Advanced GPS Hybrid Simulator Architecture

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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

NAVSYS has developed an Advanced GPS Hybrid Simulator (AGHS) architecture to address next generation GPS testing issues for the civilian and military markets. The AGHS is a hybrid software, digital and radio frequency (RF) GPS simulator design. In addition to providing digital and RF signal simulation capability, the AGHS can also be used to record and play-back real-world GPS signals from field tests.

This paper describes the modular AGHS architecture and its various uses. Digitally created simulation files were created with the system and played back into the NAVSYS Advanced GPS Receiver (AGR). Test results are included that compare the digitally created files to their real-world counterparts showing the precision that can be achieved with the AGHS digital simulation approach. Test data collected during jammer tests conducted at the Electronic Proving Grounds at Ft. Huachuca, Arizona is also presented.

INTRODUCTION

The next generation of GPS test and evaluation systems will need to incorporate the capability to test new technologies including (but not limited to) the new civilian and military signal structures, Controlled Reception Pattern Antennas (CRPA), the Wide Area Augmentation System (WAAS), the Local Area Augmentation System (LAAS), and the Joint Precision Approach Landing System (JPALS). There is a need for a flexible, re-programmable signal simulator architecture that can handle both the legacy GPS signals and also future signals that are planned to be implemented in the next generation GPS satellite constellation, including new frequencies, new code modulations and data formats.

For high accuracy applications, such as precision approach and landing, the fidelity of the carrier phase generated by the simulator is key. Using the hybrid digital signal generation approach, high fidelity signal simulation and truth data generation is possible eliminating many of the signal uncertainties that can be added using conventional signal generation and modulation methods.

The DoD is transitioning to much wider use of CRPAs to provide GPS anti-jam (A/J) improvements. Civilian use of high gain antenna arrays is also increasing for high accuracy applications. The phase-coherent multiple outputs of the AGHS can be used to simulate the effect of the GPS wave-front arriving at multiple antenna elements.

Modern GPS User Equipment (UE) adopt a digital architecture where the RF inputs are converted to digital signals and digital signal processing is used to extract the GPS satellite data. To allow high accuracy testing, the simulator should provide digital signal outputs in addition to the conventional RF outputs. The digital simulation outputs provide a high-resolution truth reference for performing mathematical analysis of the effects of the signal structure, or for testing high accuracy applications such as carrier-phase tracking for precision approach and landing.

ADVANCED GPS HYBRID SIMULATOR (AGHS) ARCHITECTURE

The AGHS architecture leverages NAVSYS' MATLAB Signal Simulation[1] capability, and the Digital Storage Receiver (DSR)[2] data recorder and remodulator capability to provide high fidelity hybrid RF and digital signal simulation. The AGHS architecture is illustrated in Figure 1. The individual components that comprise the AGHS are described further in the following sections.

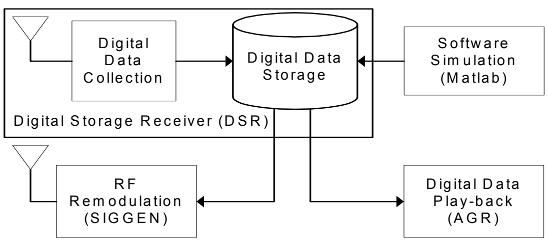

Figure 1 Advanced GPS Hybrid Simulator Architecture

DIGITAL STORAGE RECEIVER (DSR)

The core of the hybrid simulator is NAVSYS' broad-band DSR product[3]. The DSR is designed to capture segments of digitally sampled GPS data and record them to disk. The recorded digital signals can be generated either through logging real-world GPS signals collected from a GPS receiver Digital Front End (DFE), or by recording files generated with our MATLAB Signal Simulation Toolbox.

Figure 2 Sixteen Element L1/L2 Antenna Array

The DSR can be configured to record data from up to 16 independent antenna elements. This allows logging of real-world data from a digital phased array, such as the High Gain Advanced GPS Receiver (HAGR) array shown in Figure 2, or from dual frequency (L1/L2) 7-element Controlled Reception Pattern Arrays such as the CRPA shown in Figure 3.

