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GNSS Space-Time Interference Mitigation: Advantages and Challenges

Abstract The use of space-time processing methods in GNSS interference mitigation is of great interest due to their effectiveness in both narrowband and wideband interference suppression. Techniques to reduce the distortion and bias on the cross correlation function due to space-time filtering are also very important especially for high precision GNSS applications. In this paper, different types of space-time interference mitigation methods are studied in terms of computational complexity, effectiveness and distortions. Distortions on cross correlation functions due to space-time filtering and related errors in position solution are analyzed using a real GPS L1 data set.

Keyword space-time processing, GNSS, interference mitigation

1. Introduction

The performance of GNSS services can be compromised by interference signals. Many civilian and military applications relying primarily on GNSS are vulnerable to various types of in-band interference. Even a low-power interference signal can easily jeopardize GNSS receiver’s performance within a radius of several kilometres. For instance in a jamming incident near Newark’s Airport a few years ago, a truck driver who employed a low cost jammer to jam his vehicle GPS tracking system accidentally interrupted the airport’s GNSS-based equipment. Although laws prohibit the possession or usage of such devices, low-cost jammers called personal privacy devices (PPD) can be still procured. Unintentional interference or jammers can dramatically degrade the performance of receivers or completely deny GNSS position and time services.

Space-processing interference mitigation techniques utilizing an array of antennas can effectively detect and suppress interfering signals regardless of their temporal and spectral characteristics. As long as the cost and power consumption of additional hardware and antennas can be justified, antenna array-based processing is one of the most powerful countermeasure methods against various types of interference and jamming signals. Array-based methods also surpass the time and frequency processing interference mitigation methods due to their capability to deal with wideband interference.

Antenna array processing in GNSS applications have been mostly centered on interference suppression [1-5]. Reference [5] drew attention on usage of minimum power distortionless response (MPDR) beamformer to suppress interfering signals in GPS applications and prevent signal attenuation.

The number of antennas determines the number of interfering signals that can be suppressed. Despite the effectiveness of antenna array-based methods, the number of antennas and size of the array can be considered the main limitation for employing these methods. To cope with this limitation, the techniques that jointly employ time/frequency and spatial domain processing are in the forefront.

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These techniques are generally referred to as space-time adaptive processing (STAP) or space-frequency adaptive processing (SFAP) which have been studied in the literature for several years [6-10]. In the standard implementation of these techniques, each antenna is followed by a temporal filter or a tapped delay line (TDL) with the typical delay time of a sampling duration. These techniques combine spatial and temporal filters to suppress more narrowband radio frequency interfering signals by increasing the degrees of freedom (DOF) of the array without physically increasing the array size and the number of antennas.

Besides the superior advantages of space-time processing, specific considerations should be taken into account in GNSS applications to prevent induced biases in pseudorange measurements and distortions on cross correlation functions (CCF), otherwise the expected accuracy of time and position solutions is compromised [11-12]. Even if the interfering signals are spatially-temporally nullified, the non-linearity behavior of the phase response of a space-time filter may result in biased measurements and distorted CCFs during receiver acquisition and tracking stages. To reduce this distortion, an effective approach is to incorporate satellite signals’ steering vectors in the structure of the space-time filter as a constrained optimization problem [13-16]. The steering vector (or array manifold vector) contains all the spatial information of the incoming signal. Space-time methods using steering vectors are in fact the extended versions of the MPDR beamformer for spatial–temporal domain processing. There are other effective approaches to reduce the induced bias error [11,17]; however, the mentioned methods do not guarantee a distortionless response for GNSS signals since in these methods there is no explicit assumption on the linearity of the space-time filter’s phase response. [4] suggested a space-time filter design to achieve a real frequency response (formed from a filter multiplied by its conjugate in the frequency domain); however this was not analyzed and a practical realization of filter coefficients was not reported. In [7], a projection matrix to the interference-free subspace was determined to coerce the filter coefficients for each TDL in order to become conjugate symmetric and therefore to become linear phase. Moreover, by applying steering vectors in the structure of the projection matrix, the space-time filter compensates for spatial phase differences of the received signal among antenna elements and consequently the resulting space-time filter from the
combination of the linear phase TDLs remains also linear phase and the CCFs remains undistorted.

In this paper, different types of distortion due to space-time processing are introduced. Array calibration, steering vector estimation and attitude determination which are required for distortionless space-time processing are addressed. Well-known GNSS space-time interference mitigation approaches namely blind, semi-distortionless and distortionless are introduced and analyzed. The errors and distortions due to the space-time processing on CCFs and in the position domain are evaluated for different interference mitigation approaches. A real data (GPS L1 C/A) to which simulated interfering signals are added in software is used for the analysis.

