TEST RESULTS OF A DIGITAL BEAMFORMING GPS RECEIVER FOR MOBILE APPLICATIONS

Alison Brown, Huan-Wan Tseng, and Randy Kurtz, NAVSYS Corporation

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.

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.

ABSTRACT

The HAGR digital beam forming receiver maintains the digital beams directed at each satellite using the receiver's navigation solution and the satellite position derived from the ephemeris data. For mobile applications, a real-time input of the pitch, roll and heading of the vehicle on which the antenna is installed is used to compensate for vehicle motion.

This paper describes the operation of the HAGR digital beam steering array in a mobile environment and includes test data collected from the HAGR demonstrating its performance on a moving vehicle.

INTRODUCTION

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.

HIGH GAIN ADVANCED GPS RECEIVER

The HAGR design is based on NAVSYS' Advanced GPS Receiver (AGR) PC-based digital receiver architecture integrated with a digital beam steering array[1]. 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.

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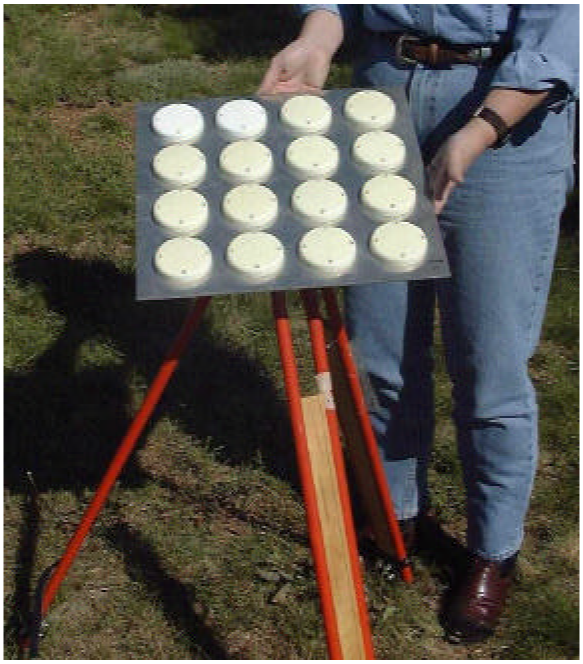

Figure 1 HAGR 16-element antenna array

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

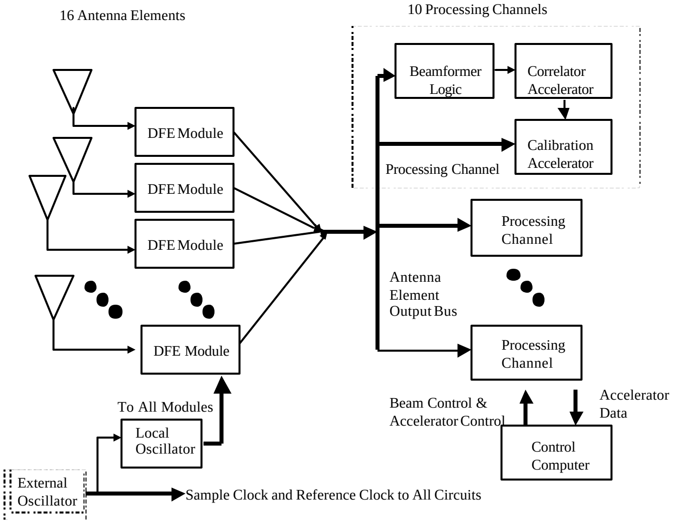

Figure 2 HAGR System Block Diagram

The HAGR system architecture is shown in Figure 2. 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 a composite digital beam-steered signal input for each of the receiver channels. This is achieved by phase shifting each of the DFE signals, digitally, to align the beam with the direction to the satellite, as shown in Figure 3.

