Modeling and Simulation of GPS Using Software Signal Generation and Digital signal Reconstruction

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

Keith Taylor is a Project Manager for NAVSYS Corporation. He is responsible for developing MATLAB based GPS signal simulation tools for user selectable signal environments and jamming scenarios. He holds an MSEE from University of Florida and a BSEE from the University of Louisville.

Neil Gerein is a Project Manager for NAVSYS Corporation. He is responsible for a rapid acquisition FFT based GPS receiver system (COGNAC) and has developed firmware for Xilinx FPGAs and Altera CPLDs. He is currently completing his M.Sc. in Electrical Engineering and holds a BSEE in Electrical Engineering from the University of Saskatchewan.

ABSTRACT

GPS satellite simulator test facilities are used to checkout the software and hardware of GPS receivers and their augmentation systems. In general, they include satellite signal simulators, differential augmentation simulators and interface emulators. All testing is run in real time and requires considerable hardware and human assets. Initially, the dynamic scenario to be simulated must be designed and stored in the simulator control computer. This scenario specifies all relevant factors including the trajectory of the GPS receiver(s), the satellite constellation, the signal power and waveforms, environmental factors including propagation errors, and jamming effects. In general, there is considerable equipment setup and calibrations that must be performed prior to actually exercising the scenario. In addition, the satellite simulator and control equipment are expensive resources typically costing on the order of one million dollars.

NAVSYS have developed a MATLAB product that allows software simulation of complex GPS environments to be constructed. 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. The output of the software simulation is a digital file for the selected scenario that represents the digitally sampled GPS signals from a GPS receiver in that environment.

The digital file can be played directly into a digital receiver to evaluate its performance under the originating environment or, alternatively, can be remodulated on a RF carrier to provide digital reconstruction of the simulated signal. The advantages of this approach can be summarized as follows:

- Enables follow-on tests at different time and locations without most expensive resources and preparation;
- Simulates nearly exact, repeatable RF conditions as many times as necessary;
- Saves exact RF conditions for historical and legal purposes.

In this paper, the software signal generation tool and digital signal reconstruction capability developed by NAVSYS is described and test results are include demonstrating its application for historical and legal purposes.

INTRODUCTION

The data playback capability through the RF Modulator enables high fidelity simulation of the GPS satellite signals. Using NAVSYS' signal simulation toolbox, the

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GPS satellite signals can be modeled under a wide variety of different environments.

This capability has been used to perform software simulation of the effects of GPS receivers in jamming environments, in high dynamic environments and during extreme atmospheric effects, such as ionospheric scintillation. With the digital data playback and RF Modulation capability, these simulated environments will be able to be played back to a GPS receiver through a simulated RF signal. This capability will give a highly flexible, high fidelity signal simulation capability for test and evaluation of the performance of GPS receivers under different conditions.

SIMULATION TOOLS

NAVSYS have developed a MATLAB product that allows digital files to be generated for completely configurable GPS signal environments. This provides low level visibility over virtually every aspect of GPS navigation, from signal characteristics to receiver design to navigation processing algorithms.

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 of the ionospheric activity 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).

In Figure 1, the overall flexibility of the toolbox is illustrated. 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 GPS jamming environments, where time, resources and repeatability are generally scarce.

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 forthcoming M-codes as well as new and exotic categories of jammers, including FM, AM, PM and frequency swept jammers.

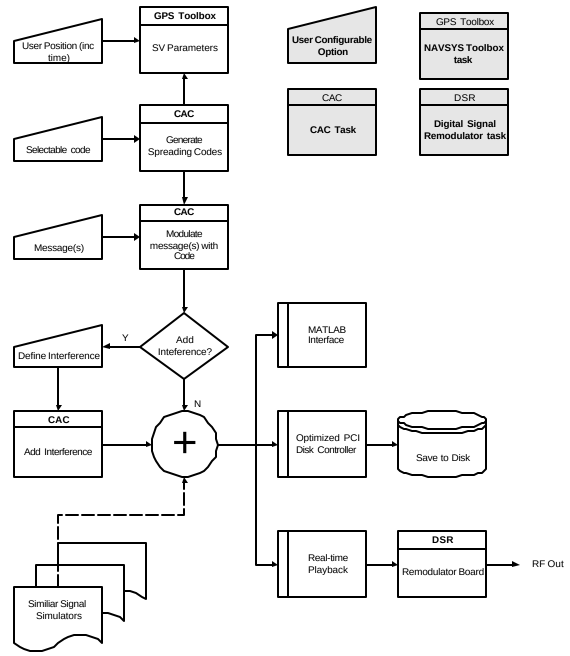

Figure 1 MATLAB Toolbox Configuration

Once the simulation data exists, it can be handled in a variety of ways. Obviously, the data can be used in the MATLAB environment, where there are existing, optimized digital signal processing routines and data manipulation tools. The communications channel (e.g., atmosphere) can be modeled to the required degree of accuracy, as can the antenna and receiver front end. This particular capability is essential in receiver and algorithm development.

