Effect of Adaptive Array Processing on GPS Signal Crosscorrelation

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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.

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.

The result of the aforementioned quasi-experimental test indicated that the crosscorrelation function (used to estimate pseudorange) can be distorted and have significant time bias, especially for incoming signal incidence within approximately 35 degrees of the jammer location (i.e., the angular region from array boresight, where the incoming jammer is located, down to approximately 35 degrees off boresight). Therefore, the experiment indicated there could be significant time of arrival errors (5 to 10 ns, or more) for incoming GPS signals over approximately 18 percent of the upper hemisphere.

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 $k = 1, 2, \ldots 7$. In particular, both the amplitude and group delay variations from channel-to-channel across the frequency band are modeled by a power series plus 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

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[*] i.e., a seven-element array with one element at the center and six on the corners of a hexagon surrounding the first element.

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

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

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 × N taps/antenna) adaptive weights used to null the interference.

For the case of one randomly-located, strong, broadband jammer on the horizon, we found that if an unconstrained jammer power minimization algorithm is used, an array in the CRPA configuration with 11 time taps per element can readily cancel the jammer while simultaneously producing a signal crosscorrelation function that is distorted only over a relatively small solid angle centered on the jammer (and on the sympathetic null that occurs at the jammer azimuth plus 180 degrees). In particular, for P-Code, the rms time delay error of the crosscorrelation function peak exceeds 5 ns only over about 5 percent of the upper hemisphere.

For two strong, broadband jammers on the horizon, the fraction of the upper hemisphere where the rms time delay error of the crosscorrelation peak exceeds 5 ns depends on the jammer azimuth separation. If the jammers are separated by more than 60 degrees, the P-Code time error exceeds 5 ns only over approximately 10 percent of the upper hemisphere. For a 45-degree jammer separation, the time-delay error exceeds 5 ns for nearly 20 percent of the upper hemisphere.

Although the concern raised in Reference 2 is certainly valid, it was found that there is still enough of the upper hemisphere where the distortion of the crosscorrelation function is sufficiently small that in most cases a GPS receiver will be able to obtain a reasonably-accurate position estimate.

References

1. R. Fante and J. Vaccaro, IEEE Trans. AES-36, 2000.

2. G. Hatke, 1998 MIT Lincoln Laboratory ASAP Conference.