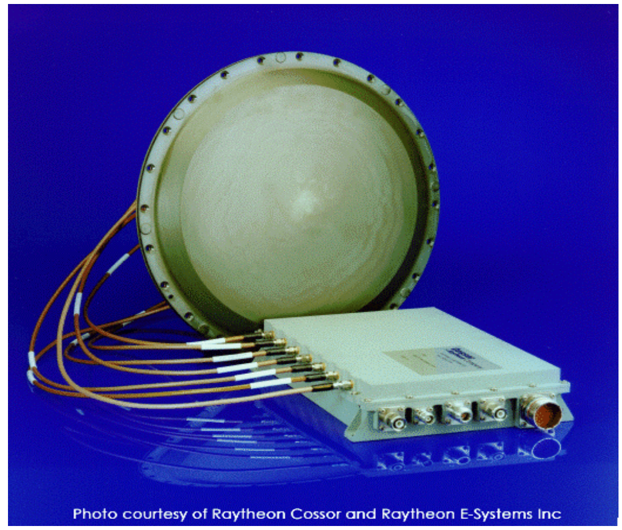

Figure 3 Controlled Reception Pattern Antenna

The digital data can be recorded at a sustained data rate of 80 Mbytes/sec. The basic system can record to 1200 GB of data. The data logger is a modular design which allows the data storage to be scaled depending on the user's requirements. Between 1 to 14 bits of data can be recorded from each antenna element to the maximum throughput allowed. Multiple data loggers can be run in parallel for wide data width and multiple antenna element recording. For example, the system can be used to record 4-bits of data from each of 14 antenna elements (7 elements L1 and 7 elements L2), or 8-bits of data from each of 7 antenna elements (7 elements L1 or 7 elements L2). The total data capacity can also be increased by using larger disk drives. Table 1 illustrates recording times with a single data logger using 75 Gbyte hard drives.

Table 1 Maximum data logger recording times

	Recording time with 8 hard drives	Recording time with 16 hard drives
8-bits L1 and 8-bits L2 @ 40 MHz sampling	128 minutes	256 minutes
12-bits L1 or 12-bits L2 @ 40 MHz sampling	171 minutes	342 minutes

When ordering the DSR component of the AGHS, the user should specify the following.

- Number of antenna elements to be used (L1 and/or L2)
- Number of bits to record from each antenna element.
- Maximum data logger capacity.

MATLAB SIGNAL SIMULATION TOOLBOX

NAVSYS' MATLAB signal simulation Toolbox was developed to allow software simulation of the GPS signal in space. This provides a high fidelity model of the GPS signal environment and can also model the effects of interfering signal sources, antenna and receiver characteristics on the received GPS signals[4].

This Toolbox is a complete set of GPS signal simulation, test, and analysis tools. The MATLAB signal simulation tool simulates the effect of the signal degradation on a conventional commercial GPS receiver, including the effect on the code and carrier tracking loops such as losing lock or cycle slipping. The Toolbox's geographic tools facilitate the transformation of data between the various coordinate systems commonly used in GPS research, including latitude-longitude-altitude, WGS-84 ECEF, North-East-Down, and body reference frames. It also provides tools to read GPS almanacs and ephemeredes and compute ECEF and line-of-sight vectors to GPS satellites as a function of user position and time. The receiver design and analysis tools model different receiver architectures and simulate different error scenarios by providing tracking and navigation algorithms, including Phased Lock Loops (PLL) and Delay Locked Loops (DLL). The user configurable options allow the operator to define virtually all aspects of a GPS signal environment, including the GPS spreading code(s), navigation message and interference scenarios. Such flexibility is particularly useful in simulating next generation GPS signal structures, or a simulated GPS jamming environment.

The MATLAB scripts used to generate a simulated data segment are shown in Figure 5. The user profile can be entered either as a sequence of waypoints (time, latitude, longitude, altitude) from which a trajectory is interpolated and the satellite range and doppler is computed using the specified satellite ephemeris, or as an option the raw satellite measurements can be provided instead. The GPS data modulation can also be specified independently or automatically constructed from the SV Ephemeris data. The raw measurements are then generated at a 1-kHz rate for signal reconstruction. Next, the user selects which spreading code to use (C/A, P, M, etc.) and its characteristics (chipping rate, repetition rate, power, etc.) for the satellites. A receiver model is then used to generate the raw digital data at the receiver sample rate (up to 40 Msps) to be recorded to the DSR data logger for later playback.