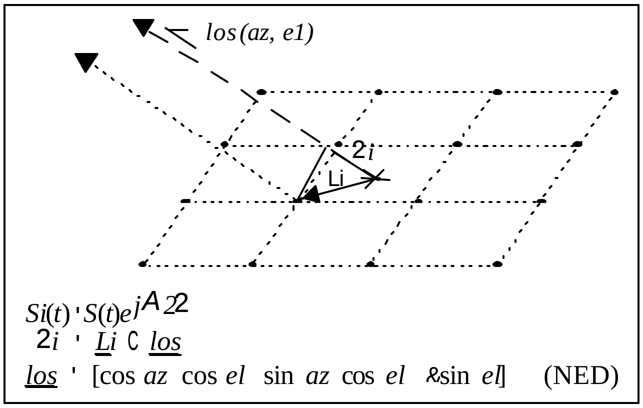

Figure 3 Beam forming satellite geometry

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. The mode, for static operation, is to enter the array orientation manually, or to align the array pointing north (the default).

The refresh rate for computing the individual weights is a function of the rate of change of attitude of the satellite and the acceptable loss in the beam steering algorithms. The directivity of the composite beam is a function of the number of elements simultaneously in view of a particular satellite. With a 4-element antenna array, the 1-dB beam width is 25°. With a 16-element antenna array the 1-dB beam width is 11° and the 3-dB beam width is 18°. The refresh rate is programmable, but was limited to 1-Hz updates in the tests performed due to the attitude sensor used. To maintain less than 1-dB gain degradation with a 4-element array the vehicle's attitude rate of change must be less than 25°/sec. For higher rates of change, a faster input rate for the attitude updates is needed (for example from an IMU). With 10 Hz attitude updates, an attitude rate of change of 250 degrees/sec can be handled without noticeable degradation.

MOBILE HAGR TESTING

The test was configured with a reference HAGR (16-element) located at a survey point and a 4-element mobile HAGR unit installed in a truck. 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 4 to Figure 6. The attitude rate of change was generally less than 1 deg/sec throughout this test.

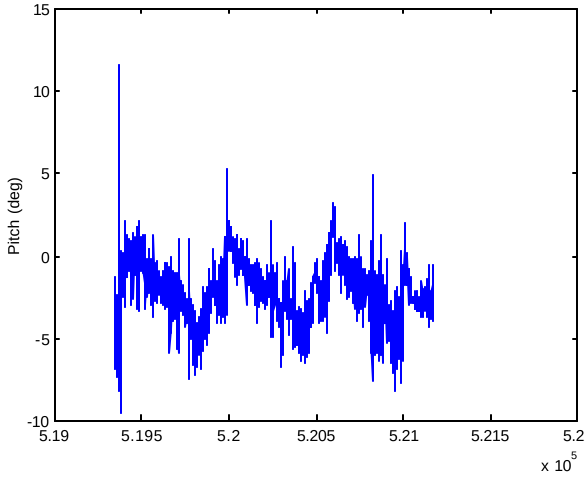

Figure 4 Mobile HAGR Testing (Pitch)

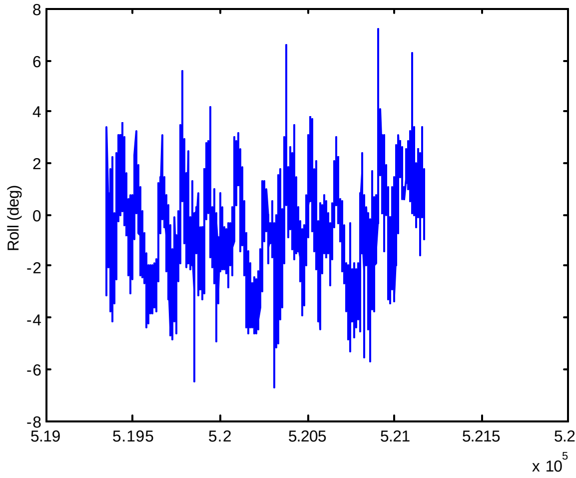

Figure 5 Mobile HAGR Testing (Roll)

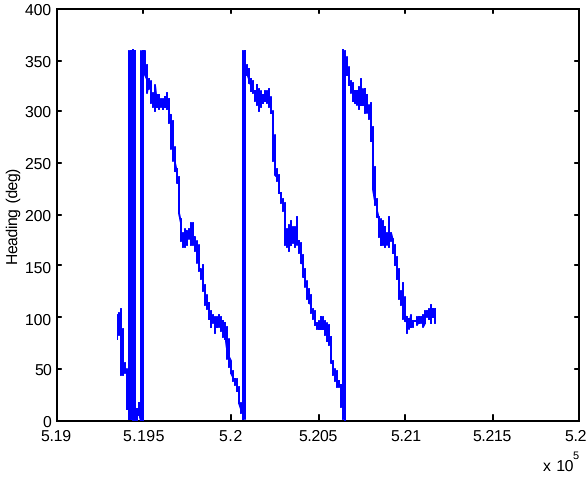

Figure 6 Mobile HAGR Testing (Heading)