Alternatively, the simulated signal can be input to existing GPS receivers. For an all digital receiver such as the NAVSYS Advanced GPS Receiver (AGR) or High gain AGR (HAGR), the data are fed serially into the channel inputs[1]. By using a Digital Signal Reconstruction (DSR) device, the signal can be remodulated at some intermediate frequency and fed directly into a conventional receiver, or back on the L1 carrier to be re-radiated.

Storing the simulated signal in file format enables the same scenario to be replayed with different equipment or modified equipment versions. This capability provides low level visibility and precise control of the actual simulated environment. For example, in source selection applications, the scenario may be rerun with many competing vendors' equipment. Furthermore, in source selection applications, it may be desirable, for historical or litigation purposes, to have a permanent record of the scenario that was run.

This simulation tool and analysis capability has been used under contract to the Army to develop high fidelity high dynamic carrier phase tracking algorithms[2], and was used by the Signal Simulation Control Working Group (SSCWG) to provide a test capability against which other signal simulators could measured.

The simulation is inherently a computationally expensive task when used exclusively with MATLAB. To expedite matters, the NAVSYS Correlator Accelerator Card (CAC) can be used in lieu of MATLAB routines. Though not required for the simulation tools, the CAC is designed around Field Programmable Gate Arrays (FPGAs) and is itself extremely flexible and reprogrammable.

DATA LOGGING AND PLAYBACK

The processing tools provided by the toolbox can also be used on real world data by incorporating a Digital Front End (DFE) and CAC. This configuration provides the most complete and accurate signal environment since it records actual signals. The primary concern here is the speed at which the data are collected and saved. Conventional hardware and PC bus speeds cannot accommodate the speed necessary for recording GPS data.

NAVSYS uses an optimized PCI controller card that bypasses the CPU of the controlling PC and transfers all the data between the CAC and storage device over the PCI bridge (Figure 2). That is, the data logger transfers the incoming data direct to the PCI controller card that records the data sequentially to one of up to eight separate hard drives. The transfer rate is specified at up to 800 Mbits/sec. Using 37.5 GB hard drives, over two hours of 8 bit, 40 Msamples/sec data, or over 80 minutes of 12 bit, 40 Msamples/sec data can be collected and stored.

Because of the flexibility of the CAC, the reverse operation is easily accomplished, whereby the stored data is passed to the CAC via the PCI controller, and then to either a full digital receiver such as the HAGR, or to a DSR for input to conventional GPS receivers.

For a fully populated system, up to seven separate receiver channels can be realized. This will ultimately allow the simulation workstation to model beamforming systems using Controlled Radiation Pattern Antennas (CRPAs) or other phased array or time delay antenna configurations.

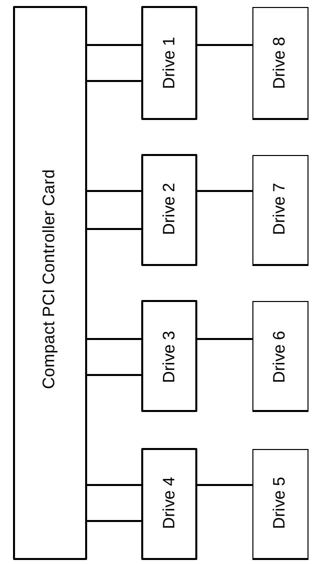

Figure 2 Real time data collection/playback

No capability currently exists to playback pre-recorded or simulated digital GPS signals to a GPS UE. This digital playback system will enable new approaches to be taken for test and evaluation of advanced GPS receiver capabilities using high fidelity digital simulation tools in place of the RF simulators currently in use today.

ADVANTAGES AND APPLICATIONS

The post-test analysis capability this simulation possesses enables it to be used to emulate segments of the GPS signal environment for detailed analysis. NAVSYS' customers have used this capability for a variety of different applications.

