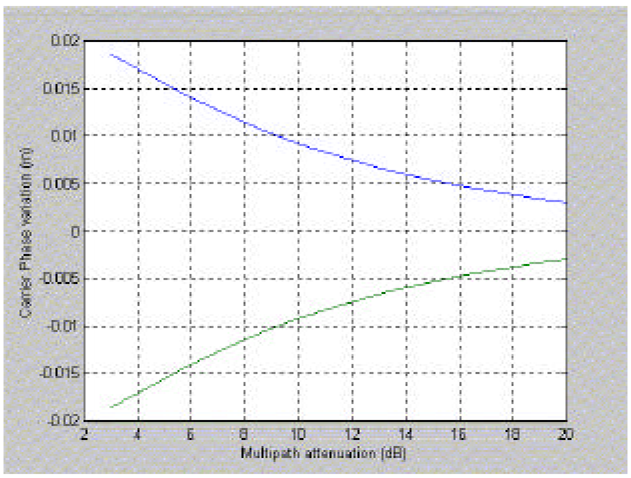

Figure 8 Multipath Phase Angle Error

In the following sections, test data is shown from the HAGR to quantify the effect of multipath errors and receiver noise on the pseudo-range and carrier-phase observations.

4 HAGR MEASUREMENT NOISE PERFORMANCE DATA

The HAGR digital beam forming has the effect of increasing the signal-to-noise ratio from the GPS satellites. In Figure 9 to Figure 15, performance data is shown from a HAGR unit compared against two conventional GPS reference receivers [2]. From these plots, it can be seen that the HAGR C/N_0 is significantly higher than the reference receiver, demonstrating the effect of the gain from the digital beam forming.