The satellites tracked by the stationary reference HAGR are shown in Figure 8 and the satellites tracked by the mobile HAGR are shown in Figure 9. The locktime for all of the nine satellites tracked during the testing is shown in Figure 10. Five satellites were tracked throughout almost the complete test period with continuous carrier phase lock – demonstrating the mobile beam steering was correctly compensating for the vehicle motion. The SNR values of the tracked satellites by the stationary reference HAGR are shown in Figure 11 to Figure 16 and the SNR values for the mobile HAGR in Figure 17 to Figure 22.

The mobile test data shows almost 10 dB of variation in the observed C/N0 data. From Figure 7 [2] this is consistent with a multipath signal received with attenuation of around 6 dB.

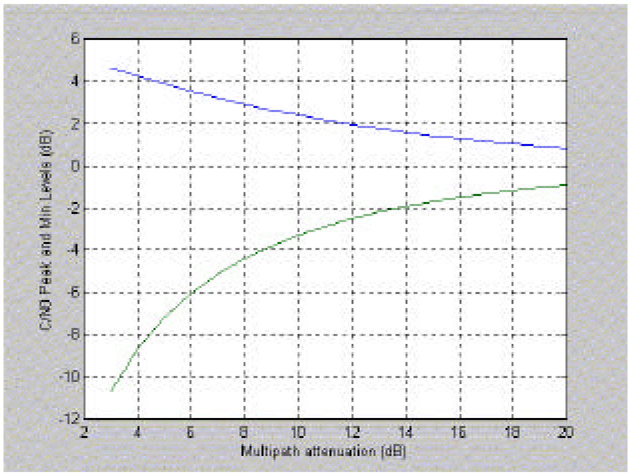

Figure 7 Multipath Amplitude Effect

Because the mobile HAGR was a 4-element configuration, the beam width is fairly wide and so will not give much multipath rejection (1dB beam is 25 degrees). Since the antenna array was installed on a truck during this testing, it is likely that there was strong multipath being received from sources such as the truck-bed. This was confirmed when the PR+CPH observations were generated. These are plotted in Figure 17 to Figure 28 and show a strong correlation with the truck motion indicating a repetitive multipath error.

In Table 1 the peak C/N0 from the 16-element reference HAGR and 4-element mobile HAGR are shown. Theoretically the 16-element HAGR will provide 12 dB of gain to each satellite tracked while the 4-element HAGR will provide 6 dB of gain. The difference between the Reference and the Mobile C/N0 is consistent with this expected 6 dB delta. The peak-to-peak offset in the PR and CPH data indicates a strong multipath presence. The maximum offset that would be observed is αTc/2, where Tc is the chip length (293 meters) and α is the attenuation from the multipath power. These type of deviations are consistent with a peak observed power level of 6 dB (α=0.25), when the peak error observed would be 36 meters.

Table 1 Comparison of Reference and Mobile Test Data

SVID	2	13	18	19	27	31
Ref C/N0 dB-Hz	54	55	54	55	55	55
Mobile C/N0 (peak)	48	49	49	49	48	49
Mobile C/N0 (rough minimum)	37	41	37	41	41	39
Pk-Pk PR+CPH delta (m)	30	25	25	12	20	25

