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A Survey on Interference Mitigation in GPS

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Abstract: **In aviation, GPS systems are used for en-route navigation and CAT 1 non-precision landing approach. These GPS receivers are jammed due to either intentional or unintentional interferences.A number of methods may be used to do so. At a signal input level, the use of adaptive A/D converters may be used to prevent the digital receivers saturating. Next, adaptive filtering techniques using either single or multiple element antennae coupled with both spatial and temporal digital processors can be used to reject both narrowband and broadband interferences. Also other digital signal processing algorithms can be used to reject specific interferences from a spread spectrum system. Finally at a systems level both GPS and INS receivers may be tightly or loosely coupled to improve the accuracy and robustness of GPS in the presence of jamming signals. The advantages and disadvantages of various generic implementations of the above methods areoverviewed and compared. Adaptive filters, both temporal and spatial are considered in detail and experimental laboratory and field trial results from such systems are presented to illustrate key issues.**

Keywords: **GPS, receivers, tracking, A/D Converter, Correlation**

1. INTRODUCTION

Due to the relative low received GPS signal powers, it is relatively easy to jam most commercial GPS receivers [1]. CA code receivers are especially vulnerable to CW interferences and it has been estimated that a 1 W CW emitter has the capability to disrupt GPS within a 40 Km radius[1].Interference to civilian receivers is likely to increase in the future due to the rapid growth of telecommunications and other wireless data transmission systems. Although these systems may not transmit on the same frequency as GPS, intermodulation products and other out of band transmissions may lie in the GPS band [1].Military users also need to consider intentional jamming. Due to the low powers required to jam GPS, jammers are cheap to build and a Russian jammer is currently being marketed [2]

Possible anti-jam enhancements to the standalone GPS receiver are summarized in Table 1.

Table 1: Possible anti-jam techniques to standard GPS receiver

Anti-jam Technique		**Additional Anti-Jam**	**Implementation**
A/D converter	Adaptive A/D	Several dB against CW interferences	Need to be implemented internal to GPS receiver
Post correlation Techniques	Adaptive Loop Bandwidth	3-20 dB against all interferences waveforms	
	Data wiping		
	Open Loop carrier tracking		
	Vector loops		
	Integration with INS		
Pre – correlation Techniques	Amplitude Domain Processing	20-40 dB against narrow band interferences	Can be implemented either internal or external to GPS receiver
	Temporal/FFT domain Filters		
	Dual polarization antenna	20-40 dB against narrow Band +Broad band interferences	
	Spatial Filters		
	Space –Time Filters		

The anti-jam enhancements are shown in increasing complexity. Simple modifications to the A/D can improve the anti-jam margins of the receiver against CW interferences. Post-correlation techniques involve modifications to the receiver tracking loops and can give limited additional protection against interferences. A major advantage of these schemes is that they are effective against all interference waveforms and require little, if any, modifications to the receiver hardware. Some can be implemented completely in software. Pre-correlation techniques can be used to further improve the anti-jam performance of the receiver.These techniques are applied prior to the tracking loops and can be packaged as an external appliqué to existing GPS receivers. They usually require significant additional DSP processing power. Amplitude domain processing and temporal filtering techniques are the simplest to implement, as they only require a single antenna element. These techniques can be directly inserted into most current GPS receiver installations, but are only effective against narrow band interferences. Spatial filters are also effective against broadband interferences, but require an antenna array. This significantly increases both the cost and size of the installation. Combined spatiotemporal filters achieve the best performance against both narrowband and broadband interferences but are also the most expensive to implement. Recently an innovative technique using a dual polarization antenna has been implemented [17], this technique can achieveimpressive anti-jam margins against all interference waveforms that are not RHCP (right hand circularly polarized). The main advantage of this technique over spatial filters is that it only requires a single antenna element and as a result is expected to be significantly cheaper. It appears promising for civilian applications, as unintentional interferences are not expected to be RHCP. This technique is not described in this paper due to limited space. The remainder of this paper is structured as follows: Initially the vulnerability of a standalone CA code receiver to interference is discussed. Then, potential anti-jam enhancements are described in order of increasing complexity. Pre-correlation adaptive algorithms in the temporal and spatial domain form the main focus of this paper and example laboratory and trial results from an adaptive filter and spatial beam former are given to illustrate key results.