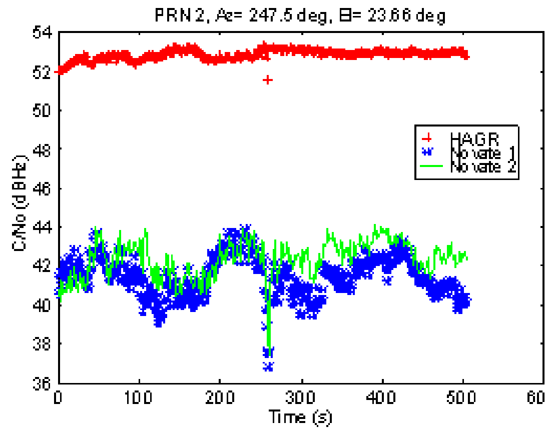

Figure 9 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 2

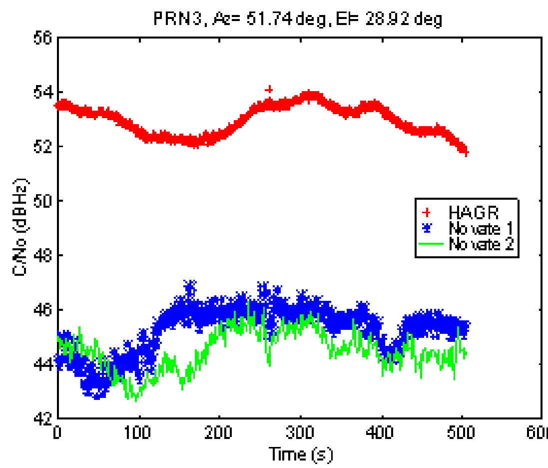

Figure 10 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 3

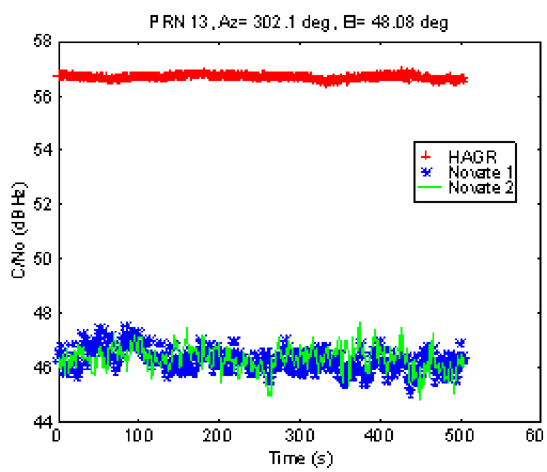

Figure 11 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 13

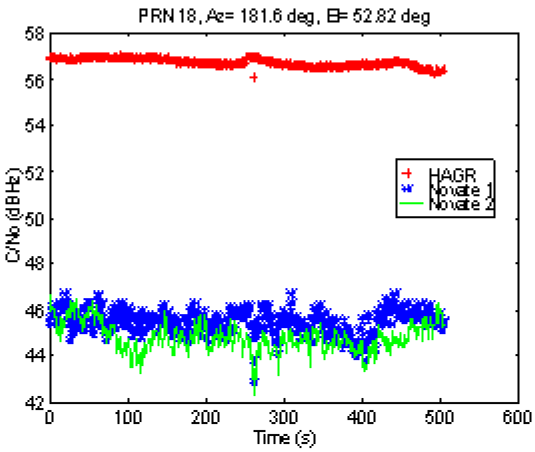

Figure 12 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 18

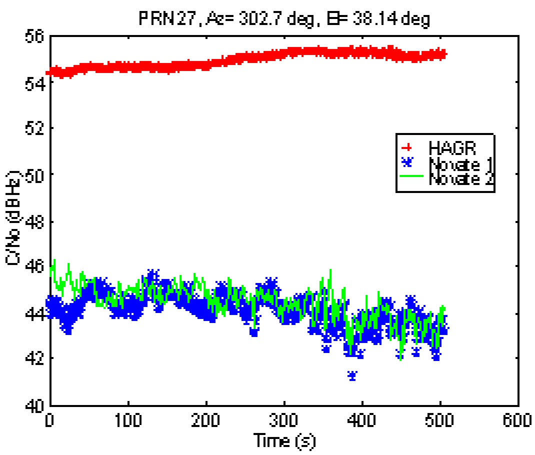

Figure 13 SNR Comparison between 16-Antenna HAGR and Novatel's for PRN 27

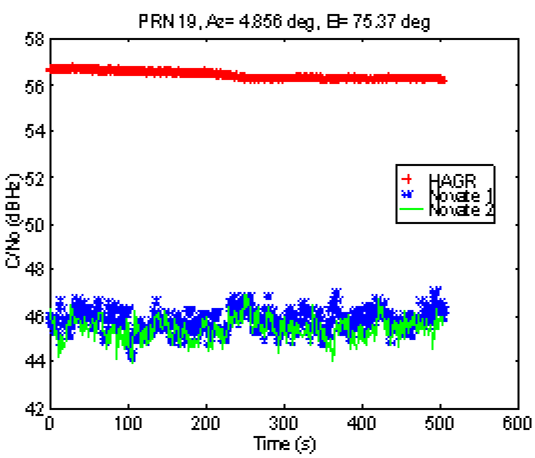

Figure 14 SNR Comparison between 16-Antenna HAGR and Novatel's for PRN 19

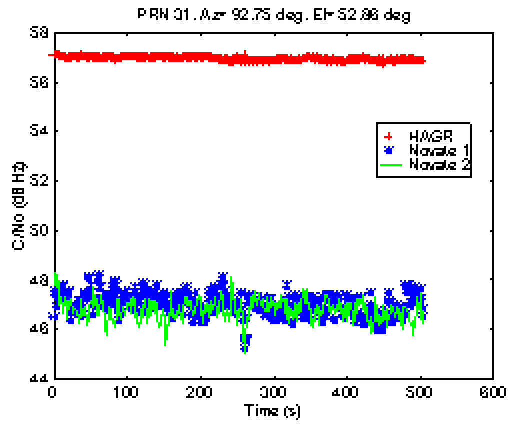

Figure 15 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 31

The pseudo-range noise can be estimated by examining the sum of the pseudo-range and the carrier–phase observations. This can be considered to observe the pseudo-range noise, the pseudo-range multipath error and the code-carrier ionospheric group delay divergence, as expressed in the following equations.

