GNSS Interference Mitigation By Null Steering Antenna Utilizing Space Time Adaptive Processing

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Abstract—**This paper explores the subject of interference suppression for the reliable use of global navigation satellite systems (GNSS). The range of applications of GNSS stretch from commercial use like surveying, automotive navigation systems etc to military applications like navy ships, aircrafts and guided missiles etc. The prevalent use of this technology makes it inflexible to provide reliable services in the presence of massive scale interferences in environment. A new architecture of null steering antenna based upon the technology of Space-Time Adaptive Processing (STAP) with optimized parameters has been proposed in this paper, which can suppress both wideband and narrowband interferences more efficiently with deeper nulls. Furthermore, the new architecture do not require a separate sensor for the reference signal rather it get the reference signal from the first sensor of the auxiliary array. Simulation results shows that the proposed architecture outperforms the conventional STAP techniques for interference suppression and place deeper nulls in direction of interference**.

Index Terms— **Null Steering, STAP, Interference Mitigation, Power Inversion.**

I. Introduction

POSITIONING and timing systems such as GPS, GLONASS, Galileo are widely used in today's human life. Currently, most mobile phones as well as vehicles are equipped with such types of systems. Despite the ever increase in demand for accurate and reliable satellite navigation and positioning dependent services, one of the main drawbacks of these system is their susceptibility to interference [1]-[3]. Global Positioning System and other satellite navigation system receivers are subject to interference, because of being extremely weak received signals, thereby degrading the performance of the GPS receiver to acquire or track the GPS signals. Generally, interference decreases the effective signal-to-interference plus-noise ratio (SINR) of received satellite signals. Therefore, even a low-power interfering signal can easily deny satellite navigation services within a radius of several kilometers.

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Interference can generally be detected and suppressed by using time, frequency and spatial domain processing or a combination of them. Time/frequency narrowband interference detection and suppression methods have been widely studied in the past [4]-[8]. Rapid advancements in electronic systems and antenna technology are resulting in powerful antenna array based solutions to further enhance the performance of navigation systems receivers in terms of SINR [2]-[3].

To antennas array with M sensors, we can achieve maximum of M-1 spatial nulls for canceling interferers. One degree of freedom is consumed in constraining the reference element weight to be unity. So it is clear that the anti-jamming performance of antenna array has a direct relationship with the number of antennas. The greater the amount is, the stronger the interference suppression is. Because more weights are to be computed to approach the optimum weight vector as the number of antenna increases, and the nulls will be much deeper.

Since there are a lot of deliberate and unintentional interferences present in the environment which usually exceed the number of antennas. Therefore, to deal with this problem, techniques employing both time/frequency and spatial domain processing such as space-time adaptive processing (STAP) and space-frequency adaptive processing (SFAP) were utilized in past. The technology of STAP was first introduced by Frost in 1972[1]. Brennan and Reed introduced the use of STAP for adaptive radar in 1973[9]. Afterwards STAP is extensively researched for implementation in real time application. Many structures and algorithms were discussed to improve the STAP performance. Some good literature to understand the concept of STAP in detail is available in [9]-[11]. A new structure of null steering antenna has been proposed in this paper that can make efficient use of sensor elements and cancel more interference as compared to the traditional STAP antenna array.

The remaining paper proceed as follows: Section 2 describes the conventional structure of null steering antenna based on Space Time Adaptive Processing. Section 3 demonstrates the proposed methodology and signal model for the new structure of null steering antenna based on STAP. The simulation results of the proposed STAP structure are given in section 4. Finally section 5 offers some conclusions drawn on the basis of simulation results.

II. Null Steering Antenna

Null steering antenna [12]-[13] is capable to suppress interference signal requiring minimal knowledge of the desired signal or without the any prior knowledge, and can effectively weaken the strong signal among the weak signals. This approach perform well provided that interference signal is stronger than the desired signal. Since the signal of GPS satellite is very weak and well below the thermal noise, while interference signal is generally above the noise floor. Null steering antenna makes up the shortcoming of GPS signal effectively. The conventional null steering antenna architecture based on STAP is shown below in figure 1:

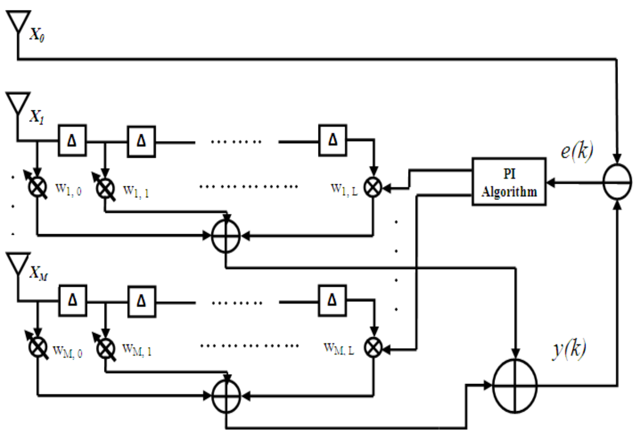

Fig. 1. Traditional Null Steering Antenna based on STAP.

The selection of weights and structure of the array determines the radiation pattern of an antenna array. Selection of the weights has received extensive attention, primarily because the radiation pattern is a linear function of the weights. However, the STAP structure has received relatively little attention even though it also strongly influences the radiation pattern. The reason for this is primarily due to the complex way in which the structure affects the radiation pattern. In this paper we have addressed both the issues together. The main aim of this paper is to determine optimized array structure in conjunction with proper selection of weights in antenna arrays to get superior results.

III. Proposed Methodology

A. STAP Model

The combined space-time adaptive processor with M element antenna array followed by an L-th order tapped delay act as a finite impulse response (FIR) filter in time domain [14].

The generic space adaptive algorithm can suppress the narrowband interference easily because it is comparatively simple than broadband interference. In case of broadband interference, the group of phase factor is very complicated. It is a time delay rather than a simple phase shift [15]-[16].

The proposed STAP model is shown in figure 2. Rather than deploying a separate sensor element for the reference signal, we get the reference signal from the first sensor element at first instant. This strategy simplifies the structure as well as increase the degree of freedoms also. Now both the reference signal and the signal on first channel of auxiliary array contain the same noise with desired signal lie in the noise. There is a possibility that noise will be suppressed because of the fact that output is taken as the difference of reference signal and weighted summed signal of the auxiliary array. To deal with this issue, the first weight w_{10} is constrained to be zero.

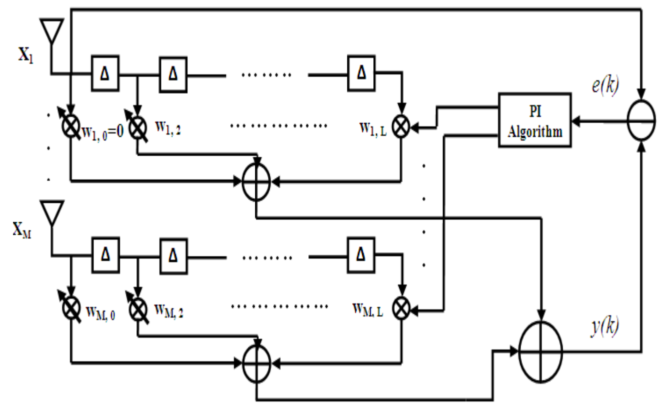

Fig. 2. Proposed Null Steering Antenna based on STAP.

B. Signal Model

Consider a uniform linear array with M antenna elements as shown in figure 2 above. Each antenna element is followed by an L-length tapped delay line filter. The output from each element is sampled every T seconds and the output of each tap is multiplied by a complex weight and summed to form the array output $y(t)$. All the M element represents auxiliary array and the reference signal is taken from the first sensor of the array and. The signal captured as a reference is given by:

$$x_{ref} = \sum_{j=1}^{J} f_j(t) + n_{ref}(t) \tag{1}$$

Where $f_j(t) = A_j(t)e^{j\omega_j t}$ are interferences and desired signal and $n_{ref}(t)$ is the uncorrelated noise present on each sensor.