For example, a similar digital recording architecture described above has been used to collect flight test data that provided measurements on the signal reception characteristic of a GPS pseudolite from an aircraft with a top and bottom mounted GPS antenna[3]. This flight test data was then played back post-test to replay the flight experiment through different configurations of a pseudolite receiver to develop optimized tracking performance in the environment.

This same architecture has also been used for tracking missiles. NAVSYS delivered hardware to the Space Strategic Defense Center (SSDC), which was installed on two Strypee missiles[4]. The digital front-end was connected to a 2 Mbps telemetry link and the data was recorded at the range for post-processing. This digital GPS translator architecture was used to demonstrate the ability to maintain carrier lock under high dynamics using test data collected from these missile launches and from test data collected at the Holloman test track[5].

An older generation version of our NDAQ was used to collect GPS signals from an aircraft flying above the ocean to characterize the specular component of the GPS signal that would be received by sea-skimming missiles. This was post-processed producing the first quantified results of multipath signals in a land and sea environment[6].

DIRECT P(Y) CODE ACQUISITION

To maintain a strategic advantage in a tactical situation, the DoD plan to deny access to the C/A code signals. This will require all DoD UE to perform direct Y code acquisition. Under the MAGR-U ACTD program, a massive digital correlator is being demonstrated. However, large-scale digital correlators are very power intensive and are not suited for low-power hand-held operations. The Rapid Acquisition FFT (RAFFT) algorithm developed by NAVSYS utilizes the simulation toolbox and provides a much more efficient solution to enable large numbers of correlations to be performed extremely rapidly. This allows rapid search and acquisition of the Y-code GPS signals. The performance improvement in the signal acquisition and tracking performance using the RAFFT device also opens up A/J applications for GPS receivers

The problem of acquiring a long pseudo-noise code has conventionally been handled in the case of GPS by first acquiring a shorter code, C/A, which, in conjunction with the data message, enables time synchronization for subsequent acquisition of the P(Y) code. The disadvantage of first acquiring the C/A is that it is an unencrypted code and can be more easily spoofed. The classical difficulty with the long code is that the search process, which must be performed in the two dimensions of code phase and carrier frequency, takes too long under most practical signal to noise ratios. The P(Y) code has a very low repetition-rate-to-bandwidth ratio and, as a result, synchronization of a receiver to a specified modulation constitutes a major difficulty.

Considerable research and effort are now being expended to reduce the acquisition time by either: 1) aiding the receiver with extremely accurate time and frequency 2) increasing the hardware resources in the receiver, usually accomplished with a massively parallel correlator design, which increases the number of independent correlators

Equation 1

$$I_k = \int_{(k-1)T_c}^{kT_c} I(t)dt \quad Q_k = \int_{(k-1)T_c}^{kT_c} Q(t)dt$$

The process of aligning the biphase modulated P(Y) code to within half a code chip, is referred to as acquisition. The locally generated PN-code is set at some initial code epoch and the carrier is set at some initial carrier frequency. This replicated signal is cross correlated with the received signal plus noise, coherently integrated over a Predetection integration time denoted as T_c, thereby generating the in-phase and quadrature samples $I(kT_c)$ and $Q(kT_c)$, respectively.

Equation 2

$$z = \sum_{k=1}^{N_{NC}} I_k^2 + Q_k^2$$

Equation 3

$$P_{FA} = \Pr ob(z \geq g s_n^2 \mid CN_0 = 0)$$
$$= Q(g \mid 2N_{NC}) = 1 - P(g \mid 2N_{NC})$$

Equation 4

$$P_{MD} = \Pr ob(z < g s_n^2 \mid CN_0 = CN_T)$$
$$= P(g \mid 2N_{NC}, N_{NC} \times CN_T)$$

As shown in Equation 2, these are then square-law detected, and, if necessary, summed with other samples. The sum of the samples is then compared to a detection threshold, the magnitude of which is dependent on the allowable probabilities of false alarm and successful detection. In Equation 3 and Equation 4 the algorithms for computing the probability of missed detector and false alarm are shown for a specified signal-to-noise threshold (CN_T). These are derived in terms of the chi-square function $P(\gamma|2N_{NC})$ and the non-central chi square function $P(\gamma|2N_{NC},\lambda)$. The correlation functions for various coherent integration times are shown in Figure 3.

