DETECTION AND LOCATION OF GPS INTERFERENCE SOURCES USING DIGITAL RECEIVER ELECTRONICS

Alison Brown, Sheryl Atterberg, and Neil Gerein, *NAVSYS Corporation*

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 Univ. In 1986 she founded NAVSYS. 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.

Sheryl Atterberg is a Product Manager at NAVSYS Corporation for Receivers, Antennas, and Data Loggers. Sheryl has a MS from Kansas State University (KSU) in Economics/ Industrial Engineering and BS degree in Engineering also from KSU. She had worked over 15 years at Lockheed Martin prior to joining NAVSYS.

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 is now being used to provide positioning and timing information for a number of applications where it is essential that the accuracy and reliability of the GPS information can be assured. These include safety of life systems, such as aircraft navigation during approach and landing, transportation applications such as railroad control, and also critical commercial applications such as mobile communication networks where GPS timing is used.

The susceptibility of the GPS signals to interference is of concern to the GPS user community. Because of the low received power of the GPS signals, outages can easily occur due to unintentional interference, and the potential exists to deny access to the GPS signals using easily obtainable RF hardware.

In this paper, an advanced GPS receiver is described that includes the capability to detect and locate GPS interference sources. This enables prompt action to be taken to protect the integrity of the GPS signal sources for safety of life or system critical applications of GPS.

INTRODUCTION

State of the art, commercial GPS user equipment now includes a variety of sophisticated digital signal processing techniques designed to enhance the performance and integrity of the GPS navigation and timing data provided. Techniques such as Receiver Autonomous Integrity Monitoring (RAIM)[1] that use redundant information within the receiver to detect and isolate satellite failures are now commonplace. Many receivers also use advanced signal processing techniques to improve the accuracy of the GPS tracking loops and reduce the effect of multipath errors. Adaptive digital filtering techniques have also been developed that can excise narrowband interference sources.

Until recently, however, only military GPS receivers have taken advantage of spatial signal processing to improve the robustness of the GPS signal through the use of Controlled Reception Pattern Antennas (CRPAs). NAVSYS pioneered the first commercial receiver to include spatial signal processing, the High-gain Advanced GPS Receiver (HAGR). This receiver uses digital spatial processing to combine the signals from up to 16 antenna elements, which allows over 10 dB of gain to be applied to each GPS satellite tracked. The digital spatial processing allows pseudo-range observations to be made to an accuracy of better than 1-meter and also reduces the effect of interference and multipath errors [2,3].

In this paper, a further enhancement of the HAGR is presented where the digital spatial processing is used to detect the presence of interfering signals and estimate the angle-of-arrival of the interfering signal to allow direction finding to the interference source. This capability provides a cost effective means for identifying and locating GPS interference sources, thereby improving the over-all robustness of GPS operation.

DIGITAL BEAMFORMING GPS RECEIVER (HAGR)

The GPS receiver embedded interference direction finding capability has been developed using the digital spatial processing capability inherent in NAVSYS' High-gain Advanced GPS Receiver[4]. 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

The performance specifications for the HAGR for a 16-element, L1 C/A code version of this product are included in reference 5. Currently an L1/L2 Precise Position System (PPS) version of the HAGR (the HAGR-200) is also in development.

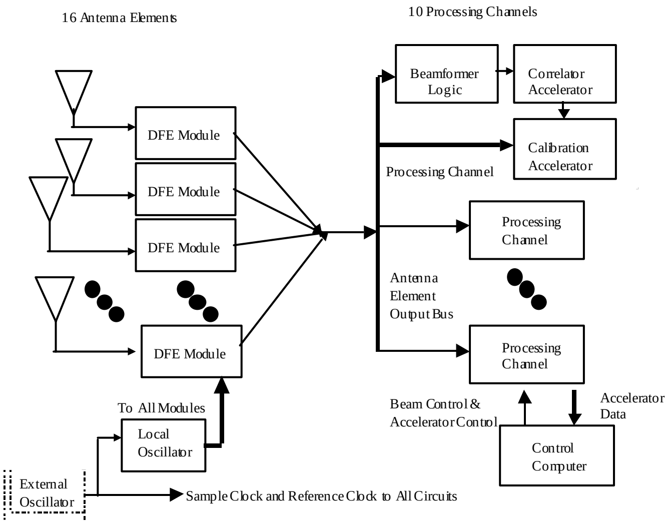

Figure 2 HAGR System Block Diagram

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.