The signal received by the m-th element in the auxiliary array is given by:

$$\boldsymbol{x}_m = \begin{bmatrix} x_{m0} \\ x_{m1} \\ . \\ . \\ x_{mL} \end{bmatrix} \tag{2}$$

Whereas;

$$x_{m0} = \sum_{j=1}^{J} f_j(t - \tau_{mj}) + n_{m0}(t) \tag{3}$$

$$x_{mL} = \sum_{j=1}^{J} f_j\left(t-\tau_{mj}-LT\right)+n_{mL}(t) \quad (4)$$

τ_{mj} represent the inter-element spacing delay. The noise $n_{mL}(t)$ is a shifted version of $n_{m0}(t)$ and is equivalent to:

$$n_{mL}(t)=n_{m0}(t-LT) \quad (5)$$

So for M-element auxiliary array we have:

$$\boldsymbol{x}_1 = \begin{bmatrix} x_{10} \\ x_{11} \\ \vdots \\ \\ x_{1L} \end{bmatrix}, \ldots\ldots, \boldsymbol{x}_M = \begin{bmatrix} x_{M0} \\ x_{M1} \\ \vdots \\ \\ x_{ML} \end{bmatrix} \quad (6)$$

And finally the received signal vector can be represented as:

$$\boldsymbol{x}(t) = \begin{bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \\ \vdots \\ \\ \boldsymbol{x}_M \end{bmatrix} \quad (7)$$

The corresponding weight vector for the structure can be defined as

$$\boldsymbol{w}(t) = \begin{bmatrix} \boldsymbol{w}_1 \\ \boldsymbol{w}_2 \\ \vdots \\ \\ \boldsymbol{w}_M \end{bmatrix} \quad (8)$$

Where $\boldsymbol{w}_1 = [w_{10} \quad \ldots \quad w_{1L}]^T$, $\boldsymbol{w}_2 = [w_{20} \quad \ldots \quad w_{2L}]^T$ and $\boldsymbol{w}_m = [w_{m0} \quad \ldots \quad w_{mL}]^T$.

The noise on first sensor of array and reference channel is same because of the fact that reference signal is taken from the first sensor. As output of the STAP is the difference of the reference channel and auxiliary array, so certainly it will suppress the noise also. Noise contains the desired signal and our goal is to suppress the interference only. By constraining the first weight of first sensor element to zero assures that noise will not be suppressed.

The auxiliary array output at time t, $y(t)$ is formed from the weighted sum of tap voltages such that:

$$y(t)=\boldsymbol{w}^H\boldsymbol{x}(t) \quad 9)$$

Or

$$y(t)=\sum_{i=1}^{M}\sum_{j=0}^{L} w_{i,j}^{*} x_{i,j} \quad (10)$$

The output of the entire STAP is given by the following equation:

$$e(t)=x_{ref}-y(t)=x_{ref}-\boldsymbol{w}^H\boldsymbol{x}(t) \quad (11)$$

In digital systems we sample the signal so after this point we will use notation ‘ k ’ instead of ‘ t ’.

MMSE (Minimum Mean Square Error) constrain the optimum weight vector $\boldsymbol{w}_{opt}$ so as to get the least mean square error between weighted sum of the signal and the reference signal, which is called the cost function $J(\boldsymbol{w})$ and can be defined as:

$$J(\boldsymbol{w})=E[e(k)e^*(k)] \quad (12)$$

$$J(\boldsymbol{w})=\xi(k)=E[|e(k)|^2] \quad (13)$$

According to the steepest gradient principle the update value of the weight vector at time $k+1$ is computed by using the recursion formula as given below:

$$\boldsymbol{w}(k+1)=\boldsymbol{w}(k)-\mu\nabla_w\xi(k)/2 \quad (14)$$

Let $\nabla_w\xi(k)$ denote the value of the gradient vector at ‘ k ’. The parameter ‘ μ ’ is a positive real valued constant known as step-size. From equation (11) and (13) we have:

$$\nabla_w\xi(k)=-2\boldsymbol{r}_{xd}+2\boldsymbol{R}_{xx}\boldsymbol{w}(k) \quad (15)$$