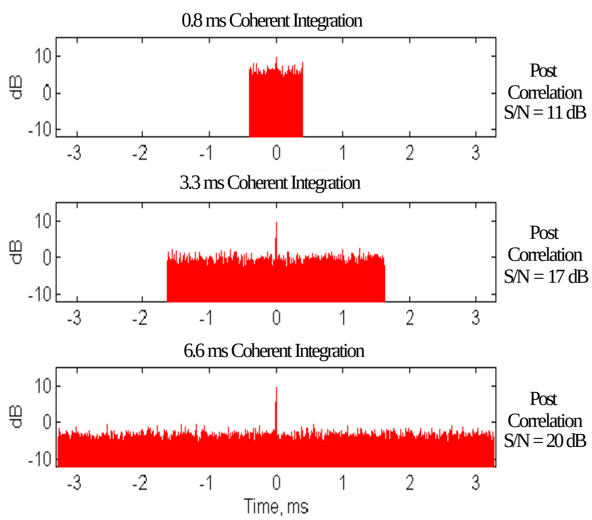

Figure 3 Correlation functions for various coherent integration times

The process of integration over T_c is known as the *predetection integration* interval. In general, to reduce the effects of noise on the operation of the detection process, it is desirable to make T_c as large as possible, before having to resort to summing over N_{NC} noncoherent samples (I^2+Q^2). However, the length of T_c is limited by the frequency uncertainty, which in turn is due to oscillator instabilities and unknown Doppler effect.

Each search must be performed for every possible code-phase/Doppler frequency bin.

The uncertainty in code phase is due to user clock uncertainties plus user to satellite range uncertainty. For example, a user clock uncertainty of one millisecond (random zero mean Gaussian bias - one standard deviation) and an additive user to satellite range uncertainty of 30,000 meters (random independent Gaussian bias - one standard deviation) would result in a 3-sigma (99%) search region of 10279 x 2 x 2 x 3≅123,345 bins. It is this large number of bins to search which creates, in many operational scenarios, the impracticality of direct P(Y) acquisition in an acceptable time.

The acquisition time varies directly with the product of the coherent integration interval, T_C and the number of summations, N_{NC}. This product is sometimes referred to as the dwell time per bin for a single search frequency. In conventional GPS receivers, the acquisition process must occur in real time implying that the signal must be always available in real time. This furthermore means that the antenna must be exposed during the lengthy long code acquisition process.

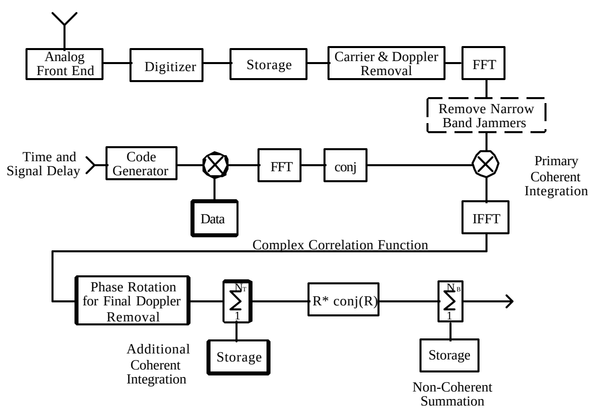

Figure 4 Digital storage receiver and processor

The ability to emulate and/or store GPS signals provides a unique strategy illustrated in Figure 4. By storing the broadband signal, the signal can be recirculated in non real-time among the correlator resources. Instead of having to slew the correlator resources in real time to the incoming signal until synchronization is achieved, the simulation can recirculate the wideband signal in post time without requiring further signal collection. Since, at least theoretically, the signal can be replayed forever, the storage concept guarantees an eventual acquisition within the given exposure time.

Theoretically, for very short data collection intervals, one would have to be concerned with the uniqueness of the sample of the code pattern; however, for practical purposes, data collection intervals less than one second are not required and therefore the uniqueness of a pattern 10^7 bits or longer is not an issue. This particular strategy can be used in situations where only "snapshots" of the signal environment are available.

INTERFERENCE

GPS has been adopted for virtually every military mobile operation and will be the primary navigation equipment for all phases of commercial flight. Of critical importance are its accuracy, integrity, availability, and continuity of service in these applications. As a low power radionavigation system, it is susceptible to both intentional and inadvertent interference.

The situational awareness of the availability and health of the GPS signal in the operational area of interest is required. If the GPS signal is being jammed, then the nature of the jamming signal, its source and location are of critical importance. This information will be necessary to take corrective action including prosecution of the interfering source.

The ability to integrate over long periods of time (non-real time) without excessive computation time permits a breakthrough in acquisition performance in the presence of jamming. The FFT based acquisition method significantly reduces the number of computations required to form a correlation over a particular time window. Very long coherent integrations are made possible by the ability to coherently combine multiple FFTs in single coherent integration.