2. GPS ANTIJAM ENHANCEMENTS

First consider a generic GPS receiver architecture, with no anti-jam enhancements.

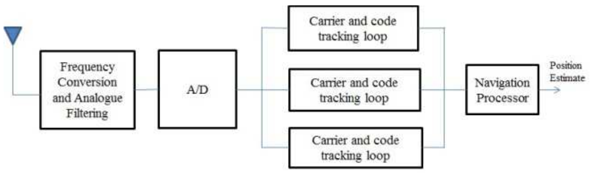

Figure 1: Generic GPS receiver architecture

After filtering and down conversion, the received signal is sampled and then input to the code and carrier tracking loops to derive timing information for input to the navigation processor.

The generic GPS receiver architecture uses parallel carrier and code tracking loops, which are updated independently of each other. No external aiding is used in the receiver. The weak link of an unaided GPS receiver is the carrier tracking loop. Typical loss of lock thresholds for the carrier tracking loop, for wideband interferences, are shown in Table 2. The thermal noise power in the CA code bandwidth is typically 20 dB above the GPS signal power and the I/S power ratios in Table 2 are about 20 dB larger than the estimated I/N power ratios.

Table 2: Typical I/S and I/N tracking thresholds for wideband interferences

Threshold	**I/S power ratio (dB) Interference /Signal**	**I/N power ratio (dB) Interference /noise**
CA code receiver acquisition	25 dB	5 dB
Navigation Data Demodulation	30 dB	10dB
Carrier lock (CA code)	30-38 dB	10-18 dB

There is some variation in the loss of lock thresholds observed in CA code receivers [3]. This is most likely due to differences in the designs of the tracking loop filters, but may also be dueto other implementation issues.

The results in Table 2 apply to wideband interferences. Loss of lock thresholds for narrow bandinterferences (bandwidth > 1 KHz) are generally 3 dB lower. Finally, CA code receivers have aspecial vulnerability to CW interferences. This is due to the relatively short period of the spreadingsequence. CW interferences with I/S values as low as 18 dB [1] can cause problems inCA code receivers. In some cases, the tracking loops will begin to track the interference signal,which can result in very large position errors (several 10s of Km), prior to the receiver registering afalse reading. These effects were observed for I/S values as low as 20 dB, (I/N values of 0 dB)[5]. In general only a few satellite signals are affected whose carrier frequency (plusDoppler) exactly matches that of the CW interference.

2.1 Enhancements to A/D Converter

To reduce the cost and power consumption of the GPS receiver, some commercial C/A code receivers use a single bit A/D converter. Under normal operating conditions, a single bit A/D will only reduce the SNR of the GPS signal by 2 dB relative to an infinite precision A/D. However, single bit A/D converters are vulnerable to CW interferences and will potentially reduce the loss of lock thresholds of the receiver by up to 57dB relative to an infinite precision A/D [7].A/Ds with 2 bits overcome this vulnerability [7]. Adaptive A/Ds can be used to further improve the performance of the GPS receiver under CW interference. Adaptive A/Ds usually use between 1.5 and 2 bits, and adaptively adjust their signalthresholds according the received power. They achieve several dB gain in SNR against strong CW interferences [7], relative to infinite precision A/Ds. This gain in SNR is due to a crude form of nonlinear amplitude domain processing.

2.2 Post Correlation Techniques

Post correlation techniques are implemented within the GPS receiver tracking loops and improve the tracking thresholds. They can often be implemented through software changes, and do not significantly increase the power consumption of the GPS receiver.

2.2.1 Adjustable Carrier Tracking Loop Bandwidth

Reducing the bandwidth of the carrier tracking loop increases its tracking threshold at a cost of degraded dynamic performance. By adaptively adjusting the tracking loop bandwidth, according to the interference power, higher anti-jam margins can be obtained under lower dynamics [4][8][6]. Simply switching to a much narrower tracking loop bandwidth when the receiver is stationary has also been tested and found to improve the carrier tracking threshold of the receiver by 10 dB [9].