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. For survey applications, the array orientation is entered manually or the array is aligned pointing north (the default). For mobile applications, 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 from an external attitude reference such as an inertial navigation system. Test data showing the performance of the antenna array in a mobile environment is included in reference 6.

HAGR DIRECTION FINDING APPROACH

The digital signal processing in the HAGR receiver has been adapted so that the digital phased array data can be used to detect and locate GPS interference sources by estimating the angle of arrival of the interference signals. The approach used is illustrated in Figure 3. The angle-of-arrival of a GPS interfering signal can be observed through cross-correlating the signals from the multiple antenna elements in the HAGR antenna array. If only

GPS signals are present, the cross-correlation product will observe only noise, since the GPS signals are below the noise floor of a GPS receiver. If an interfering signal is present, then power will be detected in the cross-correlation product. The observed phase angle of the cross-correlated signal also provides the angle-of-arrival (AOA) of the interfering signal. When this information is combined with the attitude of the antenna (pitch, roll, and heading), which is provided by the inertial attitude reference, the line-of-sight to the interference source is provided which can be used to estimate the location of the interference signal through triangulation, as shown in Figure 3.

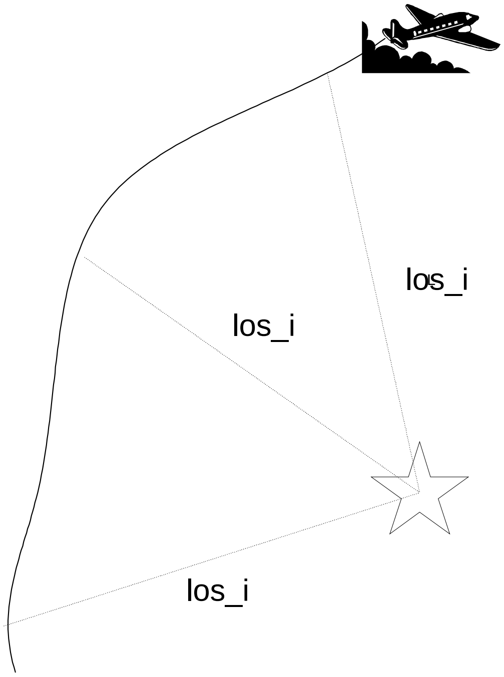

Figure 3 Interference Solution from Observations of Angle of Arrival

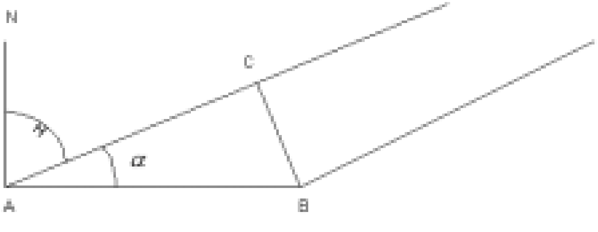

Figure 4 Relationship between DF-Phase and Direction of the Interference Source

The AOA data computed by the HAGR-Direction Finding (HAGR-DF) module is sensed by tracking the filtered complex product of the digital signals from two or more antennas. Each of the antennas in the HAGR array receives the signal from one or more jammers, shifted in phase by the AOA subtended on the baseline between the antennas, as shown in Figure 4. The observed phase difference (θ) between the two antennas is a function of the differences in the signals path length (AC in Figure 4) and is computed as shown below, where the direction cosine matrix (C_B^N) defines the attitude of the antenna baseline, $x_B - x_A$ is the relative separation of the antennae in body coordinates, and los_J is the line-of-sight to the interference source in the navigation frame.

