Survey on Interference Mitigation via Adaptive Array Processing in GPS

D. Lu[1,2], Q. Feng[2], and R. Wu[2]
[1]Xidian University, China
[2]Civil Aviation University of China, China

Abstract—Due to the extremely low power, GPS signal can be easily affected by interferences. In this paper, from the point of adaptive array processing, we review the existing spatial and space-time interference suppression methods which attempt to mitigate interferences before the GPS receiver performs correlation. These methods comprise self-coherence restoral technique based on the nature of GPS signal, space-time minimum mean square error, power minimization technique, GPS multipath mitigation technique using the vertical array etc. Also we summarize their performance and applicability by analyzing all these techniques, in which some of our work and opinions are included.

1. Introduction

Global Positioning System (GPS) is a satellite-based navigation system which can provide the position, velocity and timing information for users in all weather conditions, anywhere in the world and anytime in the day. Therefore, it has been widely used in civil and military applications such as navigation by general aviation, positioning for users and so on. Because of its high precision, general acceptability and easier equipment of user's receiver, GPS will gradually become a main means of global navigation.

However, GPS signal is susceptible to interferences from either intentional or unintentional sources for the reason that it arrives at the receiver at a very low-power level, typically 20∼30 dB below the receiver's thermal noise level [1]. Based on that, the performance of GPS navigation and positioning degrades dramatically. Hence, one of the hot topic of using GPS is to cancel the interference as completely as possible without any distortion of desired GPS signal.

Conventional GPS suppression methods including time-domain and frequency-domain filtering techniques [1–4] employ DFT technology to suppress interference by taking out abnormal spectrum line of digital intermediate frequency signal. These methods have the advantages of easy implementation and low cost, but they can not mitigate multiple narrowband interferences as well as wideband interferences owing to its incapability of differentiating between desired signal and interference in the spatial domain. However, array signal processing techniques can efficiently suppress the above interferences according to the spatial information. Adaptive nulling technique [5] based on array antennas can adaptively place nulls in the direction of interferences, which is very popular to be used in improving the performance of GPS receiver. Unfortunately, the above method may be inadequate for broader band operation, especially when interference multipath is present. In order to solve this problem, space-time adaptive processing (STAP) techniques [6–9] are proposed in recent years. STAP can greatly increase the number of degrees of freedom under the equivalent antennas condition and thus can efficiently suppress wideband interference. So it is a trend of GPS interference mitigation.

This paper mainly discusses the existing methods based on adaptive array processing. The following section will describe some spatial techniques emphasis on self-coherence restoral technique using the nature of GPS signal. In Section 3 we firstly give a uniform data model, and then several STAP methods consisting of maximum signal-to-interference ratio algorithm, minimum mean square error, space-time Capon algorithm and power minimization technique are described. GPS multipath mitigation technique using the vertical array is given in Section 4. While, concluding remarks are given in Section 5.

2. Spatial Adaptive Processing Techniques

As demand for accurate GPS positioning, adaptive beamforming algorithm should not cause any significant distortion of the desired GPS signals when it is used to suppress interferences. Such algorithms include the direction finding algorithm [10], which is an adaptive beamforming algorithm based on estimation of the directions of arrival (DOAs) of the received signals, and directional constrained adaptive beamforming algorithm, which is based on the principle that if the dynamic of the GPS receiver is not too high and the beampattern is not too narrow, rough coordinates of the receiver and the coordinates of the satellites in view can be used to calculate the DOAs of the signals of interest from different satellites, and so on. However, these algorithms do not fully take advantage of the GPS signal structure. So Wei Sun proposed a GPS interference mitigation method using self-coherent feature of GPS signal [11, 12].