2.2.2 Data Wiping

Data wiping techniques enable longer coherent integration times by removing the 50 Hz navigation data from the received signal. Techniques for achieving this are discussed in [10] and [4]. One method simply assumes that the navigation data does not change with time, and memorize a complete data frame. Data wiping techniques can improve the tracking threshold of GPS receivers by up to 6 dB [4]. These techniques are most effective for GPS receivers that already have high anti-jam immunity (narrow tracking loop bandwidths) and are not expected to significantly improve the tracking thresholds of most unaided GPS receivers.

2.2.3 Open Carrier Tracking Loop

A GPS receiver based on open loop carrier tracking has been patented by Sigtec. The carrier frequency is estimated via an FFT, rather than a phase locked loop. By removing the carrier tracking loop, the receiver can maintain lock on GPS signals at higher I/S ratios. From quoted figures, such a receiver can track GPS signals in thermal noise at –185 dBm. This corresponds to a I/S tracking threshold of 45 dB under normal GPS signal strengths.

2.2.4 Vector Tracking Loop

In a standard GPS receiver, each tracking loop update occurs independently of the others. The outputs of the tracking loops are then combined in the navigation processor. Vector tracking loops integrate the tracking loops and navigation processor, such that each tracking loop update is also based on information from other tracking loops. The main advantage of these techniques seems to be in situations where more than 4 satellites are visible. In this case common information from several satellites can be used to reinforce the signal strengths of the weaker ones [11].

Another approach is to use the common information from multiple GPS satellites to estimate the platform dynamics, which can then be used to aid the tracking loops, allowing them to operate at a reduced bandwidth, increasing their interference immunity [10].

2.2.5 Integration with INS

In a tightly coupled GPS/INS system, the INS measurements can be used to aid the carrier tracking loops. This removes the dynamics from the loops and allows them to operate at a much narrower bandwidth. Typically, a factor of 10 reduction in bandwidth is achieved, resulting in an additional anti-jam of 10 dB [4].

INS measurements can also be used to replace the carrier tracking loop, after it has lost lock. The loss of lock threshold of the receiver is now determined by the tracking threshold of the code tracking loop which is typically 10 dB higher than the carrier tracking loop [4].

2.3 Pre-Correlation Techniques

Pre-correlation techniques can be used to achieve significant additional antijammargins. They are mainly implemented in digital signal processing (DSP) and can be applied either directly after the A/D converter in Figure 1, or be packaged as an external RF insert.

2.3.1 Amplitude Domain Processing

Amplitude domain processing techniques modify the amplitude of each digital sample in such a way that non Gaussian interferences are suppressed, resulting in an overall improvement in SNR. A block diagram of the required DSP processing is shown in Figure 2.

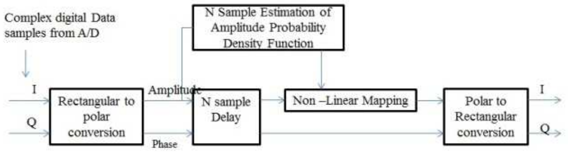

Figure 2: Amplitude domain processing

In Figure 2 each of the signal amplitude values are reassigned according to a nonlinearmapping. The calculation of the optimal nonlinear mapping is based on statistical decision theory and acts to deem phases those samples in which signal detection is unlikely. To calculate the nonlinear mapping, the probability density function of the signal amplitude needs to be estimated. Amplitude domain processing was found to give the following SNR improvements: 30 dB against a single CW, and 20 dB against a swept CW, 22 dB against two CW and only 2 dB against 4 CW interferences [6]. One of the main advantages of amplitude domain processing is that it can reject very fast sweeping interferences, as it does not need to track the interference frequency, a significant disadvantage is that it does not handle more than 2 CW interferences [6].