Where;

$$\boldsymbol{r}_{xd}=E[\boldsymbol{x}(k)x_{ref}^*(k)] \quad (16)$$

$$\boldsymbol{R}_{xx}=E[\boldsymbol{x}(k)\boldsymbol{x}^H(k)] \quad (17)$$

Equation (16) and (17) give the theoretical estimate values of correlation matrix $\boldsymbol{R}_{xx}$ and the cross correlation vector $\boldsymbol{r}_{xd}$, but in practical application it cannot be applied, so we derive these two values by the following expressions:

$$\hat{\boldsymbol{r}}_{xd}=\boldsymbol{x}(k)x_{ref}^*(k) \quad (18)$$

$$\hat{\boldsymbol{R}}_{xx}=\boldsymbol{x}(k)\boldsymbol{x}^H(k) \quad (19)$$

Substitute the estimate of equation (15) for the gradient vector $\nabla_w\xi(k)$ in equation (14); we get a new recursive equation for updating the weight vector:

$$\boldsymbol{w}(k+1)=\boldsymbol{w}(k)-\mu\boldsymbol{x}(k)[x_{ref}-\boldsymbol{w}^H(k)\boldsymbol{x}(k)] \quad (20)$$

IV. SIMULATION RESULTS

A uniform linear array comprised of 2 elements, each of which is connected to a 3 tap FIR filters, is simulated in MATLAB. Elements are assumed to be omni-directional, and spacing between the adjacent array elements is half a wavelength of the carrier. Simulations were performed in four different scenarios to test the superiority of the proposed STAP model over the conventional STAP model. The complete details about the interferer scenarios are listed in table 1 given below.

The interference categorized as wideband QPSK and narrowband interference. Wideband is in the sense that the band of QPSK is wider than the desired signal. Narrowband interference is single frequency interference also termed as CW interference.

Assuming space has two interferences with the angle of incidence $\theta_1=30°$ and $\theta_2=-30°$, the suppression of interference by conventional STAP and proposed STAP are shown below in figures 3-6.

TABLE I
INTERFERER'S SCENARIOS

No. of Sensors	No. of FIR Filters	Wideband Interference (10 MHz -QPSK)	Narrowband Interference (CW)	Total Interferences
2	3	0	2	2
2	3	2	0	2
2	3	1	1	2
2	3	1	1	2

Figure 3 depict the spectrum of the conventional and proposed STAP with two CW interferences. Since CW interference is a single frequency signals and consumes only one degree of freedom, so both conventional and proposed STAP suppress the interference signal efficiently. The depth of null is more in proposed structure as compared to the conventional structure of STAP. The figure shows that there is suppression of desired signal in the proposed method. But as the GPS signal is spreaded over a larger bandwidth using DSSS scheme, so even if it is suppressed with the interference at some point which is a very narrow part of the spectrum, still it can be recovered efficiently.

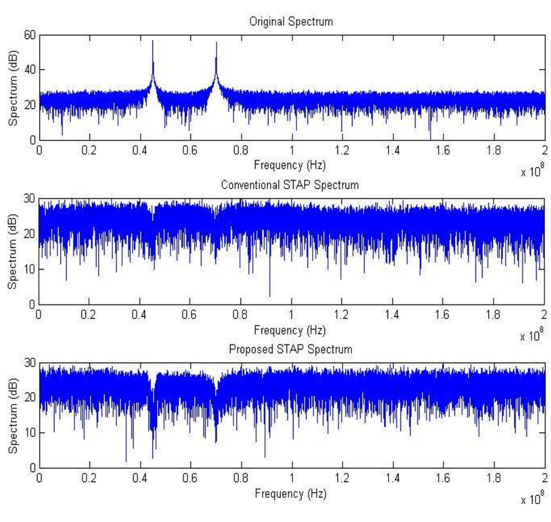

Fig. 3. STAP Spectrum with two CW Interferences

Figure 4 presents the respective spectrums for the conventional and proposed STAP model. The two QPSK interferences of 10 MHz bandwidth are prominent with higher peaks in the original spectrum. The conventional STAP cannot suppress the interference efficiently. Still there are peaks present in the conventional STAP spectrum. Furthermore the spectrum is also not flat at points other than that of interference. In Contrast to Conventional STAP, the proposed STAP efficiently suppress the interferences and provide a flat response at other locations in the spectrum.