Equation 8

$$PR = R + b_u - b_{SV} + I + \Delta_M + n_{PR}$$

Equation 9

$$CPH = N - (R + b_u - b_{SV} - I) / l + q_M + n_{CPH}$$

Equation 10

$$PR + l\,CPH = N + 2I + \Delta_M + n_{PR} + lq_M + l n_{CPH}$$

The initial value for this sum is removed whenever new carrier lock is achieved. The PR+CPH sums are plotted in Figure 16 to Figure 24. The growth in this parameter over time is caused by the code-carrier divergence. The short-term variation is caused by receiver noise and the periodic variation is caused by code multipath. The periodic effect is a function of the multipath constructive and destructive interference on the code tracking loops.

Table 2 HAGR PR Noise Performance Data

SVID	AZ	EL	C/N0 1	s_{PR}	C/N0 2	s_{PR}
3	285	36	49	0.89	51	0.46
6	173	18	44	0.60	44	0.48
8	134	21	48	0.46	45	1.05
9	90	28	50	0.50	48	0.77
17	113	57	55	0.21	55	0.19
21	291	50	54	0.26	53	0.31
23	21	66	55	0.35	54	0.47
26	43	13	49	0.33	52	0.27
29	212	40	52	0.38	53	0.36

In the Table 2, the short term noise is listed for each of the two HAGR units tested. The gain provided by the beam steering has maintained the signal-to-noise generally above 50 dB-Hz, providing sub-meter level short term noise on the pseudo-range performance.

The difference in the PR+CPH offsets shown in Figure 16 to Figure 24 is dominated by multipath errors. These are on the order of 1-2 meters of error, and are especially apparent on satellites 8, 9 and 29. On satellite 8, the C/N0 fluctuation is on the order of 6 dB and the PR error is around 5 meters. From Figure 7, a 6-dB fluctuation in amplitude indicates a multipath signal is being received with a signal level 10 dB below the direct signal. The pseudo-range multipath error would be expected to be roughly 10% of the group delay for signals within the beam of the HAGR. Since this is a low elevation satellite, it is expected that the multi-path signal would be very close to the direct signal and therefore within the HAGR beam. Satellite 26 also has a 3-5 dB variation in the C/N0. This would indicate a multipath signal with a level about 11-15 dB down from the direct signal. The pseudo-range errors for this satellite range between 2-5 meters, indicating a signal reflection source around 50 meters away. Again, this is a low elevation satellite.

The majority of the satellite signals have an amplitude delta of less than 2-dB. From Figure 7 and Figure 8, the carrier phase variation would be expected to be less than +/- 5 mm when the multipath signal is below this level.

It should be noted from Figure 8 that a strong multipath signal can cause phase variations on the order of +/- 2 cm which would severely affect the kinematic GPS performance.