2.3.2 Adaptive Temporal Filters

Prior to de-spreading, the GPS signal is spread over a 2 MHz bandwidth (CA code). This allows narrow band interferences to be notched out in the frequency domain without causing significant distortion to the GPS signal. A number of techniques have been proposed to achieve this including FFT bin clipping [12], adaptive FIR prediction filters [13] adaptive IIR filters [10] and frequency tracking [16]. All of these techniques potentially have greater anti-jam margins than amplitude domain processing, and the dynamic range of the A/D usually limits the maximum anti-jam. They are more effective against multiple CW interferences than amplitude domain techniques, but are also more sensitive to fast sweeping interferences, as they need to track the interference frequency. To illustrate the operation of an adaptive filter, a technology demonstrator built and tested by CSSIPwill be briefly described. The basic structure is shown in Figure 3.

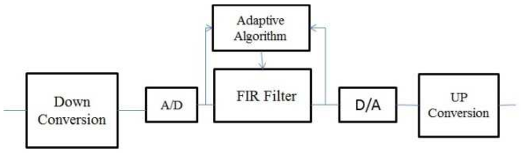

Figure 3: Adaptive prediction filter for rejecting narrow band interferences

The adaptive algorithm, based on linear prediction, periodically captures a block of data from which the optimal

FIR filter coefficients are calculated to notch out the interference. These coefficients are then downloaded to the FIR filter. The optimal filter will tend to maintain near unity gain at all frequencies, apart from the interference frequency. As an example, consider the filter transfer function obtained from a multi-tone interference, as shown in Figure 4. The adaptive algorithm was implemented on a DSP and took about 1ms to complete 14 iterations.

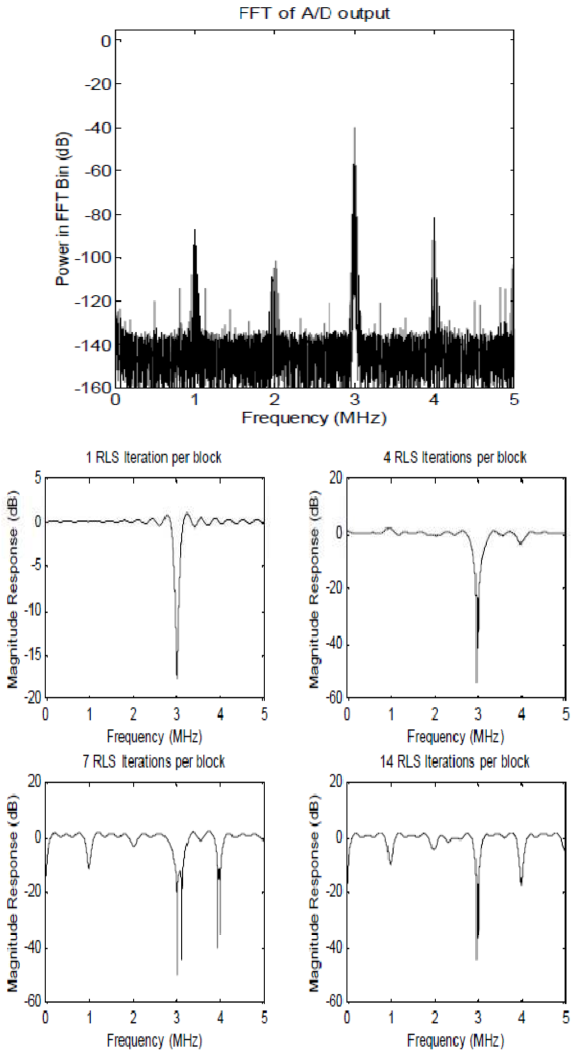

Figure 4: Multi-tone interference and resulting filter responses (the filter has 63 taps)

The system in Figure 3 uses a 12bit A/D with a 63 dB dynamic range, theoretically giving up to 63 dB additional anti-jam. Only 4045 dB additional anti-jam could be obtained against realistic CW interferences. The main limitation on the maximum anti-jam seemed to be due to the broadening of the interference spectra, at high interference powers, due to phase noise on the interference. Mayflower market a standaloneinterference canceller based on an adaptive FIR filter [20].

