Effect of Adaptive Array Processing on GPS Signal Crosscorrelation

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BIOGRAPHY

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ABSTRACT

Adaptive space-time arrays can be used to cancel jammers interfering with GPS receiver operation. However, there is a concern that the adaptive filter used for jammer cancellation can distort the GPS signal crosscorrelation function, especially if a non-constrained jammer cancellation algorithm, such as power minimization, is used. We have examined this issue via both experimentation and simulation. The experiments were conducted using a seven-channel linear array that has five adaptive time taps per channel. A jammer waveform is injected into each channel, thus, simulating a broadside jammer minus antenna effects. When a power minimization algorithm was used for jammer cancellation, it was found that significant distortion of the crosscorrelation function would be encountered for signals incident on the array from a significant portion of the upper hemisphere around the jammer location. Simulations confirmed these results.

Simulations alone were then used to assess the performance of a CRPA with 11 adaptive time taps/element. Strong jammers were placed on the horizon and the crosscorrelation function calculated for various angular locations of GPS satellites. It was found that for this configuration and with 11 adaptive time taps/element (rather than only 5) the crosscorrelation distortion was not as severe, and significant errors were confined to a relatively small solid angle around the location of each jammer.

INTRODUCTION

The use of space-time adaptive (STAP) processing in conjunction with antenna arrays has been proposed to mitigate the effects of jammers and jammer multipath on GPS receivers. While adaptive array processing has been found to cancel jammers, concerns have been raised that the resulting distortion of the frequency response (across the operating band) produced by the adaptive array may be sufficient to adversely affect the nature of the crosscorrelation functions received from each GPS satellite. Such distortion may lead to pseudorange errors and, hence, incorrect position estimation. Although, it was shown [1] that this is not a concern when using a constrained optimization algorithm (i.e., a different constraint for each GPS satellite in view when performing the jammer nulling) it could be a very valid concern [2] when using an unconstrained jammer cancellation algorithm. One example of such a technique is simply choosing the adaptive weights so as to minimize the output power of the array. In this paper, we will explore the effect of frequency response distortion caused by adaptive processing.

APPROACH

We studied this problem using a dual-pronged approach that is part measurement and part simulation. The quasi-experimental portion was performed using a seven-channel linear array that had five adaptive time taps per array element. Using a RF splitter, identical jamming signals were directly inputted to each channel, effectively simulating a plane-wave jammer at broadside (minus the antenna effects). The experiment was then conducted using the following steps:

1. Auxiliary channels were equalized to match the reference channel.
2. Gain settings were adjusted to achieve desired jammer power levels.
3. Digitized baseband outputs from each channel's equalizer filters were recorded.
4. The STAP processor was permitted to compute and apply a set of weights.
5. Digitized baseband outputs from each channel's STAP filters were recorded.
6. The current set of STAP coefficients was saved to file.
7. Steps 2 through 6 were repeated ten times per input jammer power level.
8. Steps 2 through 7 were repeated for each type of jamming waveform.
9. Post-STAP channel recordings for each jamming scenario were read into Matlab and summed.
10. Null depths were computed in Matlab as the ratio of post-equalizer reference channel power to post-STAP residual powers.
11. Using the saved STAP coefficients and treating the array as if it represented a controlled reception pattern antenna (CRPA) configuration, transfer functions were computed for multiple incoming-signal azimuths and elevations, and their effect on the crosscorrelation of different classes of signals (CA-Code, M-Code, P-Code) was computed.

Because the quasi-experimental approach discussed above cannot be used to simulate multiple jammers located arbitrarily in angle (we were limited to simulating a jammer at boresight), we used simulation alone to evaluate those scenarios. We instituted (to ensure accuracy) the requirement that the simulations reproduce the results of the experiment for the limiting case of a boresight jammer. The simulations were performed for a seven-element array in a CRPA configuration, with either 5 or 11 adaptive time taps behind each element (the 5 tap array with a boresight jammer can be used to directly compare the simulation with the experimental data, because for a boresight jammer, it does not matter if the array is linear or in a CRPA configuration, so the comparison is accurate at this angle).