The method considers interference suppression in GPS using spatial processing that incorporates the known temporal structure of the GPS signal. And it utilizes the replication property of the C/A-code within the navigation symbol to suppress interferences which are aperiodic or have a different periodic signal structure from that of the GPS signal. A block diagram of the proposed algorithm is shown in Fig. 1, which consists of a main channel and a reference channel. The samples in the main channel and the reference channel are processed by a beamformer$\mathbf{w}$and another processor $\mathbf{f}$ respectively, where the samples of reference channel are lP chips ($P = 1023,\ 1 \le l < 20$) delay of the main channel's data. These samples in the main channel are given by:

$$\mathbf{x}(n) = \mathbf{a}s(n) + \sum_{j=1}^{K} \mathbf{b}_j i_j\,(n) + \mathbf{v}(n) \tag{1}$$

where $\mathbf{x}(n)$ is the $M \times 1$ data vector, $s(n)$ is the desired GPS signal and $i_j\,(n)$ is the jth interference, $\mathbf{a}$ and $\mathbf{b}_j$ are $M \times 1$ steering vectors of the desired GPS signal and the jth interference respectively, and $\mathbf{v}(n)$ is the thermal noise vector. This paper provided that GPS signal, interference, and noise are uncorrelated unless special statement.

Due to the repetition of GPS signal, GPS signal samples of two channels in Fig. 1 have the same values as long as they are within the same symbol. However, the interference samples have different values because they are aperiodic or have a different periodic signal structure from that of the GPS signal. Thus the samples in the reference channel are given by:

$$\mathbf{x}(n - lP) = \mathbf{a}s(n) + \sum_{j=1}^{K} \mathbf{b}_j i_j\,(n - lP) + \mathbf{v}(n - lP) \tag{2}$$

The algorithm proposed can adaptively update the weight vectors $\mathbf{w}$ and $\mathbf{f}$ by maximizing the cross-correlation between the output of the main channel and the reference channel. Accordingly, we define the following cost function:

$$\mathrm{C}(\mathbf{w}, \mathbf{f}) = \frac{|R_{zd}|}{R_{zz}R_{dd}} = \frac{\left|\mathbf{w}^H \mathbf{R}_{xx}^P \mathbf{f}\right|^2}{\left|\mathbf{w}^H \mathbf{R}_{xx} \mathbf{w}\right| \left|\mathbf{f}^H \mathbf{R}_{xx} \mathbf{f}\right|} \tag{3}$$

where

$$\begin{aligned}
R_{zd} &= E\left\{z(n)d^H(n)\right\} = \mathbf{w}^H E\left\{\mathbf{x}\,(n)\,\mathbf{x}^H\,(n - lP)\right\}\mathbf{f} = \mathbf{w}^H \mathbf{R}_{xx}^P \mathbf{f}\\
R_{zz} &= E\left\{z\,(n)\,z^H\,(n)\right\} = \mathbf{w}^H E\left\{\mathbf{x}\,(n)\,\mathbf{x}^H\,(n)\right\}\mathbf{w} = \mathbf{w}^H \mathbf{R}_{xx} \mathbf{w}\\
R_{dd} &= E\left\{d\,(n)\,d^H\,(n)\right\} = \mathbf{f}^H E\left\{\mathbf{x}\,(n - lP)\,\mathbf{x}^H\,(n - lP)\right\}\mathbf{f} = \mathbf{f}^H \mathbf{R}_{xx} \mathbf{f}
\end{aligned} \tag{4}$$

The algorithm makes full use of the nature of GPS signal and does not need any knowledge of transmitted signals or the location of the satellite. Meanwhile, it is not sensitive to steering error and robust. So the algorithm is a promising method in GPS interference cancellation.

Generally speaking, spatial adaptive processing techniques are easy to implement and convenient for calculation. But it will increase array cost for an interference consuming one degree of freedom. To solve this problem, the techniques based on space-time joint processing are proposed [7–9, 13]. They all provide more degrees of freedom via time tap than only space processing.

3. Space-time Joint Processing Techniques

STAP algorithms employ the multiple receiving elements ("space") of an antenna array and multiple temporal samples ("time") to cancel interferences. The space-time weights are realized through a tapped-delay-line behind each antenna, as shown in Fig. 2. Some scholars, such as Dr. Fante and Dr. Zoltowski, have gained some achievements in GPS interference mitigation based on STAP [7, 8, 14]. In this section, based on the fruits of their study, we give the general space-time data model for GPS interference suppression.