2.3.3 Adaptive Spatial Filters

The pre-correlation techniques discussed so far were based on a single antenna element and could not reject broadband noise interferences. Spatial filters reject the interference in angle, rather than frequency, and can achieve large anti-jam margins against most interference waveforms, including broadband noise. Spatial filters requiremulti-element antenna arrays, which are significantly larger and heavier than single antenna elements. They can cancel up to *N*1 interferences, where *N* is the number of antennas in the array. *Single beam former techniques* The simplest form of spatial filter uses an antenna array connected to a single beam former whose output then feeds directly into a GPS receiver, as shown in Figure 5.

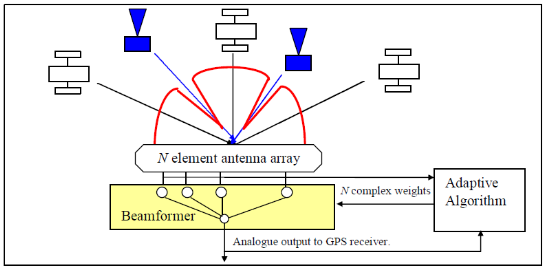

Figure 5: System architecture for single beam former, null steering, techniques.

The complete antenna array and beam former unit can be considered as a single antenna element with an adjustable beam pattern. The beam pattern of the antenna array is determined by the values of the complex weights, which are fixed for FRPA systems or continuously updated by an adaptive algorithm for CRPA systems.

The adaptive algorithm calculates the complex weights by solving an optimization problem. Anumber of optimization criteria have been proposed, most of them are based on minimizing the output power of the array subject to some constraint. The most commonly applied constraint is simply to set one of the beam former weights to unity [15] [21]. This criterion is often termed “Power Inversion” and will be the main focus of this section. It steers deep nulls in the direction of the interferences and attempts to maintain a uniform beam pattern in all other directions, as illustrated in Figure 5. By maintaining a uniform beam pattern, other than in the interference direction, it is hoped that most GPS signals will still be preserved. Other singlebeam former criteria that make use of platform attitude and the GPS signal DOA information can achieve some performance improvement over the simple power inversion array [15] especially in situations where the satellite DOA is close to an interference. However, in most situations, involving small antenna arrays of less than 8 elements, the simple power inversion array performs almost as well as more sophisticated adaptive algorithms [15]. This is because the gain of the spatial filter needs to be optimized in the direction of at least 4 satellites simultaneously.The remainder of this section will present some experimental results obtained from a CSSIP technology demonstrator implementing a spatial null steering algorithm. A block diagram of the complete system is shown in Figure 6, along with a photograph showing how it was mounted in a van on recent field trials.