In the simulation, each antenna/receiver is assumed to have a different frequency response $G_k(f)$ across the operating band, where k = 1, 2, …7. In particular, both the amplitude and group delay variations from channel-to-channel across the frequency band are modeled by a power series or a sinusoidal ripple, with the coefficients of the power series and the amplitude and the phase of the ripple chosen randomly from channel-to-channel in such a fashion as to produce a specified average cancellation ratio. The transfer function $G_k(f)$ does not include the effect of the adaptive FIR filter in each channel. The interference scenario consisted of one or more strong (J/N = 53 dB) broadband (B = 20 MHz) jammers located randomly in azimuth along the horizon. It is assumed that each of the K = 7 channels contains N time taps (we used N = 5, 11) where adaptive weights are applied and combined in such a way so as to minimize the output power of the array. Once the adaptive weights are known, one can compute the crosscorrelation function for a GPS signal incoming from an arbitrary angle (θ, ϕ) via

$$C(\tau,\theta,\phi) = \sum_{k=1}^{K} \int_{-\infty}^{\infty} df\ P(f) G_k(f) H_k(f,\theta,\phi) \exp(i2\pi f\tau), \quad (1)$$

where f = frequency, τ = delay, K = number of antenna elements, P(f) is the power spectral density of the incoming GPS signal, $G_k(f)$ is the frequency response of channel k (antenna/tuner/receiver) and $H_k(f, \theta, \phi)$ is the frequency response of the adaptive FIR filter in channel k for an incoming signal at (θ, ϕ). $H_k(f, \theta, \phi)$ implicitly contains the NK (K antennas $\times$ N taps/antenna) adaptive weights used to null the interference.

RESULTS

We first performed an experiment where a broadband jamming signal was injected into a seven-element linear array, simulating a jammer at zenith with a jammer-to-noise ratio J/N = 53 dB. The seven-channel array was pre-equalized to a cancellation ratio of 25 dB, and the array then used 5 adaptive time taps per antenna to cancel the jammer. Although the cancellation ratio was measured, the actual channel transfer functions were unknown. The adaptive weights on each antenna were computed by using the "power minimization" algorithm for different blocks (sampling rate = 26 MHz) of injected jammer-plus-noise data. The resulting loss and crosscorrelation function C(τ, θ, ϕ) was then computed for different GPS codes (C/A, P, M) for varying values of the GPS satellite elevation EL = $\pi/2 - \theta$. It was found that depending on the angular location of the GPS incoming signal, the crosscorrelation can be distorted and have a peak that is considerably displaced from the correct code delay, as can be noted from Figure 1 for the case of P(Y) code.

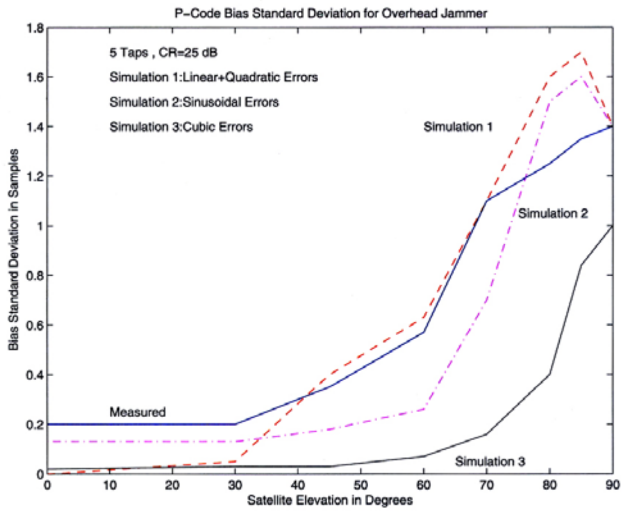

Figure 1. P-Code Bias Standard Deviation in Samples (One Sample = 38.5 ns) for Overhead Jammer

Simulations were also done for the aforementioned geometry, using three different transfer functions to model the unknown experimental channel mismatch. In Simulation 1, we used $G_k(f) = 1 + a_kF + b_kF^2$ where F = 2f/B, a_k, b_k are complex and differ randomly from antenna to antenna. In Simulation 2, we chose $G_k(f) = 1 + \alpha_k \sin(2\pi\nu F + \phi_k)$ where α_k, ϕ_k differ randomly from antenna to antenna. Finally, in Simulation 3, we used $G_k(f) = 1 + C_kF^3$, where the C_k are complex and differ from antenna to antenna. We note that simulations bracket the measured data fairly well.