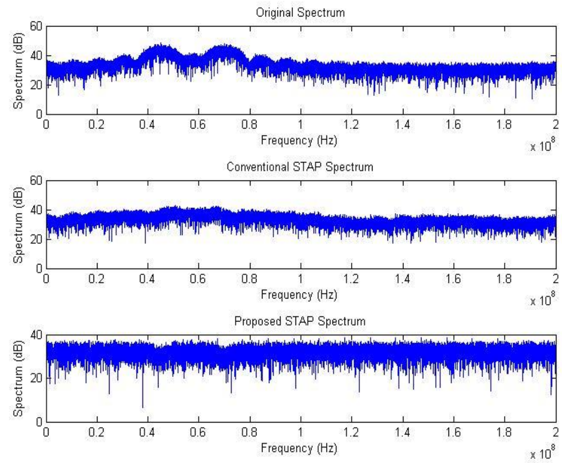

Fig. 4. STAP Spectrum with two QPSK Interferences.

Proposed STAP outperforms the conventional STAP model in the scenario given below. Figure 5 shows the respective plots of conventional and proposed STAP. The CW interference occupies the same band as that of QPSK interference of 10 MHz bandwidth. The conventional STAP fails to suppress the interference and the peaks are prominent in case of conventional STAP. While the proposed STAP effectively and efficiently suppress both the interference and a smooth spectrum is obtained by suppressing both the interferences to the level of noise

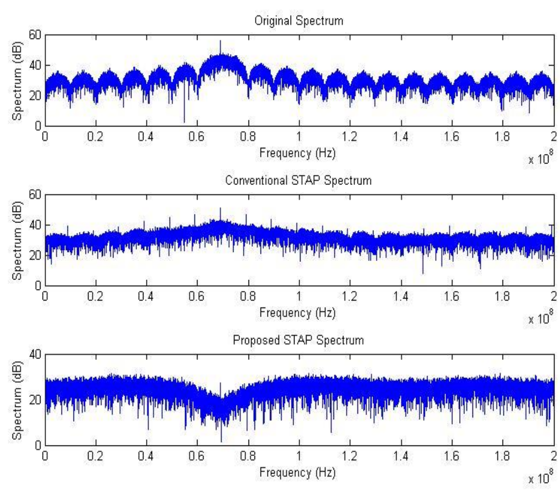

Fig. 5. Spectrum with one CW and one QPSK Interference occupying same band of frequency.

Considering the same scenario as above but the CW interference and QPSK interference of 10 MHz bandwidth are separated. Again the proposed STAP model outperforms the conventional structure. The conventional STAP is unable to suppress the interference as while the proposed STAP suppressed the two interferences efficiently as shown in figure 6.

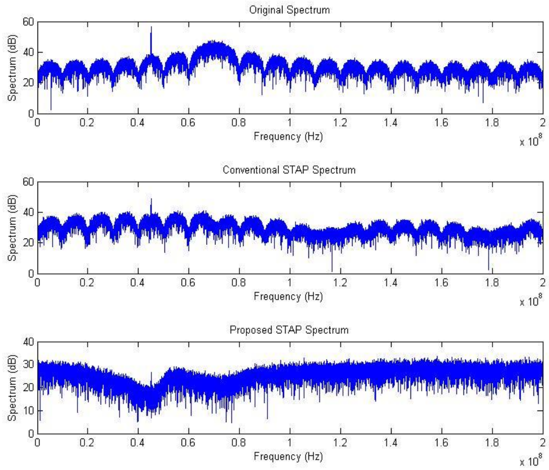

Fig. 6. Spectrum for conventional STAP with one CW and one QPSK Interference.

V. CONCLUSION

The spread spectrum technique applied in the structure of GPS Navigation signals provides a certain degree of protection against interference for narrowband interfering signals and multipath; however, the spreading gain alone is not sufficient to avoid interference whose power is much stronger than the GPS signal power or to mitigate non-resolvable multipath components. In this paper a new architecture for null steering antenna has been proposed. In the new architecture, the reference signal is attained from the first sensor element of the auxiliary array and the first weight of that sensor element is constrained to be zero in order to ensure that noise should not be suppressed as desired signal lie in noise. Furthermore, the nulling capability of the proposed STAP is extended beyond the sensor-limited spatial degrees of freedom. The simulation results show that the proposed structure outperforms the conventional STAP system. In the first two scenarios of two CW interferers and two QPSK interferers, the results of proposed and conventional STAP are very close. While the last two scenarios in which there are 1 CW and one QPSK interferer present, the proposed STAP outperforms the conventional STAP which validate the performance enhancement of the proposed STAP to null out both narrowband and wideband interferences.

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