$$\cos(\theta) = (C_N^B los_J{}^{(N)}) \bullet (x_B{}^{(B)} - x_A{}^{(B)}) / \left| x_B{}^{(B)} - x_A{}^{(B)} \right|$$

The signal received at two of the antennas in the HAGR array can be represented by the following equation.

$$s_A(t) = \sum_{i=1}^{NSV} A_i C_i(t) e^{j\omega_{Si}t} + \sum_{j=1}^{NJ} J_j(t) e^{j\omega_{Jj}t} + n_1(t)$$

$$s_B(t) = \sum_{i=1}^{NSV} A_i C_i(t+\tau) e^{j\omega_{Si}t+\phi_i} + \sum_{j=1}^{NJ} J_j(t+\tau) e^{(j\omega_{Jj}t+\theta_j)} + n_2(t)$$

The complex product of these two signals reduces to the following observation equation when these assumptions are made: (1) that the received interference signal power is much higher than the GPS signal power (J>>A), and (2) that the group delay between the antennas is small with respect to the sample time ($\tau << T_s$). The last assumption is generally true for short baselines between the antennas. For example, if the antennas are separated by 1/2 wavelength (9.5 cm), the group delay is only 0.3 nanoseconds.

$$s_1(t) s_2{}^*(t) = \left(\sum_{j=1}^{NJ} J_j(t) e^{j\omega_{Jj}t} + n_1(t) \right) \left(\sum_{j=1}^{NJ} J_j(t) e^{-j(\omega_{Jj}t+\theta_j)} + n_2{}^*(t) \right)$$

When the interference signal is assumed to be random (or pseudo-random) noise, the following assumptions hold true.

$$E[J_j(t)^2] = A_j{}^2 \quad E[J_j(t) J_k(t)] = 0 \ (j \neq k) \quad E[n_1(t) n_2(t)] = 0 \quad E[J(t) n(t)] = 0$$

The expectation of the product between the two antenna signals further simplifies under these conditions to the following equation.

$$E[s_1(t) s_2{}^*(t)] = E[\sum_{j=1}^{NJ} J_j{}^2 e^{j\omega_j t} e^{-j(\omega_j t+\theta_j)} \;]$$

$$= \sum_{j=1}^{NJ} J_j{}^2 e^{-j\theta_j}$$

The above complex product is generated by the HAGR correlator hardware as described below. This provides a detection of the accumulated interference power arriving at the two antennas. When an interference signal is detected, the receiver correlator hardware is used to track the received carrier phase and Doppler frequency of the search for each interference signal. With two antennas, the direction of only a single interference source can be resolved. When multiple antennas (N) are used, the complex products allow up to N-1 interference sources to be resolved.

The angle of arrival of the interference source (α) is related to the observed phase angle (θ) through the following equation, where L is the antenna separation in cycles (see Figure 4).

$$L\cos\alpha = N + \theta$$

$$\alpha_i = a\cos(\frac{N_i + \theta}{L}) \quad -L < N_i + \theta < L$$

$$\alpha_{2i} = -a\cos(\frac{N_i + \theta}{L})$$

If the antenna separation is greater than ½ wavelength, then there are multiple possible solutions for the angle of arrival due to phase ambiguities in the observation. When the antenna separation is less than or equal to ½ wavelength, then there is only one possible solution. The angle of arrival defines a cone of possible directions of the interference source around the antenna baseline. If multiple antennas are used from the HAGR antenna array, then this cone resolves to a single line of sight vector in the direction of the interference source. The location of this source can then be estimated from successive observations of the angle-of-arrival from a moving platform, such as an aircraft, as illustrated in Figure 3.