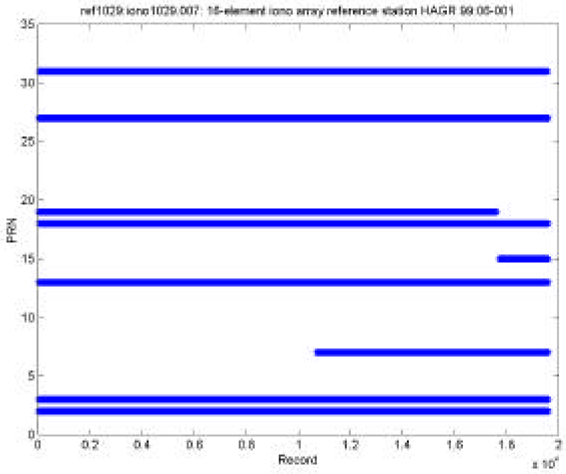

Figure 8 Satellites tracked by Reference HAGR

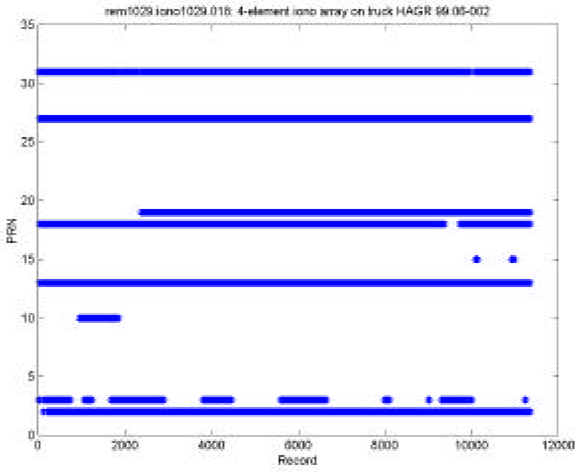

Figure 9 Satellites tracked by Mobile HAGR

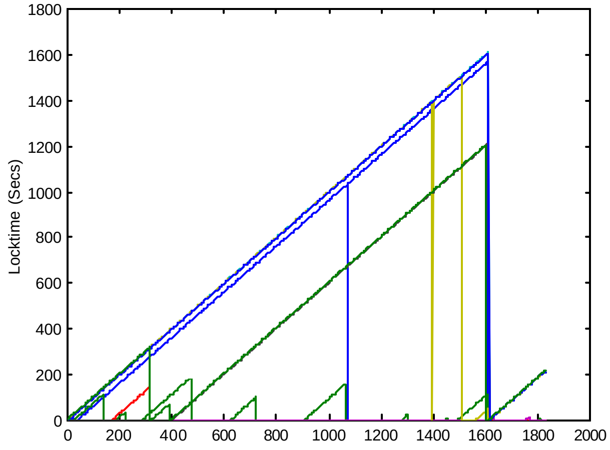

Figure 10 Locktime on all satellites tracked

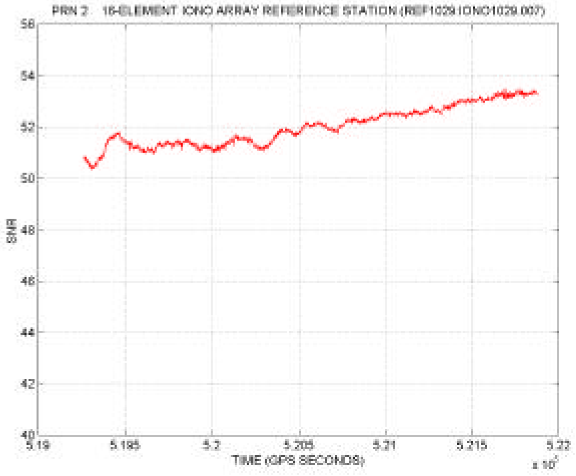

Figure 11 Reference HAGR C/N0 (dB -Hz) PRN 2

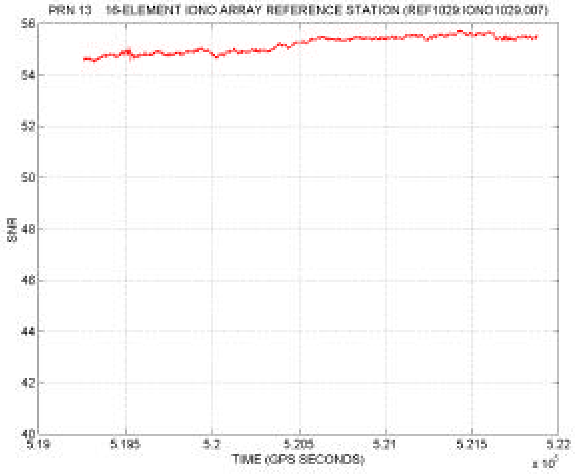

Figure 12 Reference HAGR C/N0 (dB -Hz) PRN 13

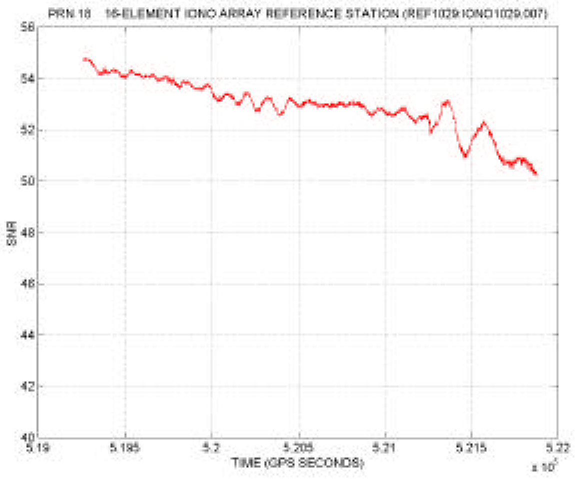

Figure 13 Reference HAGR C/N0 (dB-Hz) PRN 18