The enhanced signal simulation and acquisition capabilities also make it possible for the system to process GPS signals that have been severely attenuated (in the neighborhood of 25 dB attenuation giving a C/No of 13 dB-Hz). With the next generation GPS satellite constellation it is being considered to increase the signal power transmitted by the satellites. It is necessary to quantify the signal attenuation into buildings, urban canyons, and dense foliage in order to determine whether the increase in signal power would enable operation in these different environments, increasing the GPS signal availability for urban warrior scenarios. The U.S. Coast Guard Academy is investigating this issue, but the signal attenuation makes it impossible for a normal receiver to detect the signals and make a signal strength measurement.

The simulation toolbox not only allows one to simulate a scenario with increased GPS signal power, it also permits the theoretical design and evaluation of tomorrow's GPS receivers.

SIMULATION RESULTS

Figure 5 shows the resulting spectrum of a signal of a single satellite, both C/A and P code generated using the MATLAB toolbox. After adding noise to achieve a jamming to signal ratio (JSR) of 44 and 50 dB, the results from the RAFFT algorithm for a perfectly coherent integration, and subsequent non-coherent integrations, are shown in Figure 6 and Figure 7. The number of accumulations was determined by specifying a probability of correct detection of 95% and consulting Figure 8. There is clearly a discernable peak at zero time offset, so we would expect good acquisition for this scenario.

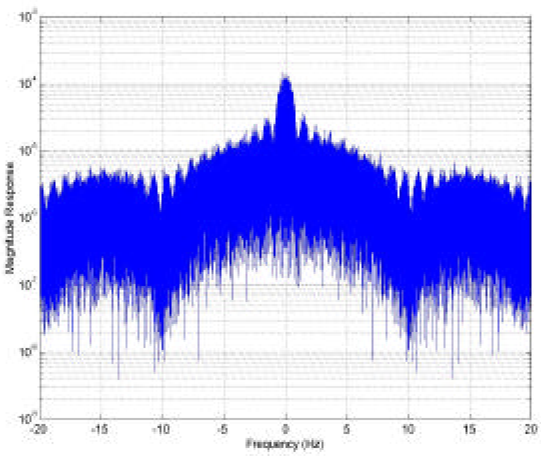

Figure 5 Spectrum of simulated signal, C/A and P code

The probability of correct detection (here detection is finding the correct peak not the squaring operation) can be generated by numerically integrating the following equation 5, where f(s) is the density function for the correlation peak with the signal, f(nmax) is the density function for the largest noise correlation given the correlation window, and Th is a minimum threshold. $f(n_{max})$ can be determined by numerically differentiating $F(n_{max}) = F(n)^W$ where F(n) is the cumulative distribution function of a single noise correlation and W is the number of independent correlation values.

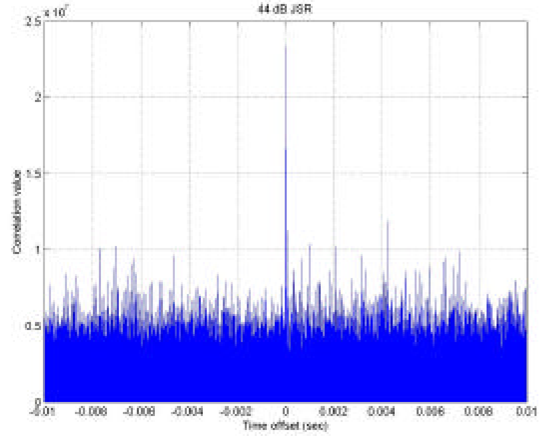

Figure 6 RAFFT for JSR = 44 dB

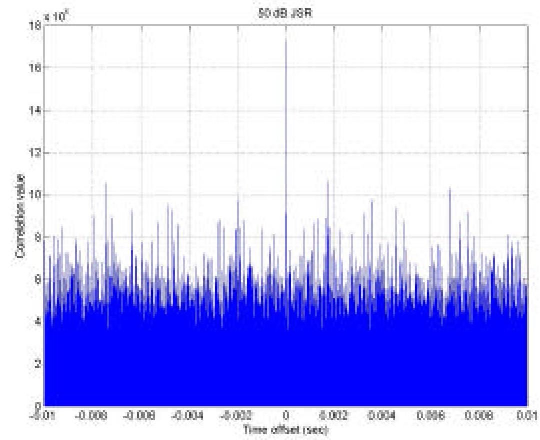

Figure 7 RAFFT for JSR = 50 dB

Equation 5

$$Pcd = \int_{n_{max}=0}^{Th} \int_{s=Th}^{\infty} f(s) \cdot f(n_{max}) \cdot ds \cdot dn_{max} + \int_{n_{max}=Th}^{\infty} \int_{s=n_{max}}^{\infty} f(s) \cdot f(n_{max}) \cdot ds \cdot dn_{max}$$