HAGR DIRECTION FINDING FIRMWARE

The HAGR code and carrier tracking is implemented in firmware using a custom correlation board developed by NAVSYS, which includes multiple Xilinx Field Programmable Gate Arrays (FPGAs). This approach provides flexibility in the HAGR design since the Xilinx firmware can be easily reprogrammed to implement different signal processing functions to optimize performance depending on the HAGR implementation. In the conventional HAGR mode of operation, the firmware is programmed to implement multiple code and carrier tracking channels, each assigned to a different satellite pseudo-random-noise (PRN) code and operating from a different composite antenna beam generated by the beam-steering electronics (see Figure 2). The logic implemented by each of these tracking channels includes the code generation, carrier generation and complex multiply and accumulation functions needed to generate the early, prompt and late In-phase (I) and quadrature (Q) sums used to run the software code delay-locked loop (DLL) and carrier phase locked loop (PLL).

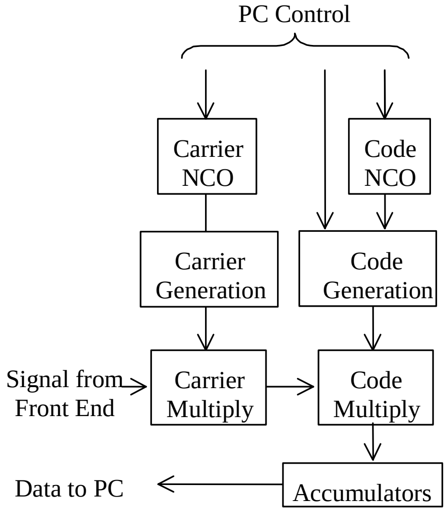

Figure 5 Conventional HAGR Channel Functions

The HAGR-DF module designates one or more of the HAGR channels to generate the interference detection logic instead of the conventional tracking logic shown in Figure 5. In this mode, the signals from two of the antenna elements are processed using the logic shown in Figure 6.

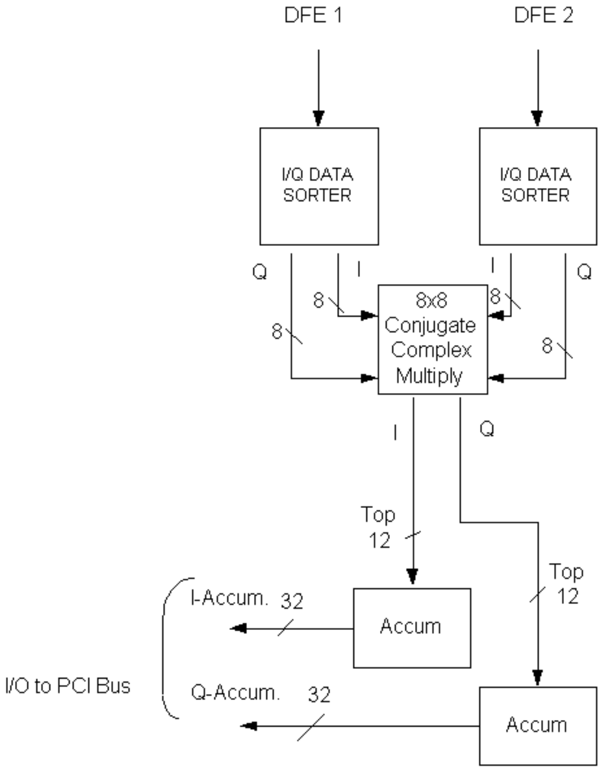

Figure 6 Direction Finding Channel Function

The complex conjugate of the I and Q sampled data from the two DFEs is computed and the resulting product is accumulated and passed to the HAGR-DF for processing at a 1-kHz rate. The HAGR-DF software is used to detect the power level of any interference signal and track the carrier phase of the complex conjugate signal from which the AOA can be computed as described in the previous section.