Because these tools are linked directly to MATLAB, it is relatively simple to define and implement new signal components as they become available. Of primary interest are the new GPS signal structures including the new civilian and M-codes as well as new and exotic categories of jammers, including FM, AM, PM and frequency swept jammers. The signal spectrum from a simulated data set including C/A, P and M-code is shown in Figure 4.

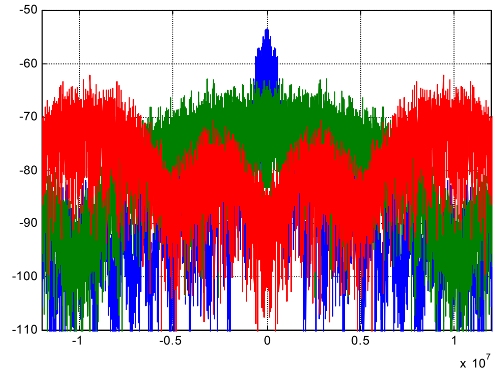

Figure 4 MATLAB Simulated C/A, P and M-code Signals

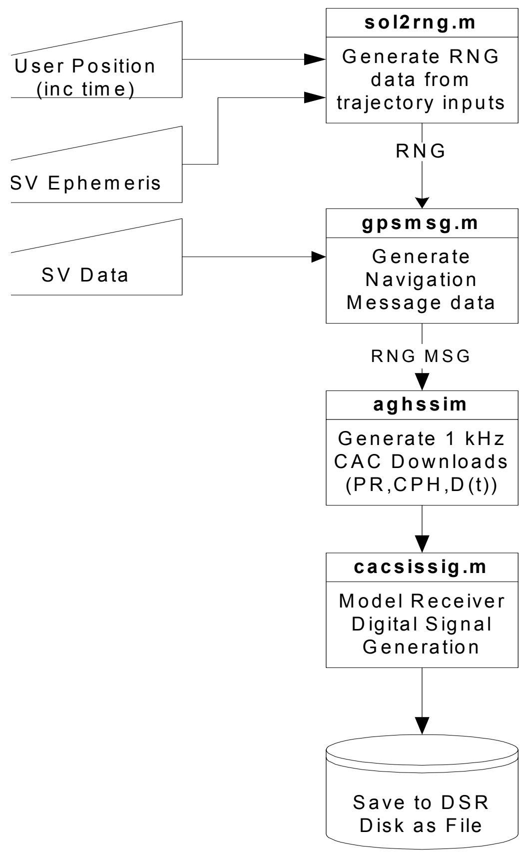

Figure 5 AGHS MATLAB Signal Simulation

RF REMODULATION AND DIGITAL PLAYBACK

The RF Remodulation component of the AGHS is used to remodulate the GPS digital data from the DSR data logger onto an RF carrier for output to GPS User Equipment under test. Both single and dual frequency modes of operation are supported.

The AGHS also can be configured with a digital signal playback capability. In this mode, the digital signals from the DSR are played back directly into the digital signal processing card of our AGR[5] in place of the real-time digital signals from the AGR (DFE). The software reprogrammable features of the AGR allow it to be configured to emulate the performance of different types of receivers by adjusting tracking loop bandwidths and thresholds. This provides a convenient mechanism for evaluating the performance of alternative receiver configurations.

The AGHS can also be configured to replay signals recorded from multiple antenna elements back into the digital spatial processing logic of NAVSYS' HAGR[6]. The weights applied by the HAGR are software generated which allows analysis of the performance of different spatial processing algorithms on the same AGHS recorded data set.