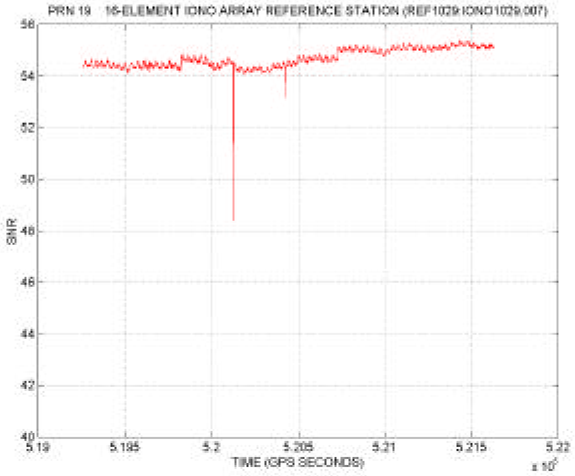

Figure 14 Reference HAGR C/N0 (dB-Hz) PRN 19

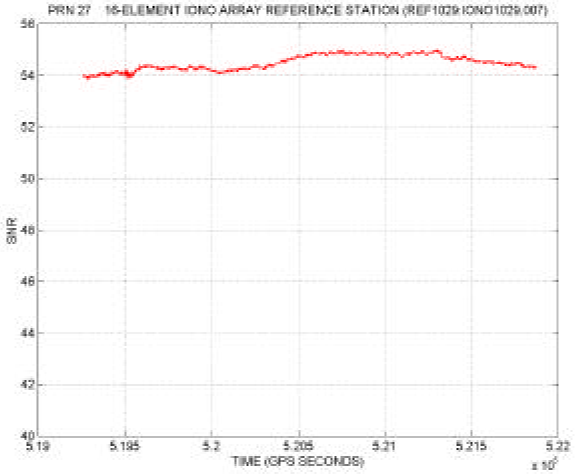

Figure 15 Reference HAGR C/N0 (dB-Hz) PRN 27

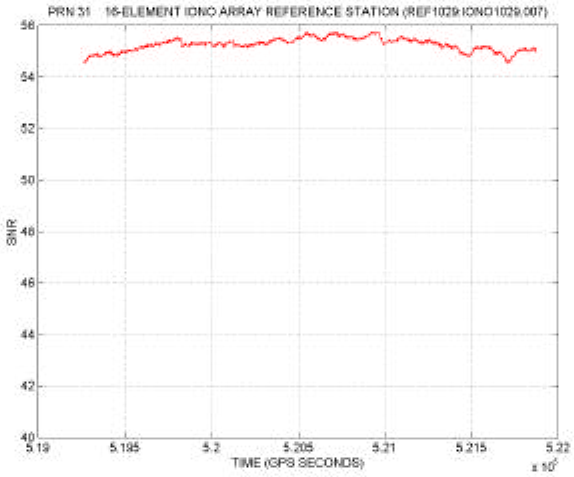

Figure 16 Reference HAGR C/N0 (dB-Hz) PRN 31

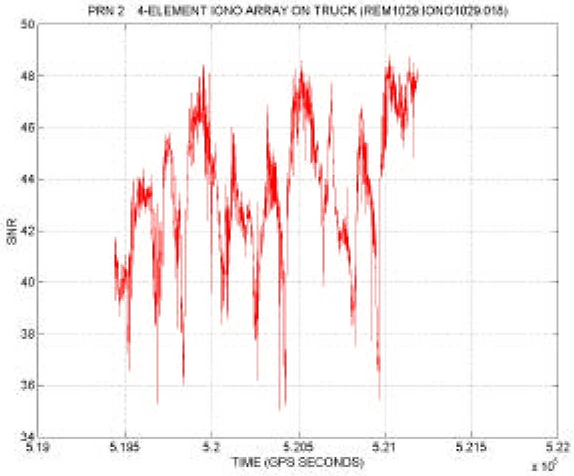

Figure 17 Mobile HAGR C/N0 (dB-Hz) PRN 2

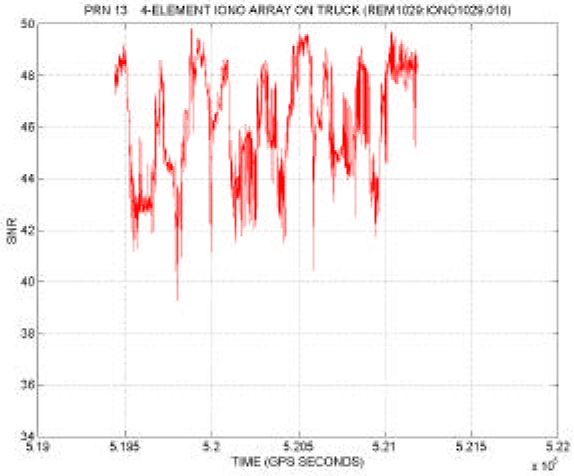

Figure 18 Mobile HAGR C/N0 (dB-Hz) PRN 13

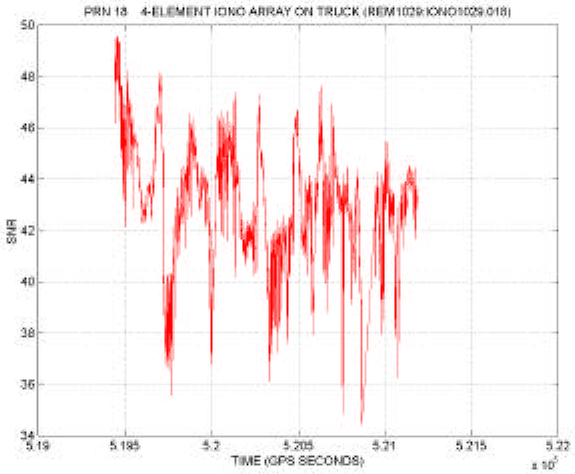

Figure 19 Mobile HAGR C/N0 (dB-Hz) PRN 18

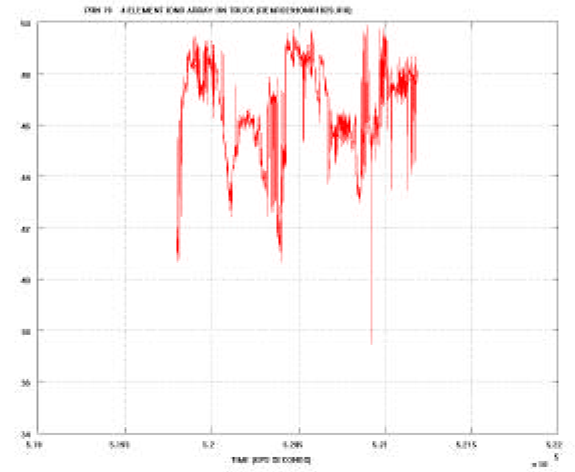