3.1. Data Model

The space-time data model can be written as:

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \sum_{j=1}^{K} \mathbf{B}_j \mathbf{i}_j(t) + \mathbf{V}(t) \tag{5}$$

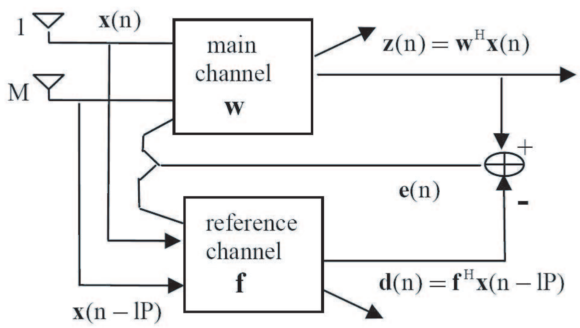

Figure 1: Block diagram of the interference suppression based on the self-coherence of GPS signal.

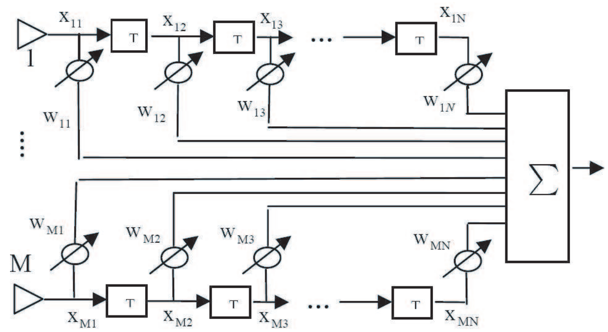

Figure 2: Block diagram of the STAP technique for GPS interference mitigation.

where $\mathbf{x}(t) = [x_{11}(t) \ldots x_{M1}(t)\, x_{12}(t) \ldots x_{M2}(t) \ldots\, x_{1N}(t) \ldots x_{MN}(t)\,]^T$ is the received data (M is the number of antenna and N is the number of tap each antenna), $\mathbf{A} = \mathbf{I}_{N\times N} \otimes \mathbf{a}$ and $\mathbf{s}(t) = [s(t) \ldots s(t-(N-1)T)]^T$, $\mathbf{B}_j$ and $\mathbf{i}_j(t)$ have the same structure as $\mathbf{A}$ and s(t) respectively.

3.2. STAP Algorithm

3.2.1. Maximum Signal-to-Interference-plus-Noise Ratio

This approach chooses weight vectors $\mathbf{w}$ to maximize signal-to-interference-plus-noise ratio of the output of beamformer. Accordingly, there is the following cost function:

$$\mathbf{w}_{opt} = \arg\max_{\mathbf{w}} SINR = \frac{\mathbf{w}^H \mathbf{R}_s \mathbf{w}}{\mathbf{w}^H \mathbf{R}_n \mathbf{w}} \tag{6}$$

where $\mathbf{R}_n$ is interference-plus-noise covariance matrix. Because the GPS signal strength is at least 20 dB below the thermal noise floor, $\mathbf{R}_n$ can be estimated by averaging approximately $4MN$ independent samples of the received signal [15], namely:

$$\mathbf{R}_{\rm n} \approx \mathbf{R} = E\left\{\mathbf{x}(t)\mathbf{x}^H(t)\right\} \approx \frac{1}{4MN} \sum_{q=1}^{4MN} \mathbf{x}\,(q)\mathbf{x}^H\,(q) \tag{7}$$

$\mathbf{R}_s$ is the desired GPS signal covariance matrix, which can be derived by the density of power spectrum of GPS signal. Note that this method requires information on platform attitude in order to determine $\mathbf{R}_s$, and meanwhile the processor is required being repeated for each GPS satellite which is used to determine user's position.

3.2.2. Minimum Mean Square Error Algorithm

This method obtains the weight vector by minimizing the mean square error between the desired GPS signal and the output of the processor in Fig. 2. Accordingly, the cost function is given by:

$$\mathbf{w}_{opt} = \arg\min_{\rm w} E\left\{\left(s_d - \mathbf{w}^H\mathbf{x}\right)\left(s_d - \mathbf{w}^{\rm H}\mathbf{x}\right)^H\right\} \tag{8}$$

where s_d is the desired signal. By solving this optimum question, we can find:

$$\mathrm{w}_{opt} = \mathrm{R}^{-1}\mathbf{g}_s \tag{9}$$

where $\mathbf{g}_s = E\left\{\mathbf{x}s_d^*\right\}$ is the first column of $\mathbf{R}_s$. Note that the processor is also repeated for each GPS satellite to calculate user's position and requires attitude information.