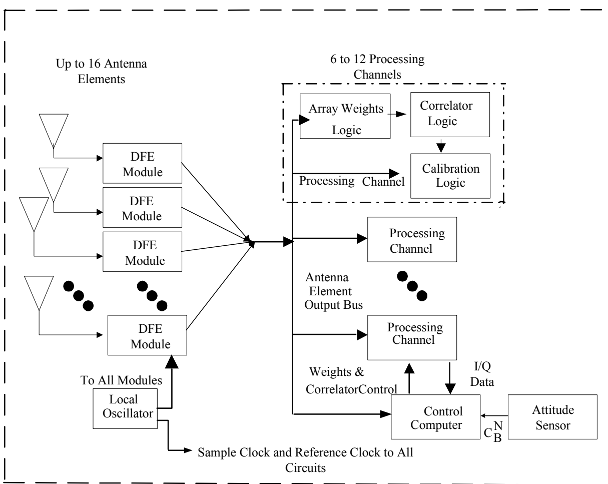

Figure 6 P(Y) HAGR System Block Diagram

AGHS DIGITAL SIMULATION TEST RESULTS

To demonstrate the high fidelity of the AGHS digital signal generation functions, a stationary simulation was run, with position solutions entered to compute the rng data (sol2rng) at 1 Hz intervals. A Yuma format almanac file was used to create the navigation messages used. The DSF file created by the AGHS was then tracked using the AGR and the pseudo-range and carrier phase accuracy was compared against the simulated rng data inputs.

The accuracy of the simulation was verified by comparing the actual observations (pseudo-range, carrier-phase and navigation solution) from tracking the digital signal format (DSF) file in the AGR with the simulated range profile that was generated. In Figure 7, the signal-to-noise ratio from the simulated data is shown. To observe the measurement accuracy, the double-difference carrier-phase observations (simulation truth – tracked data) are plotted in Figure 8. The 1-sigma standard deviation of the double-differenced carrier phase observations are between 2.8 mm and 3.6 mm for all eight satellites tracked. With a nominal C/N0 of 38 dB-Hz, the 1-sigma double-differenced carrier phase observations should have a value of 4 mm based on the theoretical AGR measurement noise level. This indicates that the simulation is operating at the limit of the expected precision. The pseudo-range + carrier-phase observations from the tracked data are shown in Figure 9. These show that the 1-sigma pseudo-range noise is around 0.4 m which is close to the theoretical level expected based on the signal-to-noise ratio.

The navigation solution generated from this data, differenced with the simulated location is shown in Figure 10. The solution is computed correctly indicating the simulation has modulated the navigation data correctly onto the signal. The variation in the navigation solution is caused by the pseudo-range noise described above, scaled by the satellite geometry dilution of precision. There was no carrier smoothing used in computing this navigation solution.

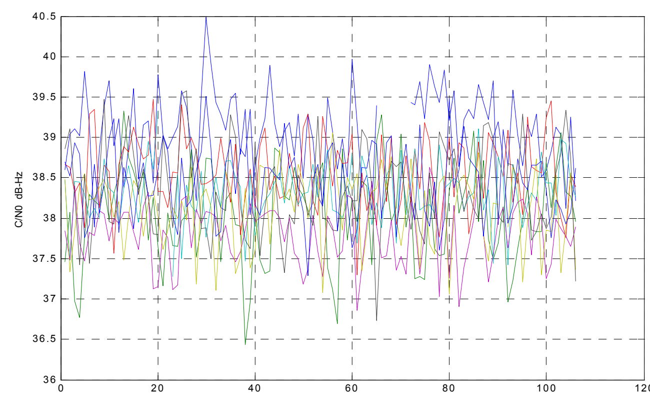

Figure 7 Signal-to-Noise Ratio Data

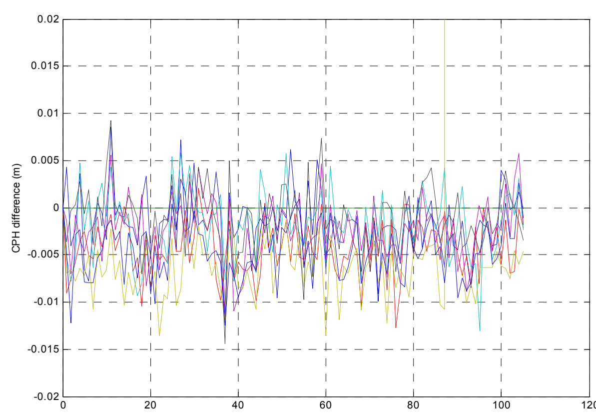

Figure 8 Double-Differenced Carrier Phase (m)

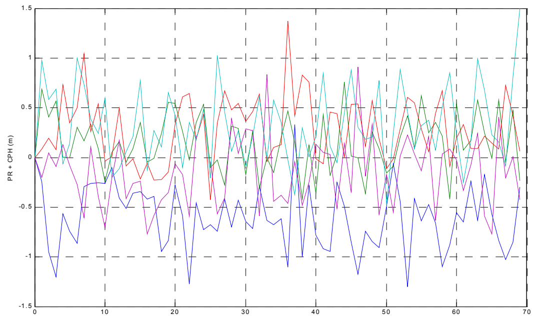

Figure 9 Pseudo-range + Carrier-phase (m)