DIRECTION FINDING TEST RESULTS

To test the performance of the HAGR-DF, a GPS interference signal was inserted into two of the HAGR antenna elements. The power of the input signal was observed using a spectrum analyzer and the detected signal power and carrier phase from the HAGR-DF software was recorded. The output of the complex conjugate signal is given in dB-Hz relative to the receiver noise floor. Since the signal represents the interference power squared, the output signal-to-noise ratio increases 20 dB for each 10 dB increment in input interference power level.

In Figure 7, the C/N0 recorded for the interference detection channel is plotted against the observed input interference power. This testing was performed using a 2 MHz bandwidth pseudo-noise signal as the interference source.

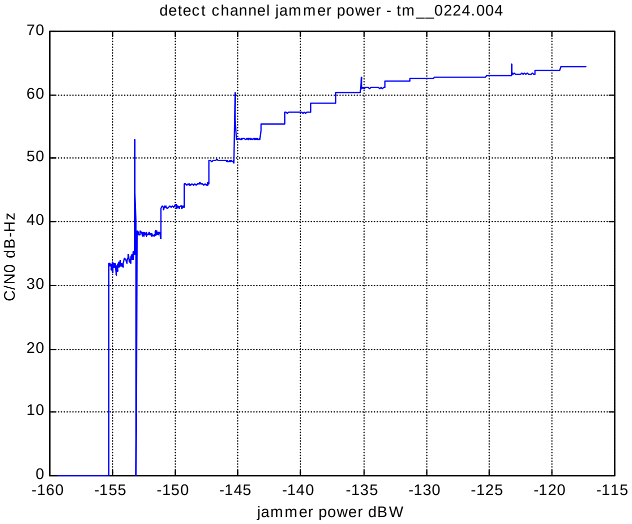

Figure 7 - Detect channel C/N0 with 2MHz Broadband Interference

In Figure 8, the observed carrier phase for the complex conjugate interference signal is plotted. As can be seen from Figure 7, the HAGR-DF can detect narrow-band noise interference signals at power levels above -155 dBw, or at interference/signal levels of above 5 dB. The dynamic range of the current generation HAGR DFEs results in the power detection being linear over an input power level of roughly 15 dB. A next generation DFE is currently in development that includes a 16-bit A/D converter that will provide a significant increase in dynamic range for detection and observation of interference signals.

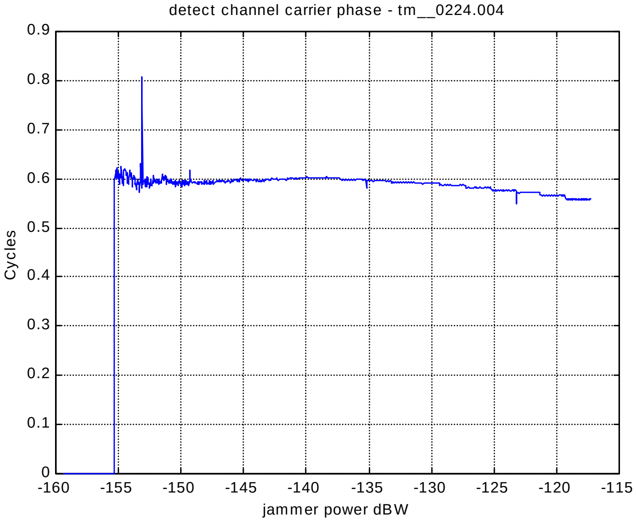

Figure 8 - Detect channel carrier phase with 2MHz Broadband Interference

In Figure 9 and Figure 10, the same plots are shown illustrating the detected power and observed carrier phase for a CW interference source. In this case, the HAGR-DF channel was able to detect signals above –159 dBw in power or at interference/signal levels of above 1 dB.