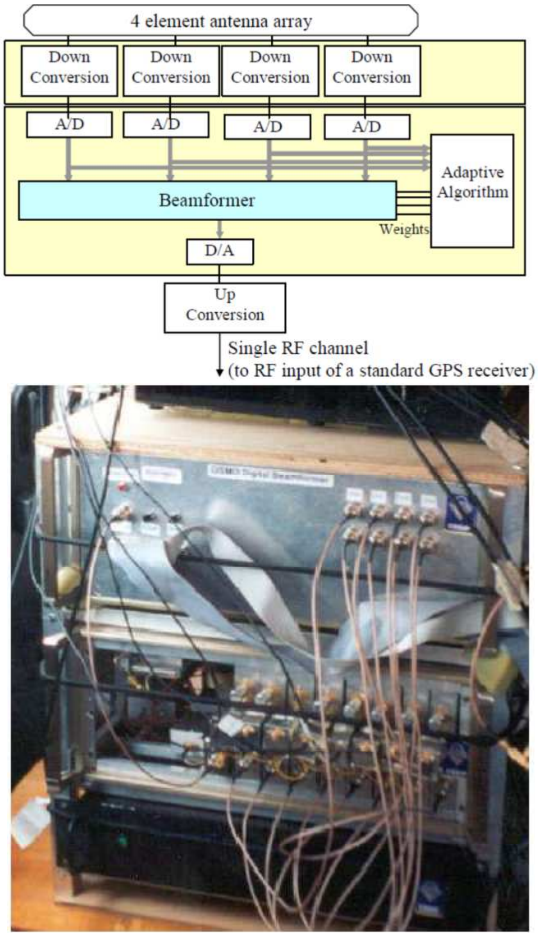

Figure 6: Technology demonstrator implementing a spatial null steering algorithm

The actual beam forming operation is implemented in the digital domain, requiring a separate down conversion stage and A/D for each antenna element. The adaptive algorithm continuously captures blocks of input data from which it calculates the optimal beam former coefficients based on the power inversion criteria. This beam former thus steers nulls at interferences while attempting to maintain unity gain in all other directions.The dynamic range of the A/D limits the maximum additional anti-jam available from the spatial filter. A 12bit A/D was used, with a useable dynamic range of 63 dB for CW signals. In practice, only about 40 dB of additional anti-jam against broadband interferences was obtained from the system. The reasons for this are partly due to the fact that broadband interferences saturate the A/D at lower powers than CW interferences. Also, the current system does not have an automatic gain control (AGC) to adjust the input signal power to avoid clipping in the A/D. About 1015dB of additional anti-jam is expected from an AGC. Figure 7 shows the C/No figures on the GPS receiver connected to the spatial filter as a function of interference power.

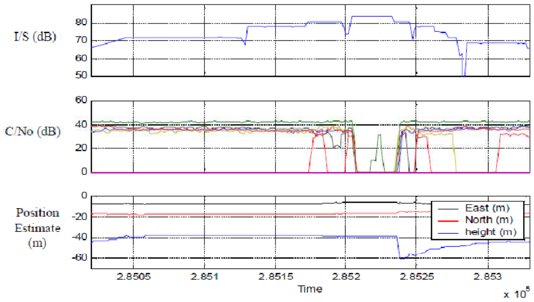

Figure 7: Maximum anti-jam against single broadband interference.

There is essentially no degradation in the C/No values until the A/D converter clips, at a J/S value of 80 dB. The van was stationary during the test, and the deviation in the position estimate prior to loss of lock is less than 5 m. This indicates that the spatial filter does not significantly impact the accuracy of the position estimate.One of the main limitations of spatial processing is that GPS signals arriving from DOAs near those of the interference will also be cancelled. To demonstrate this point, some results involving multiple interferences from different DOAs will be presented. In Figure 8, the C/No values of the satellites tracked by the GPS receiver connected to the beam former are shown as two interference sources are either moved or turned on or off. Both interferences were at an elevation angle of roughly 0 degrees. Interference source 1 started at an azimuth angle of 325 and was move to an azimuth angle of 25 and 55 degrees, while interference source 2 remained fixed. A third out of band interference source, at an azimuth angle of 205 degrees was also present, with an INR of around –3 dB (I/S = 1720dB), after filtering.

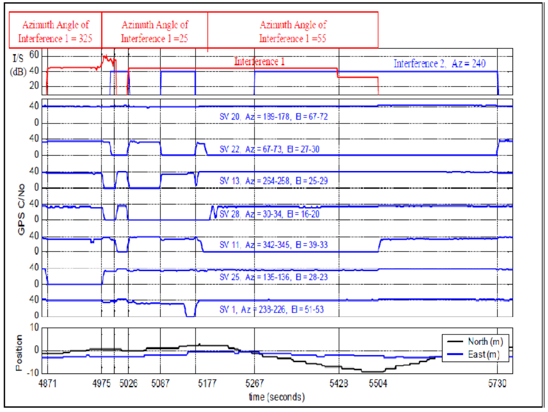

Figure 8: Satellite C/No values as a function of interference DOA.

The above diagram illustrates that as the DOA of interference 1 is changed, different GPS satellites move in and out of the spatial nulls. The satellites that are cancelled are not always directly adjacent to the interference source. Some tend to be offset by 180 degrees. However, even when there are two interferences, shortly after t = 5087 and 5267, the spatial filter still picks up over 4 GPS satellites. This illustrates that the simple power inversion array is quite effective in maintaining some gain in the direction of most GPS satellites, even though it blindly steers nulls at interferences.

Multiple Beam former Techniques

It is possible to use a separate spatial filter for each GPS satellite. The basic system architecture is shown in Figure 9. Multiple spatial filters, or beam formers, each tracking a different GPS signal are implemented in digital electronics. They can share the same antenna array, down conversion stages and A/D converters.