3.2.3. Space-time Capon Beamforming

When the direction of desired GPS satellite signal can be estimated, this algorithm minimizes the output power with attempting to preserve the gain in the desired signal direction for each of the N "tap times" of the processor in Fig. 2. This leads to the power minimization with N linear constraints:

$$\begin{aligned} &\min_{\mathbf{w}} \mathbf{w}^H\mathbf{R}\mathbf{w} \\ &s.t.\ \mathbf{w}_i^H\mathbf{a} = 1,\ \ i = 1, \ldots, N \end{aligned} \tag{10}$$

where $\mathbf{w} = [\mathbf{w}_1, \ldots, \mathbf{w}_N]^T$, $\mathbf{w}_i = [w_{1i}, \ldots, w_{Mi}]$. And (10) can be rewritten as:

$$\begin{aligned} &\min_{w} \mathbf{w}^H \mathbf{R} \mathbf{w} \\ &s.t.\ \mathbf{w}^H \mathbf{A} = \mathbf{1}_{N\times 1} \end{aligned} \tag{11}$$

Using the method of Lagrange multipliers, the solution to (11) is:

$$\mathbf{w}_{opt} = \mathbf{R}^{-1}\mathbf{A}(\mathbf{A}^H\mathbf{R}^{-1}\mathbf{A})^{-1}\mathbf{1}_{N\times 1} \tag{12}$$

This result is similar to the one obtained by standard capon beamforming (SCB). So the approach is called space-time capon method. Like the SCB, the performance of the approach becomes worse when steering vector error exists. Therefore, some robust STAP algorithm will be developed based on the robust capon beamforming algorithm [16].

3.2.4. Space-time Power Minimization Algorithm

Because the received GPS satellite signals are well below the thermal noise floor, this method is extraordinary efficient for GPS interference cancellation. It simply constraints the weight on the first tap of reference antenna 1 (see Fig. 2), and then minimizes the output power, namely:

$$\begin{aligned} &\min_{\mathbf{w}} \mathbf{w}^H \mathbf{R} \mathbf{w} \\ &s.t.\ \mathbf{w}^H \boldsymbol{\delta}_{MN} = 1 \end{aligned} \tag{13}$$

where $\boldsymbol{\delta}_{MN} = [1, 0, \ldots, 0, \ldots, 0]^T$ is the $MN \times 1$ vector. Using the method of Lagrange multipliers, the solution to (13) is

$$\mathbf{w}_{opt} = \frac{\mathbf{R}^{-1}\boldsymbol{\delta}_{MN}}{\boldsymbol{\delta}_{MN}^H\mathbf{R}^{-1}\boldsymbol{\delta}_{MN}} \tag{14}$$

This approach has the advantages of not requiring to know the DOA of the incoming GPS signal and implementing easily. So it is adopted by some available GPS antennas [13] to mitigate interference.

3.3. Reduced-rank STAP Technique

Because of the large dimensionality of the space-time covariance vector and weight vector, STAP techniques will lead to a larger computational burden and slower convergence. Therefore, the study on reduced-dimension techniques becomes a hot topic in recent years [8, 17]. Reduced-dimension techniques are mainly to constraint weight vector to lie in a lower dimensional subspace by the transformation matrix $\mathbf{T}_{NM\times D}$ $(D < NM)$, namely let:

$$\mathbf{w} = \mathbf{T}\mathbf{w}_r \tag{15}$$

so (13) can be rewritten as:

$$\begin{aligned} &\min_{\mathbf{w}} \mathbf{w}_r^H \mathbf{T}^H \mathbf{R} \mathbf{T} \mathbf{w}_r \\ &s.\ t.\ \mathbf{w}_r^H \mathbf{T}^H \boldsymbol{\delta}_{MN} = 1 \end{aligned} \tag{16}$$

the solution to (16) is

$$\mathbf{w}_r = \frac{(\mathbf{T}^H\mathbf{R}\mathbf{T})^{-1}\mathbf{T}^H\boldsymbol{\delta}_{MN}}{\boldsymbol{\delta}_{MN}^H\mathbf{T}(\mathbf{T}^H\mathbf{R}\mathbf{T})^{-1}\mathbf{T}^H\boldsymbol{\delta}_{MN}} \tag{17}$$

where the dimension of $\mathbf{T}^H\mathbf{R}\mathbf{T}$ is $D \times D$, which is less than the one of $\mathbf{R}$. This leads to lower computational complexity and rapid convergence. We can obtain the matrix $\mathbf{T}$ by techniques such as the cross-spectral metric (CS) or principal-components (PC). But both techniques are quite computational burden since it is necessary to generate the eigenvectors of covariance matrix before finding $\mathbf{T}$.