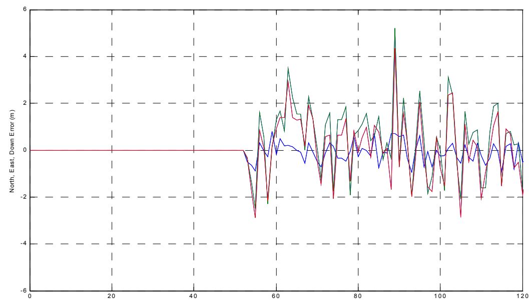

Figure 10 Navigation Solution Error

DATA RECORDING AND PLAYBACK

The DSR component of the AGHS was used to record a test segment from a conventional GPS signal simulator and then play back this test segment as a digital signal into NAVSYS' AGR. In this test, our customer used the Digital Storage Receiver to log a test segment of GPS RF data generated using a conventional GPS satellite simulator. This was programmed to generate a high dynamic trajectory emulating a sled-test. The DSR recorded digital data was then played back into the digital signal processing card in NAVSYS' AGR. The AGR configuration parameters were optimized to allow high dynamic tracking. The tests were repeated with different configuration parameters to evaluate their effect on maintaining lock during the simulated trajectory. The navigation solution file generated by the AGR from this test segment is illustrated in Figure 12. This showed the capability to maintain carrier lock on the GPS signals through jerks of up to 50 g/sec.

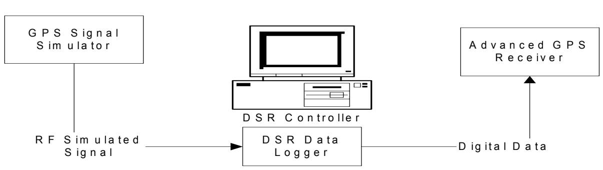

Figure 11 Digital Storage and Playback Test Set-up

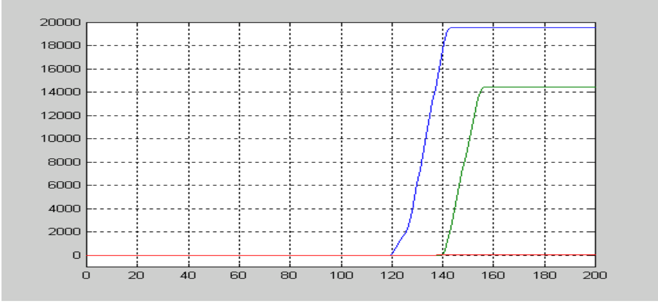

Figure 12 AGR 50 g/sec Navigation Solution (N,E,D offset (m))

AGHS GPS JAMMER TEST RESULTS

The AGHS was used at the Army's Electronic Proving Ground (EPG) at Ft. Huachuca, Arizona, during live jamming tests. The jamming source was a 10 MHz wide noise jammer centered at L1. During the tests the DSR component of the AGHS was used to log a copy of the RF signal environment for historical purposes from a 16-element phased array. The digital data recorded from one antenna element was later played back into the NAVSYS AGR to show the effects of the jamming on a conventional GPS receiver. The AGR configuration parameters can be changed on playback to evaluate the effects of jamming on various tracking loop parameters. Figure 13 shows one playback scenario, with the jamming starting at 1:00 pm local time. In this AGR configuration all channels lost bit sync when jamming started but maintained carrier lock with the exception of one lower power satellite.

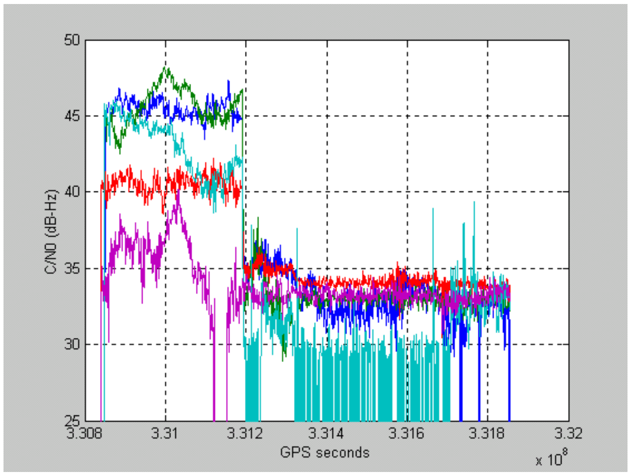

Figure 13 AGR reported C/N0 values for jammer playback file

The NAVSYS HAGR[7] was used as a reference receiver during the jamming. The reprogrammable 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 eight GPS satellites simultaneously.