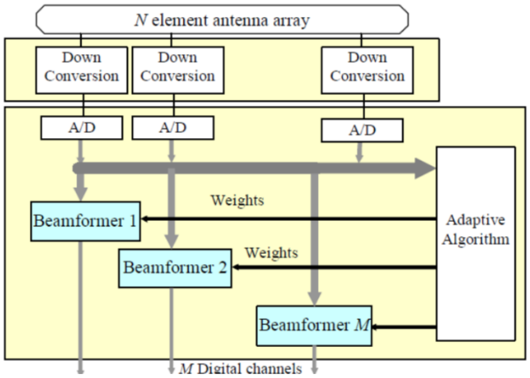

Figure 9: Multiple digital beam former architecture

The weights for each beam former are again adjusted according to an optimality criterion. A commonly applied criterion (Minimum Variance Distortion lessResponse, MVDR) minimizes the output power of each spatial filter subject to it having unity gain and phase in the direction of the desired GPS signal [18].

The main benefits of using multiple MVDR beam formers, over simple power inversion arrays include:

- Each beam former only needs to steer a beam at a single GPS satellite. This gives a factor of *N* improvement in SNR in a noninterference environment over the simple power inversion array.
- Each beam former can be constrained to have unity gain in the direction of the desired GPS satellite. This avoids phase discontinuities in the GPS signals, and allows the array to be used for accurate carrier phase differential tracking techniques.
- There is a greater probability that GPS signals will be preserved. The MVDR algorithm will make best use of the available degrees of freedom to shape the spatial null such that it does not cancel the GPS signal.

Some of the main limitations of using multiple spatial beam formers include

- Each beam former output needs to be passed independently to the GPS receiver. This means that it cannot be cascaded with most current GPS receivers. New GPS receivers with digital front ends should be compatible with this class of beam former.
- The adaptive algorithm needs to know both the attitude of the platform and the GPS signal DOAs. It may be possible to derive the platform attitude by processing the outputs of several antennas in the array.

2.3.4 Space time adaptive filters

The previous two sections have considered adaptive spatial and temporal filters in isolation. In broad terms temporal filters steer nulls in frequency, while spatial filters steer nulls (and beams) in angle. Combining spatial and temporal filtering allows nulls to be steered in both angle and frequency. This allows up to *N*1 broadband interferences to be cancelled by the spatial filter and additional narrow band interferences by the temporal filter.

The most flexible way to combine spatial and temporal filtering is to replace the digital beam former in Figure 6 or Figure 9 by the fully adaptive space time architecture shown in Figure 10. An FIR filter with *M* complex taps is placed after each of the *N* antenna elements, and the coefficient of each FIR filter is updated directly by the adaptive algorithm. The fully adaptive space time processor is able to localize the interference in the angle frequency plane, as shown in Figure 10, this property generally allows it to better preserve the GPS signal in the presence of an interference.

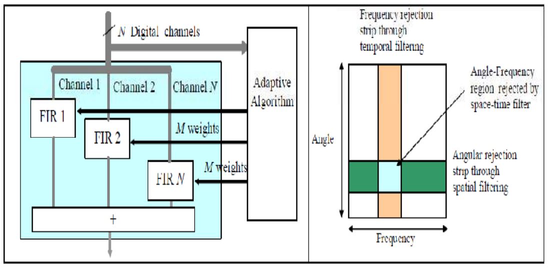

Figure 10: Fully adaptive Space Time Adaptive (STAP) architecture

Suitably modified versions of the Power Inversion and MVDR adaptive algorithms discussed above can be implemented depending on the level of system complexity [Fante, 2000].

Some of the main benefits of the spacetimeprocessing over the purely spatial filter are:

- More than *N*-1interferences can be cancelled if some are narrow band.
- In some scenarios, more nearby multipathsignals can be cancelled [Fante, 2000].
- Deeper spatial nulls are achievable due to interference bandwidth compensation.
- The STAP processor is able to steer point nulls in the anglefrequencyplane, as shown in Figure 10. Better localization of the interference results in less chance of cancelling a desired GPSsignal.