Figure 20 Mobile HAGR C/N0 (dB-Hz) PRN 19

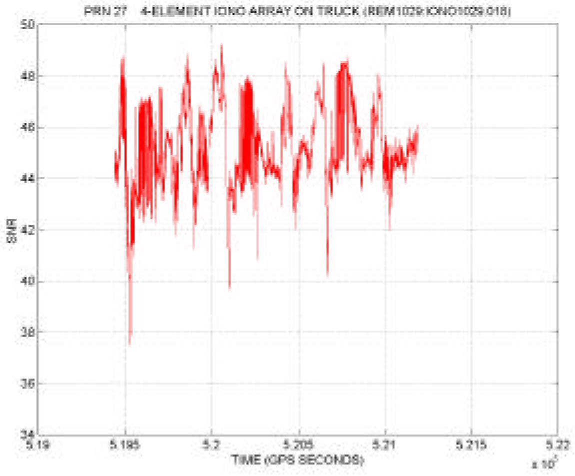

Figure 21 Mobile HAGR C/N0 (dB-Hz) PRN 27

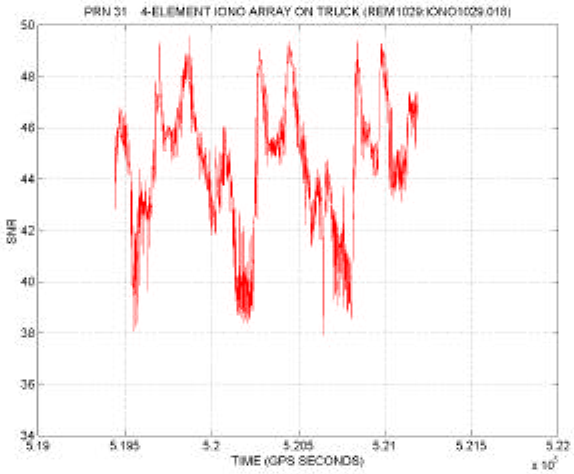

Figure 22 Mobile HAGR C/N0 (dB-Hz) PRN 31

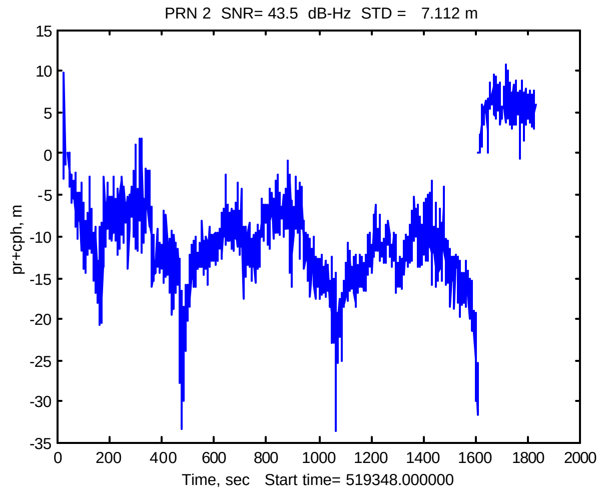

Figure 23 Mobile HAGR PR+CPH - PRN 2

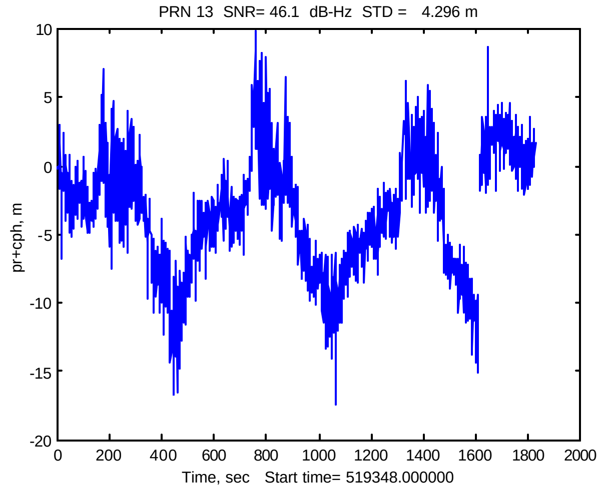

Figure 24 Mobile HAGR PR+CPH - PRN 13

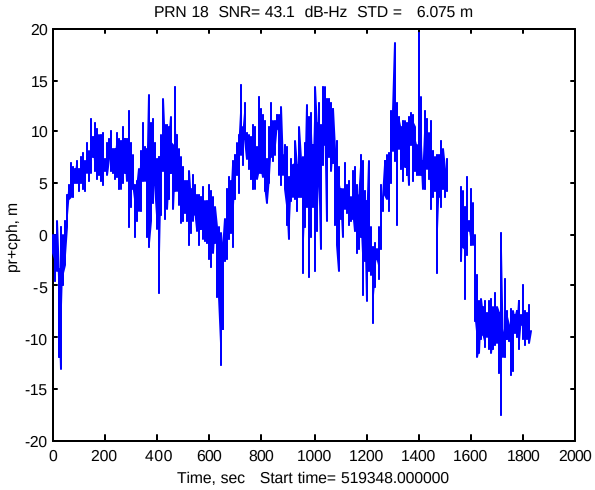

Figure 25 Mobile HAGR PR+CPH - PRN 18

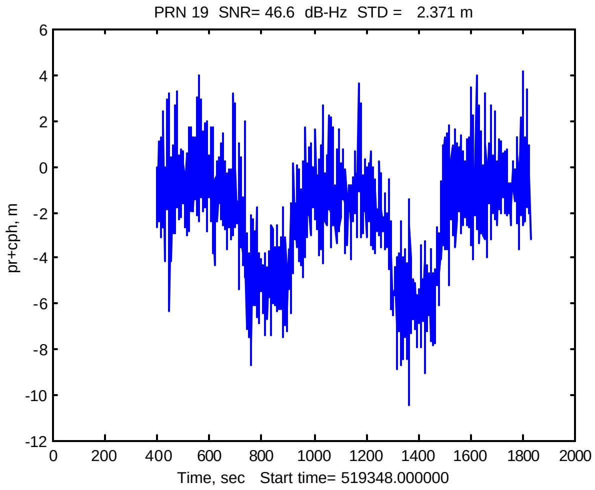

Figure 26 Mobile HAGR PR+CPH - PRN 19