We next consider the case of one or more sources on the horizon (elevation = 0°) jamming a CRPA array that is not pre-equalized, but instead uses 11 time taps/antenna both for equalization and jammer cancellation. We again assume each jammer radiates white, broadband interference, producing a 53 dB jammer-to-noise ratio in each antenna. We also assume each channel has an ambient cancellation ratio CR = 15 dB, and that $G_k(f)$ is modeled as a power series in frequency, with random coefficients from antenna-to-antenna. We then evaluate the crosscorrelation function C(τ, θ, ϕ) as a function of satellite location (θ, ϕ). For each location, we calculate 16 realizations of C(τ, θ, ϕ) and then calculate the mean shift in the peak of the crosscorrelation function (we call this shift "bias") and its standard deviation. In all cases, P-Code is assumed, although calculations for C/A and M-Code are readily done.

As a first example, we placed a jammer at 0° elevation and 45° azimuth, and examined the crosscorrelation vs. angular position. A typical example is shown in Figure 2 where we present the crosscorrelation for a satellite at 1° elevation and 44° azimuth. Note how the crosscorrelation is distorted, relative to the "no jammer" limit, when we choose a satellite close to the jammer location. We define the bias as the location of the largest peak relative to the correct delay (τ = 0); for the crosscorrelation in Figure 2, this is approximately –47 ns.

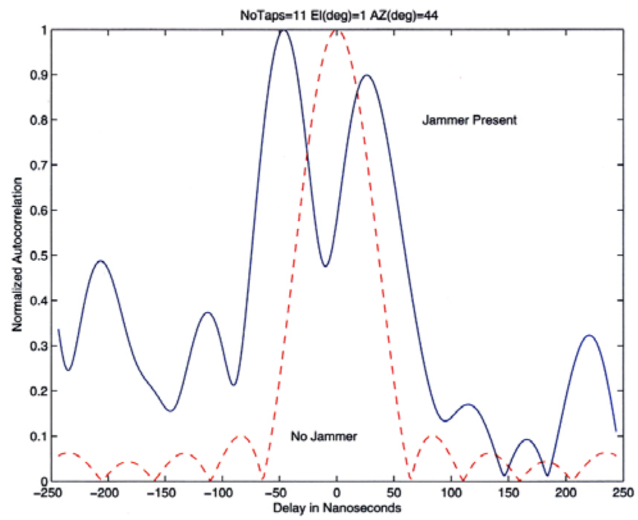

Figure 2. Correlation Distortion When Satellite at EL = 1°, AZ = 44° and Jammer at EL = 0°, AZ = 45°

In order to limit the amount of data to be presented, we show only the contours of the standard deviation of the bias (the mean bias is nearly zero, and is not shown). In Figures 3 and 4, we show the contours of the boundaries within which the standard deviation of the bias exceeds 5 ns and 12.5 ns (note that although the jammer lies at (0, 45°), there is a sympathetic region across the hemisphere near (0, 220°) where the bias standard deviation exceeds 5 ns). From these figures, we see that when 11 time taps/antenna are used and the jammer is on the horizon rather than overhead, the correlation distortion is much less severe.

We next considered the case of 2 interferers on the horizon, each producing J/N = 53 dB per antenna. Jammer 1 was located at 0° elevation and 0° azimuth and Jammer 2 was placed at 0° elevation and 45° azimuth. The regions where the standard deviation of the bias exceeds 5 ns and 10 ns for this case are shown in Figures 5 and 6. Note that the two jammers together cause bias errors over a much larger region than twice the region of a single jammer. This point is quite evident from Figure 7, where we present the fraction of the upper hemisphere where the bias exceeds 5 and 10 ns. Note that 2 jammers on the horizon produce a 5 ns bias error over nearly 20 percent of the upper hemisphere, but this is still far less than produced by a single overhead jammer illuminating a CRPA array using only five time taps per antenna.