The test results presented were collected with the HAGR operating with the C/A code. A Precise Position System (PPS) version of the HAGR (the P(Y) HAGR) is also in development with 12 channel L1 and L2 capability. The HAGR was compared with a Rockwell SOLGR receiver. The SOLGR was tracking the P(Y) code on L1. Figure 14 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 15 to Figure 26 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.

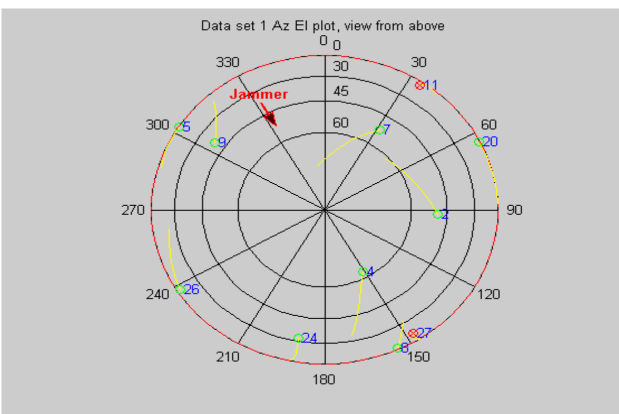

Figure 14 Satellite positions during jamming tests

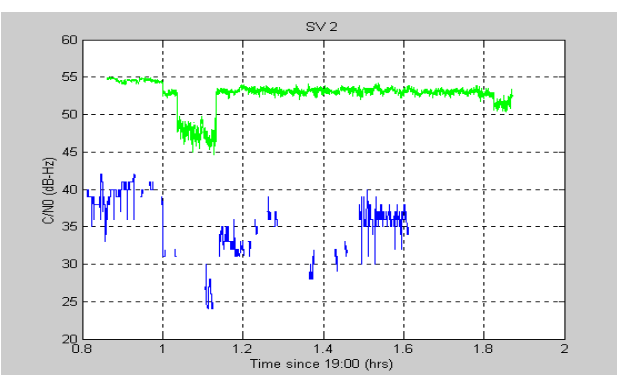

Figure 15 SV 2 C/N0

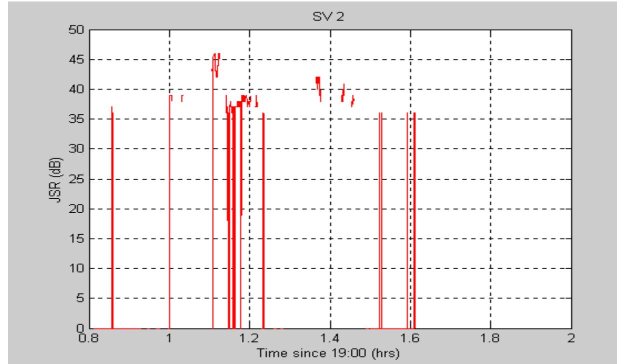

Figure 16 SV 2 SOLGR L1 P(Y) JSR

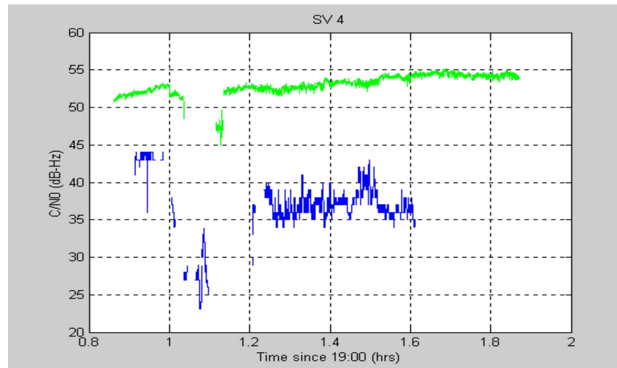

Figure 17 SV 4 C/N0

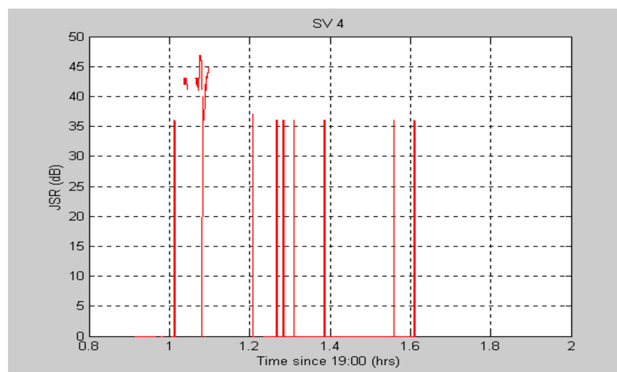

Figure 18 SV 4 SOLGR L1 P(Y) JSR