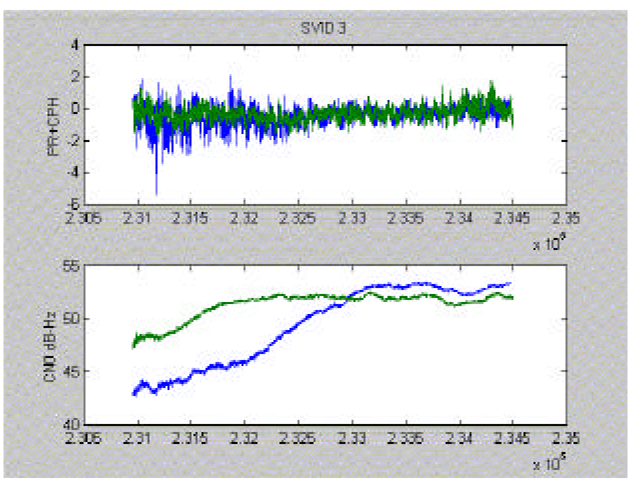

Figure 16 PR+CPH - SV 3

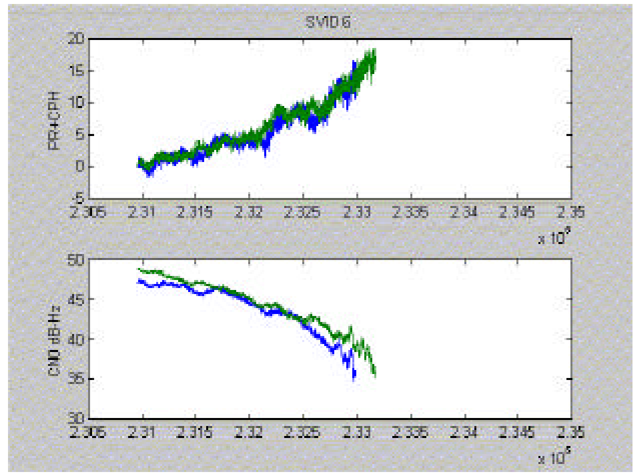

Figure 17 PR + CPH - SV 6

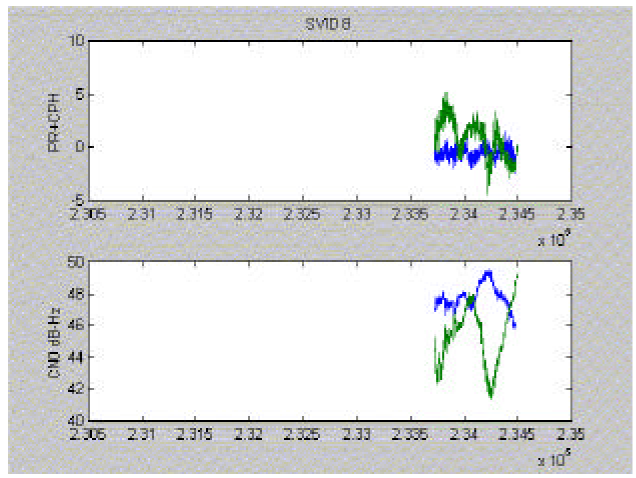

Figure 18 PR+CPH - SV 8

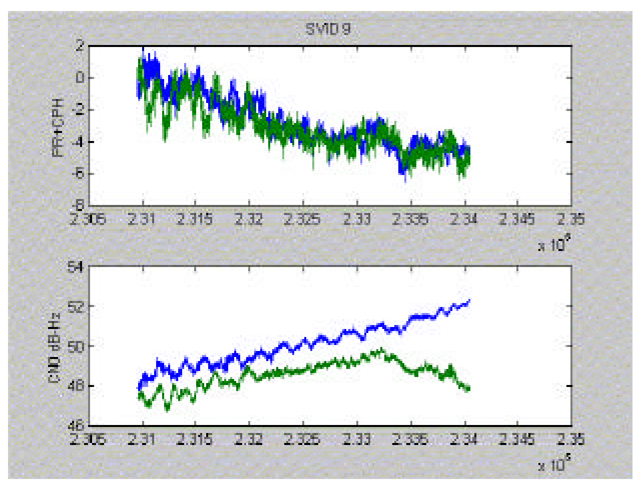

Figure 19 PR+CPH – SV 9

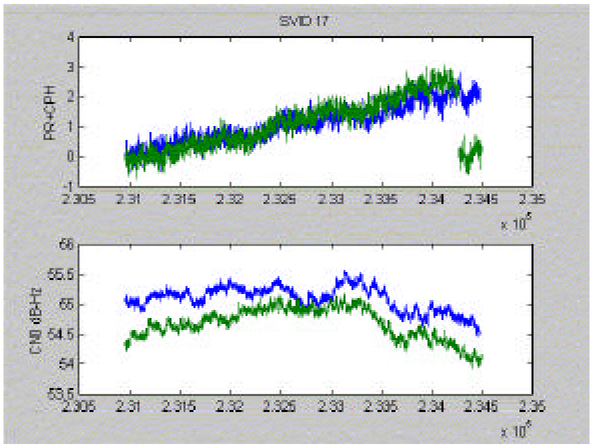

Figure 20 PR + CPH - SV 17

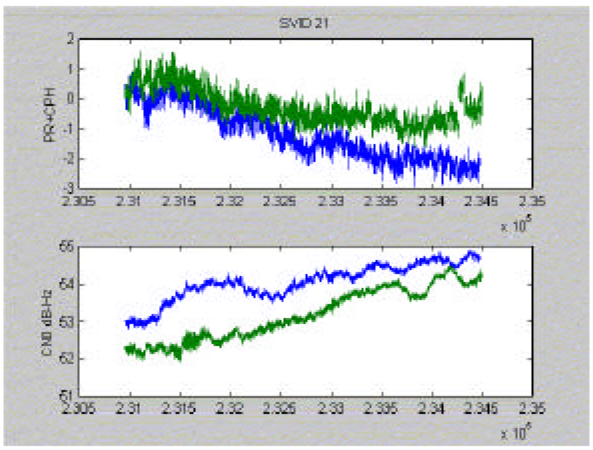

Figure 21 PR+CPH -SV 21

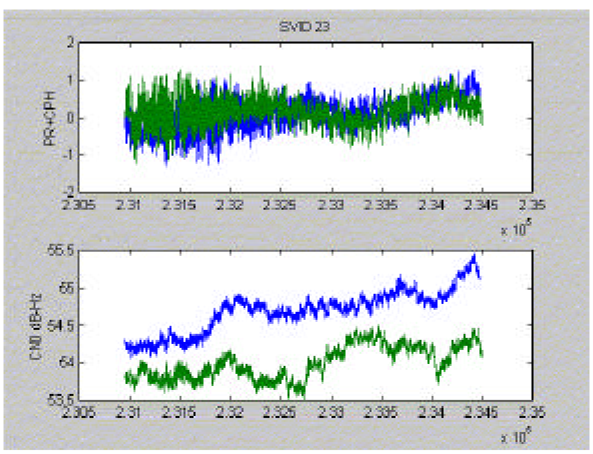

Figure 22 PR+CPH -SV 23

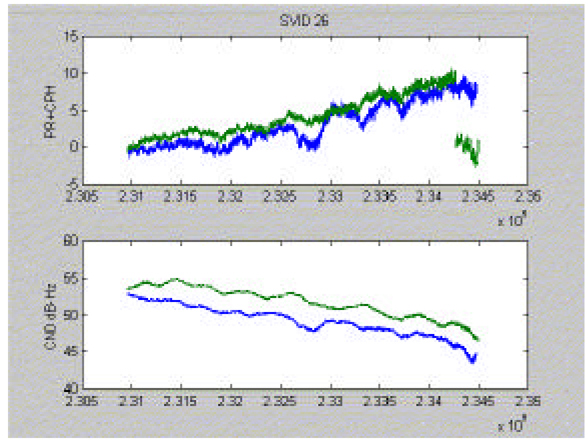

Figure 23 PR+CPH - SV26

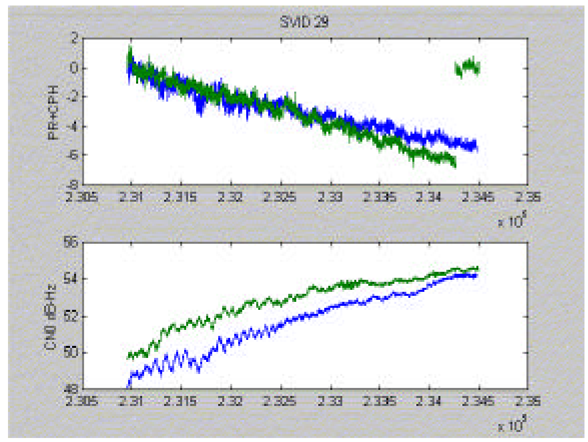

Figure 24 PR + CPH - SV 29

5 KINEMATIC GPS TEST RESULTS

The kinematic performance of the HAGR antennas was tested by setting each of the antennas on two survey marks separated about 1.5 meter apart. The NAVSYS's kinematic GPS softwae was used to process the data. A 10 degree elevation mask angle was selected. Figure 25 and Figure 26 show the processing results. During the test, 6 valid satellites were available. These test results show that the kinematic GPS positioning error achieved a standard deviation of 3 mm (1-sigma) in the north and east directions and 7 mm (1-sigma) vertically. This is consistent with a carrier phase measurement accuracy of 3 mm (1-sigma). This shows that the multipath errors on the carrier phase are maintained on the order of a few millimenters by the HAGR beam forming.

To compare the performance of the antenna array with and without the beam steering, the residual phase error on each of the individual elements is plotted in Figure 27. This shows that the carrier phase error can easily be offset by +/- 0.1 cycles (2 cm) between the individual elements.