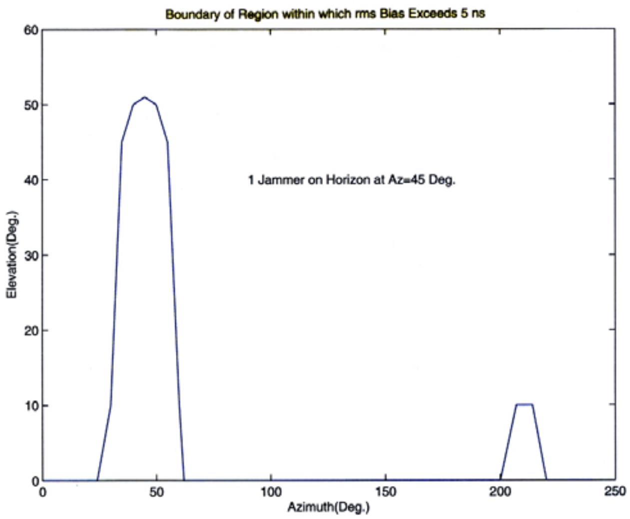

Figure 3. Boundary of Region Within Which Standard Deviation of P-Code Time Offset Exceeds 5 ns When 1 Jammer on Horizon (CRPA, 11 Taps)

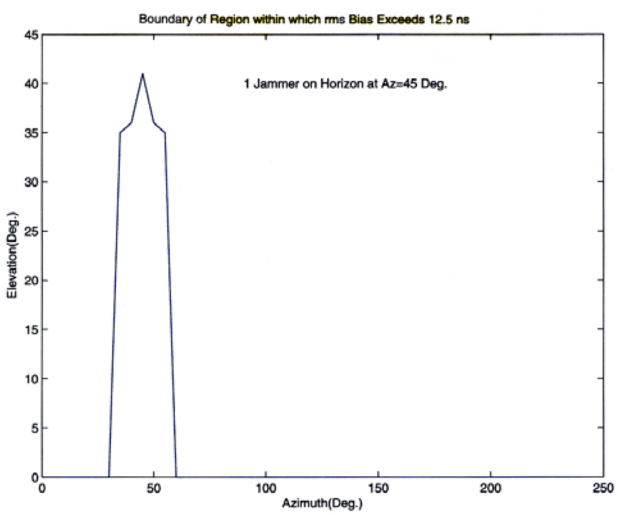

Figure 4. Boundary of Region Within Which Standard Deviation of P-Code (CRPA, 11 Taps) Time Offset Exceeds 12.5 ns When 1 Jammer on Horizon

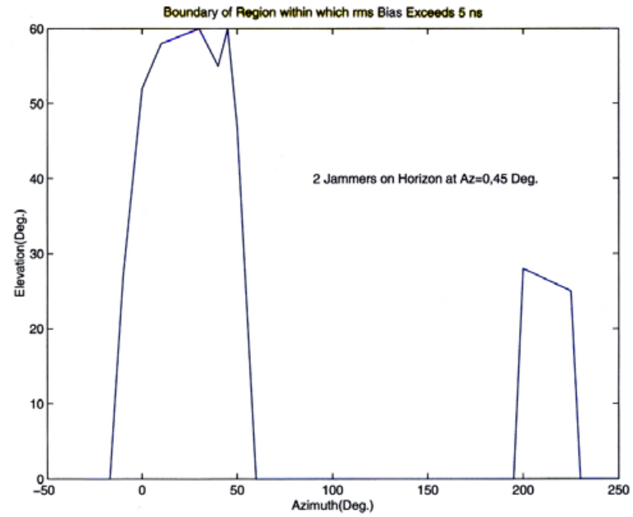

Figure 5. Boundary of Region Within Which Standard Deviation of P-Code Time Offset Exceeds 5 ns When 2 Jammers on Horizon (CRPA, 11 Taps)