A potential problem of the spacetimepower inversion array is that the additional temporal filteringcan introduce timing errors into the GPS signals [19]. This problem is not encountered inthe purely spatial power inversion array, which only impacts the signal phase information. Anotherconcern is the high computational complexity of the adaptive algorithm, which needs to calculate*NM* spacetimecoefficients. Adaptive algorithms based on nested Wiener filters have recently beenproposed that achieve rapid convergence at reduced computational loads [21].

Another method for reducing the computational load is to use a simplifiedspace-timearchitecture.A spatial filter can be simply cascaded with a single FIR filter, as shown inFigure **11**.

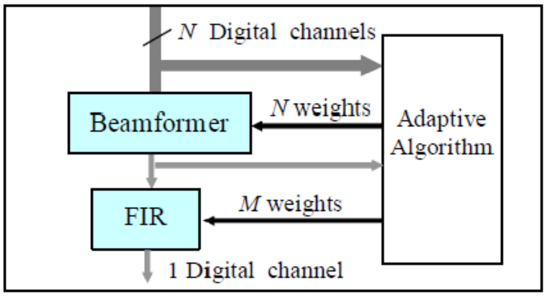

Figure 11: Simplified STAP Architecture

In this architecture, only *N*+*M* coefficients need to be updated, but a complicated adaptive algorithm is required to ensure that the broadband interferences are allocated to the spatial filter and the narrow band interferences to the temporal filter. This technique no longer has all the properties of the fully adaptive STAP power inversion array. Its main advantage over the purely spatial Power Inversion array is that it can cancel more than *N*-1 interferences if some of them are narrow band. It is also expected to be less toxic to the GPS timing information, as a common FIR filter is applied to all GPS signals [20].

3. CONCLUSIONS

GPS receivers are vulnerable to interference, due to the low received signal powers. This paper has given an overview of several techniques for improving the robustness of GPS receivers to interference.

Adaptive A/D converters can give several dB of additional anti-jam against CW interferences. Further improvements against all interference waveforms can be obtained from modifications and enhancements to the receiver tracking loops. The main thrust of these techniques is to reduce the bandwidth of the tracking loops while maintaining the dynamic performance of the receiver. The most effective technique is the integration of GPS with INS, from which between 1020dB of additional anti-jam can be obtained.

Finally, significant additional anti-jam margins can be obtained by rejecting the interference prior to the tracking loops. Pre-correlation anti-jam techniques have been the main focus of this paper. Most of these techniques can be packaged as a separate antenna electronics unit and placed in front of a standard GPS receiver.

Adaptive temporal filters can reject narrow band interferences. Additional anti-jam of up to 40 dB has been demonstrated with a prototype system. The main factors limiting the maximum anti-jam are the dynamic range of the A/D and the bandwidth of the interference.

Spatial processing techniques can reject broadband noise interferences. The dynamic range of the A/D typically limits the maximum anti-jam. Over 40 dB of additional anti-jamis achievable with current technology. The main limitations of spatial processing are that at most *N*-1 interferences can be cancelled, where the array has *N* elements, and that GPS signals in the direction of the interference will also be nullified out. The simplest spatial filter uses a single beam former implementing a power inversion array. Results from such a system were presented to demonstrate the loss of satellite signals due to spatial nullifying. It was shown that a 4element array cancelling two interference could still reliably receive 4 GPS signals. More complicated spatial filtering algorithms that incorporate multiple spatial filters were presented. These techniques give more guarantee of preserving the desired GPS signals and can be designed to preserve the phase and amplitude of the GPS signal. However, they will require a digital link to the GPS receiver.

Combining spatial and temporal processing allows more than *N*-1 interferences to be cancelled, gives deeper spatial nulls, and improves performance in certain interference multipath environments. However, care needs to be taken that the additional temporal processing does not impact the timing of the GPS signals. Also, the computational complexity of the final system is increased, resulting in slower convergence times. Research into fast adaptive algorithms for GPS space time arrays is continuing. A simplified space time architecture with reduced computational complexity has also been mentioned.

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