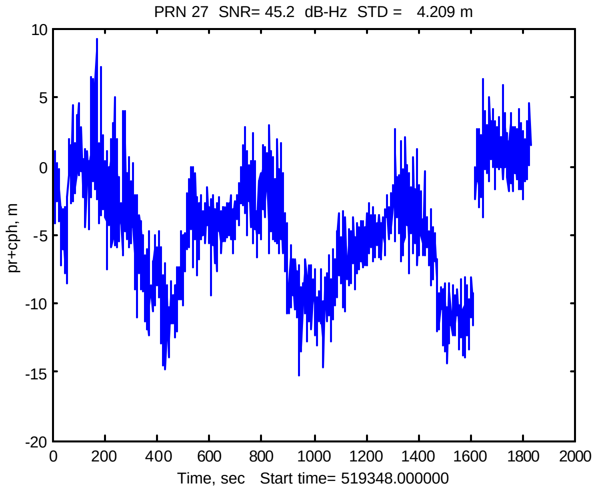

Figure 27 Mobile HAGR PR+CPH - PRN 27

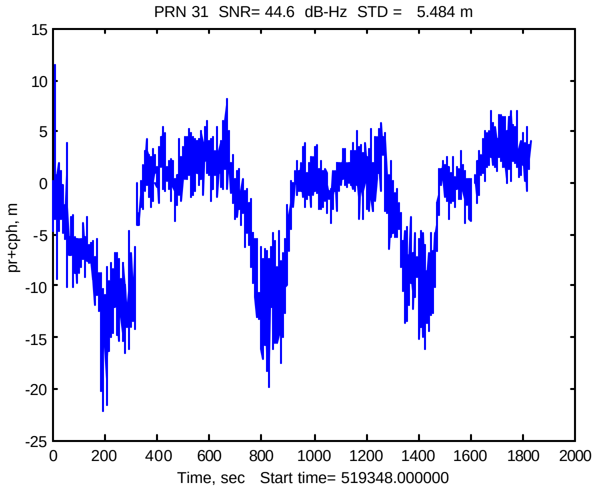

Figure 28 Mobile HAGR PR+CPH - PRN 31

CONCLUSION

These tests successfully demonstrated the ability of the HAGR digital beam former to operate in a mobile environment. The HAGR was able to maintain continuous carrier lock on the GPS signals while in motion. This enables the HAGR digital beam-former to be able to be used to provide a kinematic GPS solution from a vehicle while it is in motion. The results indicate that the performance should be comparable with previous static testing [2], which showed that the HAGR system is capable of better than 1 cm level positioning performance.

The digital beam-forming approach has the following advantages over a conventional GPS receiver, which are significant for many GPS kinematic applications, such as precision approach and landing or autonomous vehicle guidance where accuracy and reliability are key

- 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

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