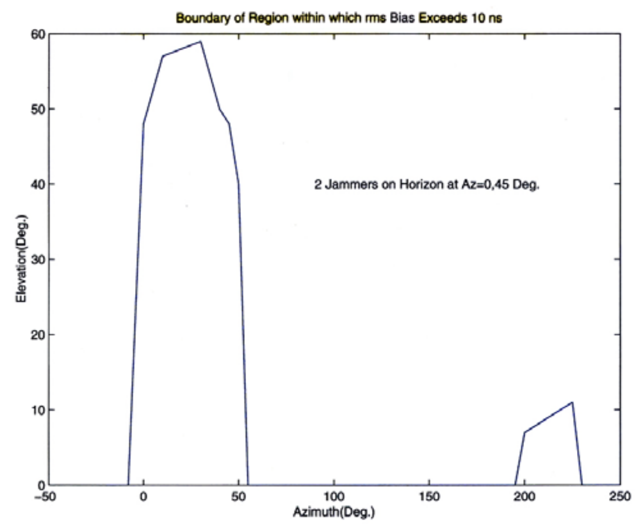

Figure 6. Boundary of Region Within Which Standard Deviation of P-Code Time Offset Exceeds 10 ns When 2 Jammers on Horizon (CRPA, 11 Taps)

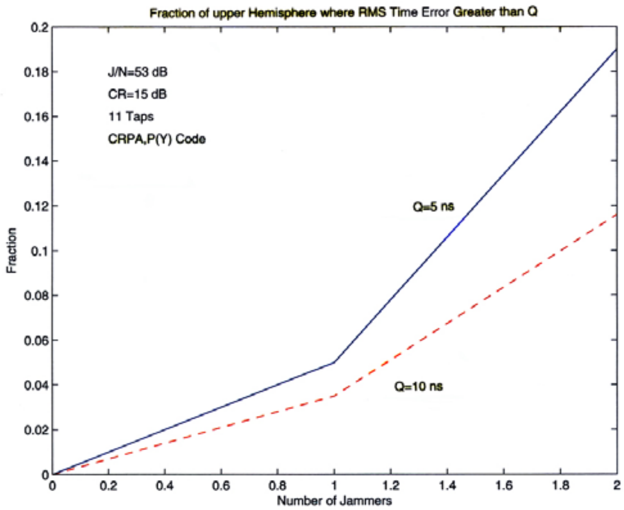

Figure 7. Fraction of Upper Hemisphere Where P-Code Time Offset Error Greater Than Q (CRPA, 11 Taps)

CONCLUSIONS

The concern raised in Reference 1 is indeed an issue: there is significant distortion and offset of the crosscorrelation function from its correct delay, especially if the satellite angular location is close to that of the jammer, where the received GPS satellite signal is severely attenuated anyway. However, for jammers on the horizon, there is a mitigating factor: the correlation distortion and offset is serious over only a small fraction of the upper hemisphere. In particular, a single jammer on the horizon produces bias errors greater than 5 ns only over 5 or 6 percent of the upper hemisphere. Most of this region is very near the horizon, which is not utilized by the GPS receiver for the position solution (because the antenna gain is usually low at the horizon).

Two closely-spaced (within 45° azimuth separation) jammers on the horizon present a more serious problem and can cause a significant (i.e., greater than 5 ns) pseudorange error over nearly 20 percent of the upper hemisphere. However, there is still a substantial portion of the upper hemisphere that remains unaffected and can be used to produce a reliable position solution. Thus, while the concern raised in Reference 1 is certainly valid, we believe that, unless very accurate position location is required (for precision results, a constrained algorithm is required), crosscorrelation errors resulting from implementation of the power minimization jammer cancellation algorithm will not produce a significant negative impact on the navigation solution.

REFERENCES

1. G. Hatke, “Space-Time Adaptive Processing Applied to GPS Adaptive Arrays,” Proceedings of 1998 ASAP Conference at M.I.T., Lincoln Laboratory, 1998.

2. R. Fante, J. Vaccaro, “Wideband Cancellation of Interference in a GPS Receive Array,” IEEE Trans. AES-36, pp. 549-564, 2000.