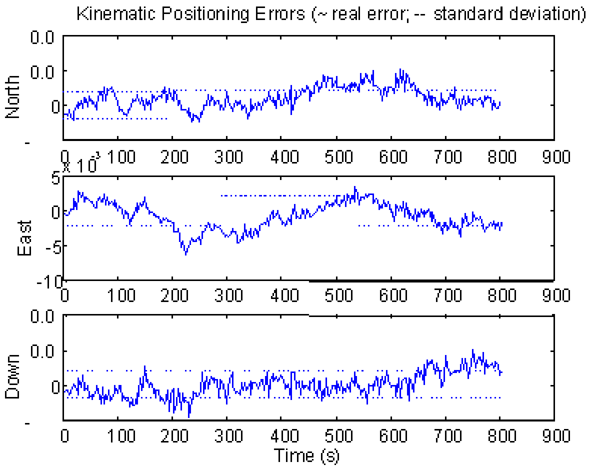

Figure 25 KGPS positioning errors

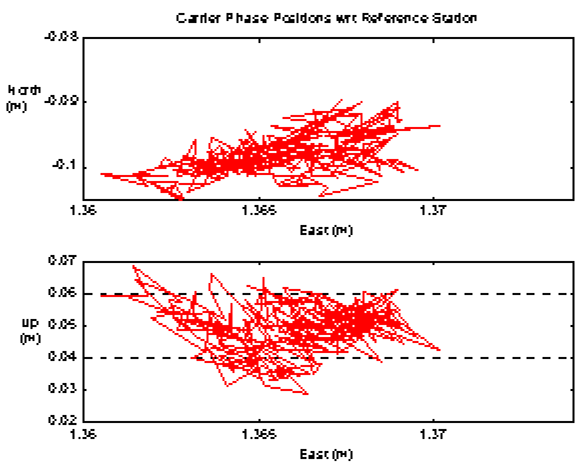

Figure 26 KGPS positioning error

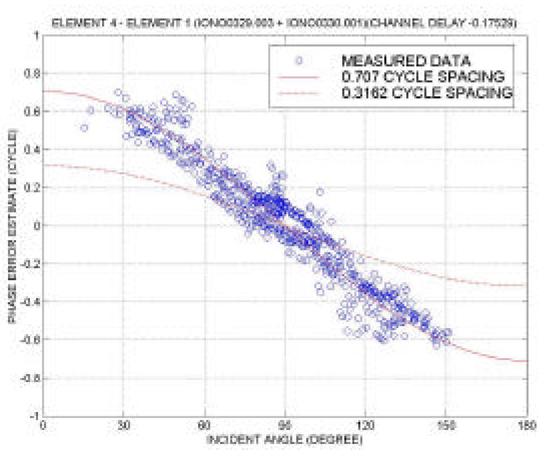

Figure 27 Carrier-phase multipath without beam steering

Further improvements in pseudo-range and carrier phase multipath reduction can be achieved by optimizing the HAGR weights to adapt to detected multipath signals. Since the HAGR digital beam steering is performed under software control, this capability could be added to the current system design. Research is currently being conducted on the performance benefits that can be achieved through an adaptive multipath spatial processing algorithm.

6 CONCLUSIONS

The test results have shown the capability of the HAGR to significantly reduce the pseudo-range random noise through the high power signal provided from the antenna gain. The current dominant error source in the HAGR is caused by multipath which provides on the order of 1-2 meters of random error on the pseudo-range, particularly for low elevation satellites. Further improvements in pseudo-range accuracy are expected through implementation of spatial processing to detect and minimize the code phase multipath errors.

Test results of the HAGR operating in a kinematic GPS mode have shown that the system is capable of better than 1 cm level positioning performance. Observations of signal level fluctuations caused by residual multipath errors indicate that the HAGR beam steering is maintaining the multipath signals below 10 dB of the direct signal, except for low elevation satellites. This would maintain the carrier phase error from the multipath effect below +/- 5mm.

ACKOWLEDGEMENTS

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[2] Dr. Alison Brown, Randy Silva, Gengsheng Zhang , "Test Results of a High Gain Advanced GPS Receiver", ION 55th Annual Meeting, Cambridge, MA, June 1999