Fortunately, Dr. Zoltowski proposed a reduced-dimension STAP technique based on multistage nested wiener filter (MSNWF) [17]. This technique accomplishes the reduced-dimension processing via the innovative multistage wiener filter and does not require computing the inversion of $\mathbf{R}$. Thus it can reduce computational complexity and improve the speed of convergence compared with CS and PC.

4. GPS Signal Multipath Mitigation Techniques

The error due to GPS signal multipath is an important factor of positioning error. At the present time, the common techniques for multipath mitigation mainly include DLL and MEDLL. Both techniques change a standard receiver structure, so their compatibility is very poor. In [18] Dr. Stoica proposed a multipath mitigation algorithm based on the vertical array, which suppress multipath interference before correlation without changing the receiver structure.

The above method assumes that the directions of arrival of the GPS multipath signals are approximately known relative to the direction of arrival of the GPS signal, which is possible in GPS vertical array. When the GPS multipath signals exist, the data model received by GPS vertical array is given by:

$$\mathbf{x}(t) = \mathbf{a}s(t) + \sum_{q=1}^{Q} \mathbf{a}_q \beta_q s(t) + \sum_{j=1}^{K} \mathbf{b}_j i_j(t) + \mathbf{v}(t) \tag{18}$$

(18) can be rewritten as:

$$\mathbf{x}(t) = (\mathbf{a} + \mathbf{V}\beta)s(t) + \sum_{j=1}^{K} \mathbf{b}_j i_j(t) + \mathbf{v}(t) \tag{19}$$

where the matrix $\mathbf{V}$'s range space is a good approximation of the one spanned by the GPS multipath signals, β is an unknown vector whose elements equal to the ratios between the GPS multipath signals and the GPS signal. According to literature [16], $\mathbf{a}$ and β can be determined by solving the following problem:

$$\begin{aligned} &\min_{\mathbf{a},\boldsymbol{\beta}} (\mathbf{a} + \mathbf{V}\boldsymbol{\beta})^H \mathbf{R}^{-1} (\mathbf{a} + \mathbf{V}\boldsymbol{\beta}) \\ &s.t.\ \mathbf{a} = \mathbf{B}\mathbf{u} + \bar{\mathbf{a}}, \quad \|\mathrm{u}\|^2 \le \varepsilon \end{aligned} \tag{20}$$

let $\mathbf{G}$ be a basis of the null space of $\mathbf{V}^H$, so (20) can be rewritten as:

$$\begin{aligned} &\min_{\mathbf{a},\beta} \mathbf{a}^H \mathbf{G} \left(\mathbf{G}^H \mathbf{R} \mathbf{G}\right)^{-1} \mathbf{R}^{-1} \\ &s.t.\ \mathbf{a} = \mathbf{B}\mathbf{u} + \bar{\mathbf{a}}, \quad \|\mathrm{u}\|^2 \le \varepsilon \end{aligned} \tag{21}$$

let $\hat{\mathbf{a}}$ denotes the solution to (21), we can find the weight vector:

$$\mathbf{w} = \mathbf{G}(\mathbf{G}^H \mathbf{R} \mathbf{G})^{-1} \hat{\mathbf{a}} \tag{22}$$

In essence, the method proposed by Dr. Stoica removes the GPS multipath signals by "pre-filtering" the received data via the matrix $\mathbf{G}^H$. Although this algorithm is appropriate to GPS vertical array, its main idea can be further extended to the general array to suppress GPS multipath signals.