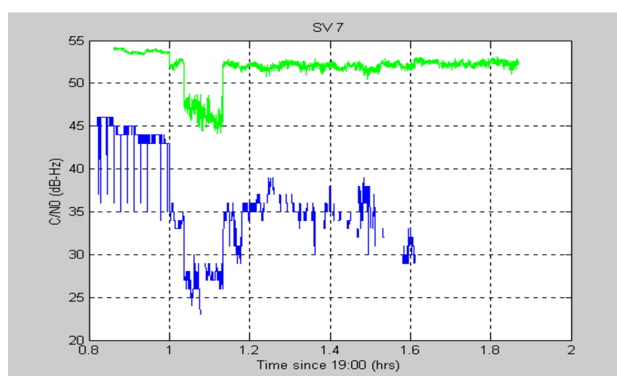

Figure 19 SV 7 C/N0

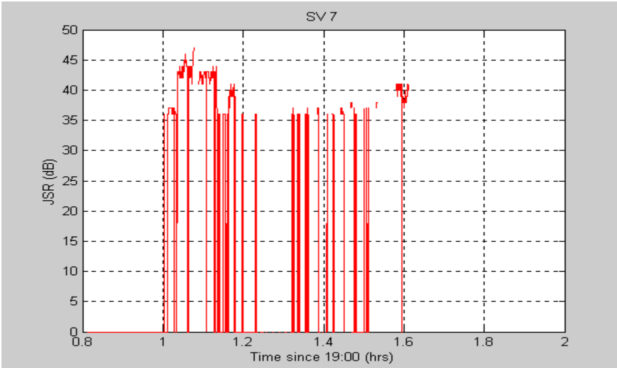

Figure 20 SV 7 SOLGR L1 P(Y) JSR

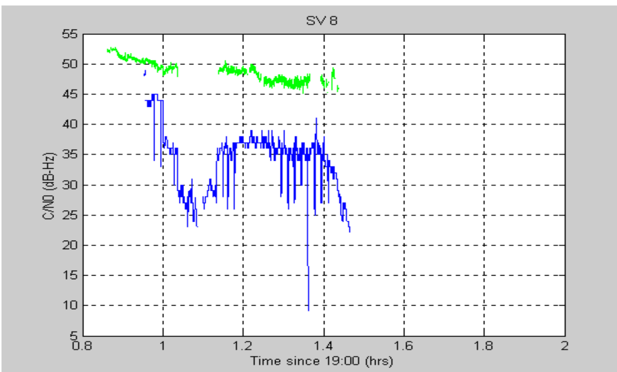

Figure 21 SV 8 C/N0

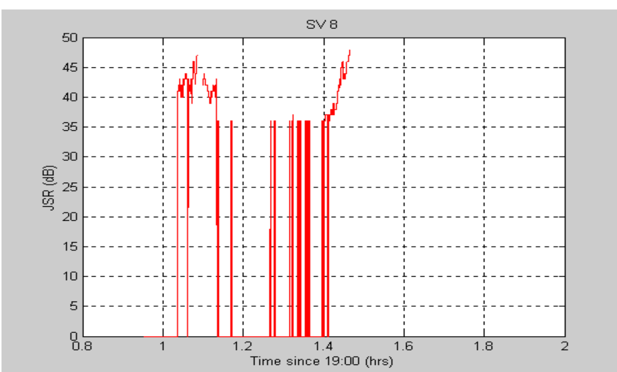

Figure 22 SV 8 SOLGR L1 P(Y) JSR

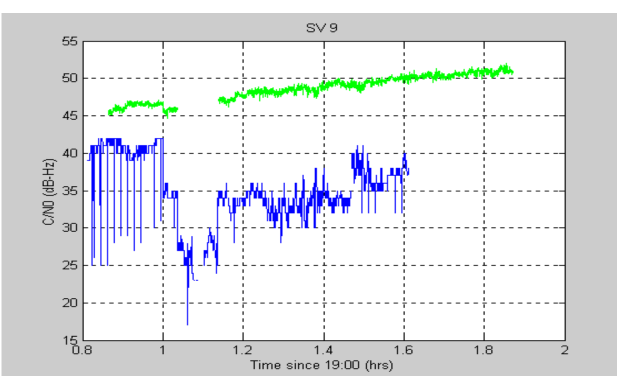

Figure 23 SV 9 C/N0

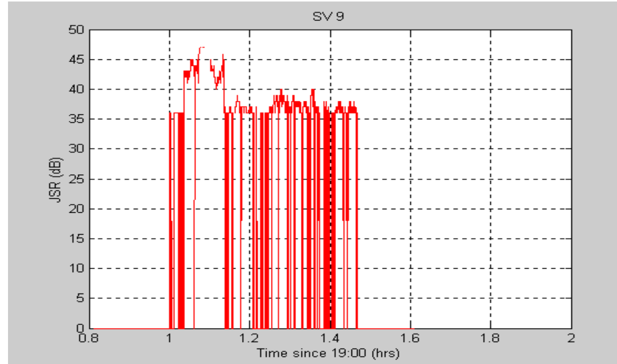

Figure 24 SV 9 SOLGR L1 P(Y) JSR

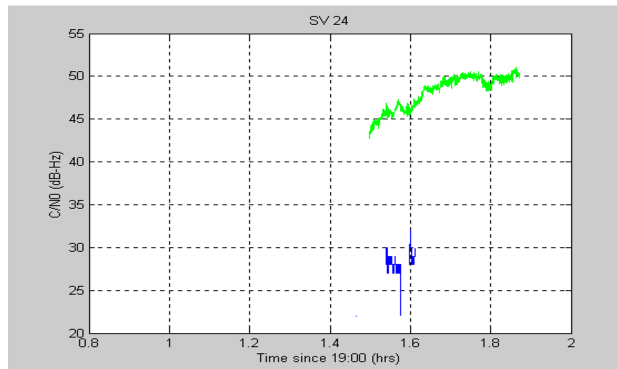

Figure 25 SV 24 C/N0

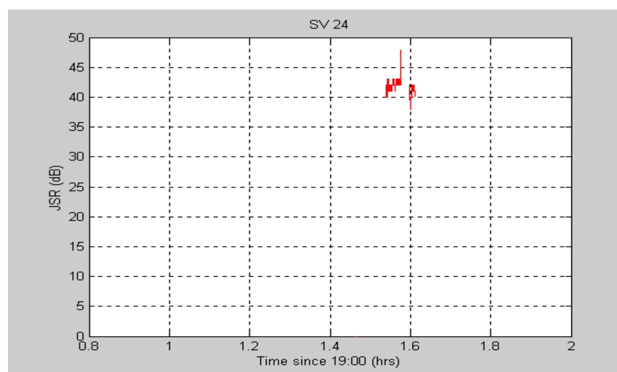

Figure 26 SV 24 SOLGR L1 P(Y) JSR

CONCLUSION

The test results presented in this paper have demonstrated the utility of the Advanced GPS Hybrid Simulator for providing high fidelity simulated GPS signals and in recording and playing back real-world test scenarios for post-test analysis.

This hybrid signal simulation approach has the following advantages over previous analog GPS signal simulators.

- Access to all levels of satellite signal generator control through NAVSYS' MATLAB satellite and signal generation scripts

- Software interface for insertion of future GPS signals or simulated jammer waveforms onto composite digital satellite signal profile.
- Digital data storage for exact reconstruction and playback of signal simulation profiles
- Digital output from the simulator of pre-recorded or real-time simulated signals
- Digital tracking of the recorded signals for high fidelity signal reconstruction and analysis
- High fidelity, phase coherent RF remodulation of digital signals for output to a GPS receiver or multi-element CRPA

ACKNOWLEDGMENTS

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