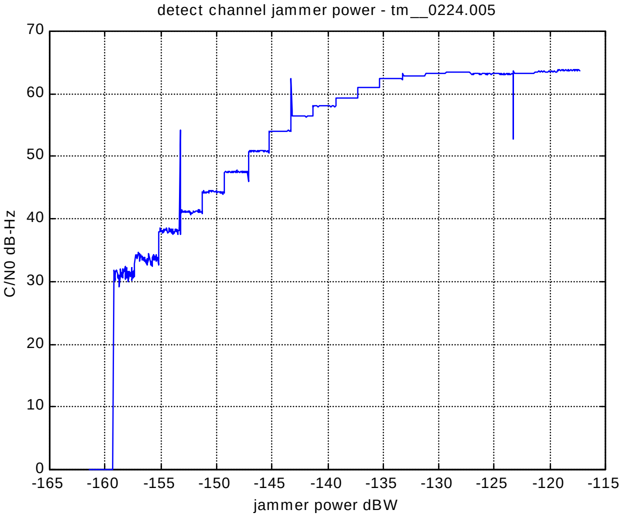

Figure 9 - Detect channel C/N0 with CW Interference

Further testing is planned of the HAGR-DF performance during Air Force jammer testing at White Sands Missile Range later this year.

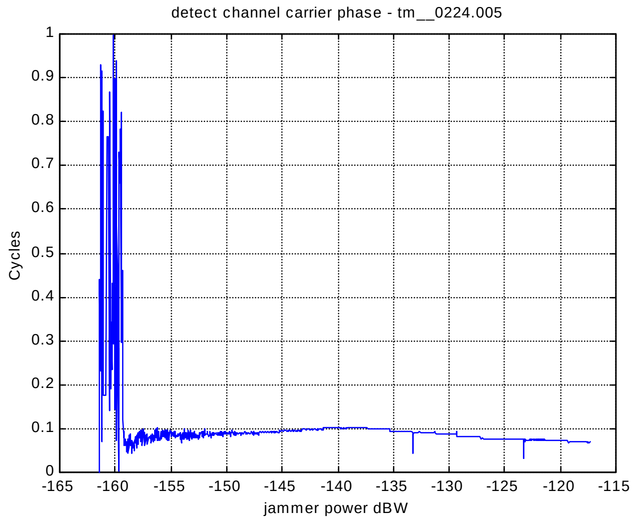

Figure 10 - Detect channel carrier phase with CW Interference

CONCLUSION

In conclusion, the digital spatial processing capability provided by the HAGR has the following advantages for improving the robustness of the GPS signals in the presence of interference.

- Enables autonomous detection of GPS interference sources
- CW interference can be detected at received power levels above –159 dBw
- Broadband interference can be detected at received power levels above –155 dBw
- Provides the angle of arrival of the interference source from which the location can be deduced
- Provides rejection of interference signals through the beamforming spatial processing used to track the GPS satellites

ACKNOWLEDGMENT

This work was sponsored under the Air Force Research Laboratory SBIR Phase II Contract F33615-99-C-1433, “Jammer and Spoofer Detection, Direction Finding and Location.”

REFERENCE

---

[1] A. Brown, “Receiver Autonomous Integrity Monitoring using a 24-Satellite GPS Constellation,” Proceedings of ION Satellite Division International Technical Meeting, Colorado Springs, Colorado, September 1987

[2] A. Brown, K. Taylor, R. Kurtz, H. Tseng, “Kinematic Test Results Of A Miniaturized GPS Antenna Array With Digital Beamsteering Electronics,” Proceedings of ION National Technical Meeting, Anaheim, California, January 2000

[3] A. Brown, J. Wang, “High Accuracy Kinematic GPS Performance using a Digital Beam-Steering Array,” Proceedings of ION GPS-99, Nashville, Tennessee, September 1999.

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

[5] A. Brown and J. Wang, “High Accuracy Kinematic GPS Performance Using A Digital Beam-Steering Array,” Proceedings of ION GPS-99, Nashville, Tennessee, September 1999

[6] A. Brown, H. Tseng and R. Kurtz, “Test Results Of A Digital Beamforming GPS Receiver For Mobile Applications,” Proceedings of ION National Technical Meeting, Anaheim, California, January 2000