5. Conclusion

Several methods used to mitigation GPS interference have been discussed in this paper. The conventional spatial techniques can adaptively null the interference, but they are incapability of canceling many narrowband interferences as well as wideband and mutipath ones due to the limited degrees of freedom. STAP can overcome the above problem. However, the computational complexity is a troublesome question. Fortunately, the reduced-dimension technique proposed by Dr. Zoltowski has made a breakthrough in GPS interference mitigation. Different from the above reduced-dimension method, the next work we will do is to develop an adaptive recursive least square (RLS) space-time algorithm combined with cyclostationary properties of GPS signal, which will improve speed of convergence by RLS algorithm. Also the algorithm belongs to blind adaptive algorithm by only using the nature of GPS signal, so it is very robust.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China under grant 60325102 and 60428101.

REFERENCES

1. Capozza, PT, BJ Holland, TM Hopkinson and etc., "A single-chip narrow-band frequency-domain excisor for a global positioning system (GPS) receiver," *IEEE Journal of Solid-state Circuits*, Vol. 35, No. 3, 2000.
2. Milstein, L. B., "Interference rejection techniques in spread spectrum communications," *Proc. IEEE*, Vol. 76, No. 6, June 1988.

3. Crochiere, R. E. and L. R. Rabiner, "Multirate digital signal processing," Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1983.
4. Jones, W. W., and K. R. Jones, "Narrowband interference suppression using filter-bank analysis/synthesis techniques," *IEEE MILCOM Conference*, San Diego, California, Paper 38. 1. 1, 1992.
5. Brown, A., D. Reynolds, et al., "Jammer and interference location system-design and initial test result," *Proceeding of the ION GPS'99[C]*, Nashville, TN, 1999.
6. Fante, R. L. and J. J. Vaccaro, "Cancellation of jammers and jammer multipath in a GPS receiver," *IEEE AES System Magazine*, Vol. 13, 25–28, November 1998.
7. Fante, R. L. and J. J. Vaccaro, "Wideband cancellation of interference in a GPS receiver array," *IEEE Transaction on Aerospace and Electronic Systems*, Vol. 36, No. 2, 549–564, April 2000.
8. Myrick, W., J. Goldstein, and M. Zoltowski, "Low complexity anti-jam space-time processing for GPS," *Proceedings of the 2001 IEEE International Conference on Acoustics, Speech, and Signal Processing*, Vol. 4, 1332–1336, 2001.
9. Moelker, D., T. van Der Pol, and Y. Bar-Ness, "Adaptive antenna arrays for interference cancellation in GPS and GLONASS receivers," *Proceeding of the IEEE 1996 Position Location and Navigation Symposium*, 191–198, 1996.
10. Wang, Y., JR Cruz, "Adaptive antenna array for cellular CDMA communication system," *Proc. IEEE ICASSP*, 1725–1728, July 1995.
11. Sun, W. and M. Amin, "GPS interference suppression using self-coherent feature of GPS signals," *IEEE International Symposium on Signal Processing and Information Technology*, Darmstadt, Germany, Dec. 2003.
12. Sun, W. and M. Amin, "A self-coherence based anti-jam GPS receiver," *IEEE Transactions on Signal Processing*, 62–65, 2003.
13. Hatke, G., "Adaptive array processing for wideband nulling in GPS system," *Proceedings of the 32nd Asilomar Conference on Signals, Systems and Computers*, Vol. 2, 1332–1336, 1998.
14. Myrick, W., M. D. Zoltowski, and J. S. Goldstein, "Smoothing of space-time power minimization based preprocessor for GPS," *Second Joint USA/Australia Workshop in Defense Application of Signal Processing (DASP99)*, Chicago, IL, Starved Rock State Park, 125–130, 22–26, August 1999.
15. Brenna, L., J. Mallett, and L. Reed, "Adaptive arrays in airborne MTI radar," *IEEE Transactions on Antennas and Propagation*, 607–615, April 1976.
16. Li, J., P. Stoica, and Z. Wang, "On robust capon beamforming and diagonal loading," *IEEE Transactions on Signal Processing*, Vol. 51, 1702–1715, July 2003.
17. Myrick, W., M. D. Zoltowski and J. S. Goldstein, "Anti-jam space-time preprocessor for GPS based on multistage nested wiener filter," *Milcom'99*.
18. Jiang, Y. and P. Stoica, "Capon beamforming in the presence of steering vector errors and coherent signals," http://www.sal.ufl.edu/yjiang/papers/R2CBASAP.pdf.