Figure 9 shows the probability of correct detection (Pcd) as a function of pre-detection S/N. It shows the probability that the signal correlation is above all the noise correlations for a 1 second window, assuming 20M independent noise correlations/sec. The curve on the right is for a single coherent integration. The curve on the left is for various additional non- coherent summations.

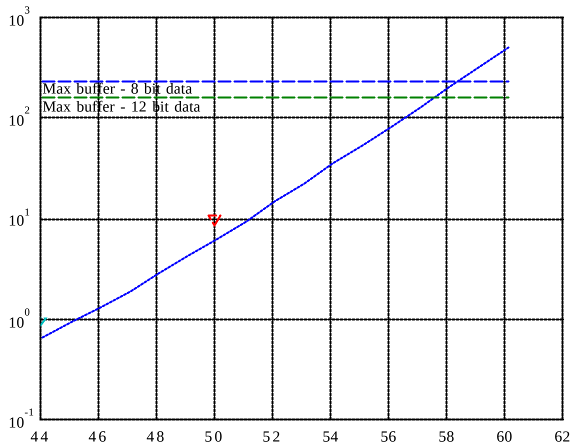

Figure 8 Theoretical required exposure intervals for a given JSR

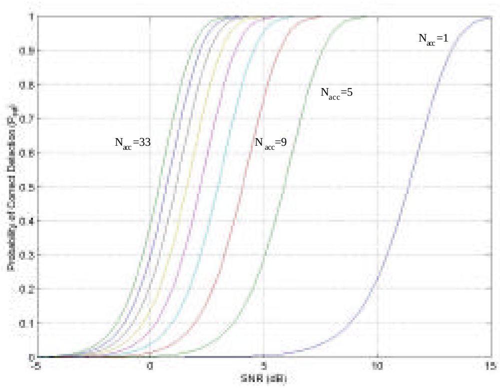

Figure 9 Probability of Correct Detection

CONCLUSIONS

The rapid improvement in computer throughput and processing power has made simulating such complex signaling schemes such as those employed by GPS a relatively easy task. The MATLAB simulation created by NAVSYS allows one to construct virtually any type of signaling environment for the GPS UE. By supplying a baseline environment, advanced concepts in GPS receiver design can be developed and tested within the MATLAB environment and transitioned to marketable hardware. A prime example of this approach is the HAGR developed here at NAVSYS.

The "extra" time afforded by digitally storing GPS signals allows more elaborate and complex processing algorithms. An example of such a system has been presented, and promises to be quite effective against jamming to signal ratios as high as 50 dB.

The digital files created by the simulation, or from recording real world data, can also be played back, either directly to an all digital GPS receiver such as the NAVSYS HAGR, or to conventional GPS receivers using the NAVSYS DSR capability, thus providing a baseline scenario for developing and comparing advanced GPS receivers.

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[1] E. Holm, A. Brown and R. Slosky, "A Modular Reprogrammable Digital Receiver Architecture," ION 54th Annual Meeting, Denver, CO, June 1998.

[2] A. Brown, A. Matini, D. Caffery, "High Dynamic, Dual Frequency Tracking with a Low Bandwidth Digital Translator", ION GPS-96 Conference, Kansas City, MO, Sept 1996.

[3] E.F.C. LaBerge, A. Brown, F. van Diggelen, T. Kelecy, "Flight Test Results of a Pseudolite-Based Precision Approach and Landing System," ION Sat Div Int'l Tech Mtg, Salt Lake City, Sept 1993.

[4] P. Stadnick, "Flight Test of an Integrated Digital GPS Translator", IEEE, 1996

[5] A. Brown, Robert Wilkison, "Direct Sensor to Weapon Network (DSTWN) Architecture," AIAA, Huntsville, AL, October 98

[6] J. Auber at al, "Characterization of Multipath on Land and Sea at GPS Frequencies", Proceedings of the Institute of Navigation GPS-94 Conference, Salt Lake City, Utah