2. System Model

Without loss of generality and for the sake of simplicity, only one GNSS signal is considered in the formulations below. Complex baseband representation of the received signal vector at an arbitrary N-element array configuration for the satellite signal and K interference signals can be written as

\[ \mathbf{r} = \mathbf{a} \, \mathbf{s} + \mathbf{B} \, \mathbf{v} + \mathbf{\eta} \]

where \( \mathbf{B} \) is a matrix whose columns indicate interfering signal steering vectors and \( \mathbf{\eta} \) is a complex additive white Gaussian noise vector. \( \mathbf{s} \) represents the GNSS signal waveform and \( \mathbf{v} \) is a vector specifying K interfering signal waveforms. In Equation (1), \( \mathbf{a} \) is an \( N \times 1 \) vector representing the steering vector of the satellite signal defined as

\[ \mathbf{a} = \left[ \begin{array}{c} e^{j \frac{2\pi}{\lambda} \mathbf{p}^H \mathbf{z}_1} \\ e^{j \frac{2\pi}{\lambda} \mathbf{p}^H \mathbf{z}_2} \\ \vdots \\ e^{j \frac{2\pi}{\lambda} \mathbf{p}^H \mathbf{z}_N} \end{array} \right] \]

in which \( \lambda \) is the wavelength of the signal and \( \mathbf{z}_n, n=1, 2, \ldots, N \) is a 3x1 unit vector pointing to the \( n \)-th antenna element and \( \mathbf{p}^H \) is a 3x1 unit vector pointing to the satellite direction in the body frame coordinate system and \( T \) stands for the transpose operation.

2.1 Space-Time Processing (STP) filter structure

Fig. 1 shows a standard implementation of the STP filter in which each antenna is followed by a temporal filter or a TDL with the typical delay time of a sampling duration denoted by \( T_c \). An antenna array with \( N \) elements and TDLs with \( M-1 \) taps leaves \( MN \) unknown filter coefficients which should be determined.

For each time snapshot, \( MN \) received samples form a \( MN \times 1 \) vector can be written as

\[ \mathbf{r} = \left[ r_{1,1} \, r_{1,2} \, \ldots \, r_{1,N} \, r_{2,1} \, r_{2,2} \, \ldots \, r_{2,N} \, \ldots \, r_{M,1} \, r_{M,2} \, \ldots \, r_{M,N} \right]^T \]

where \( r_{m,n} \) is the \( n \)-th delayed sample at the \( n \)-th antenna element. Filter coefficients corresponding to these samples are defined as

\[ \mathbf{w} = \left[ w_{1,1} \, w_{1,2} \, \ldots \, w_{1,N} \, w_{2,1} \, w_{2,2} \, \ldots \, w_{2,N} \, \ldots \, w_{M,1} \, w_{M,2} \, \ldots \, w_{M,N} \right]^T \]

in which \( H \) denotes the conjugate transpose. Hence, the space-time filter output is obtained as

\[ y = \mathbf{w}^H \mathbf{r} \]

Generally, space-time processing is based on second order statistics and is applied to the spatial-temporal covariance or correlation matrix defined as

\[ \mathbf{R}_y = \mathbf{E} \left[ \mathbf{rr}^H \right] \]

where \( \mathbf{E} \{ \} \) represents the statistical expectation. In Section 3, this correlation matrix is employed in different types of STP.

2.2 STP induced distortions

There are three types of filter distortion due to the space-time processing, namely CCF misshaping, measurement bias and signal attenuation [18]. The ideal shape of the CCF of a typical GNSS signal is a symmetric triangle. STP may cause asymmetric widening of the CCF which degrades the performance of tracking and acquisition stages. Any shift in the delay domain due to the STP process should be the same for all PRNs. Otherwise, measurement biases introduce significant errors in position solutions. Unintentional nulls due to blind STP may also cause attenuation of the signals and noise dominance such that the signal cannot be acquired or inaccurate measurements are obtained. By designing a linear phase STP filter and/or employing the steering vector of satellites in the filter structure, these errors can be significantly reduced.
3. Space-time processing methods

In this section three types of STP interference mitigation methods namely ‘blind’, ‘semi-distortionless’ and ‘distortionless’ are studied. Blind STP methods do not employ the satellite steering vector in the structure of the space-time filter. Although they can be easily implemented, some unintentional nulls may attenuate and distort the signals and degrade the receiver performance. In semi-distortionless STP methods, employing steering vectors avoids unintentional nulls and leads to less distortion. However, these methods do not guarantee a distortionless response for GNSS signals since there is no explicit assumption on the linearity of the space-time filter phase response in these methods. Third type of STP is designed to be linear phase and theoretically distortionless. These three types are studied in the following subsections.

3.1 Blind STP

Blind STP is based on the fact that the power of interference signals is much higher than that of the GNSS signals, these being below the noise floor. The blind beamformer was first studied for GPS interference mitigation in [5] which was called power minimization beamformer. Another form of implementation is based on Eigen vector decomposition. Both have been addressed previously [e.g. 19-21]. The main advantage of these methods is their low implementation complexity since their goal is only nullifying the high power interference signals and any spatial information on satellite signals is not utilized. Blind methods are applied to the baseband samples and can be implemented independently of the receiver structure. This however causes some unintentional nulls or attenuation for desired signals. Two forms of blind STP beamformers are now introduced.

Power Minimization:

The optimization problem for this case is expressed as

\[
\begin{align*}
\min_{w} & \quad w^H \mathbf{R}_i w \\
\text{s.t.} & \quad \mathbf{e}_i^H w = 1
\end{align*}
\] (7)

where

\[
\mathbf{e}_i = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}^T
\] (8)

The constraint avoids the trivial solution \( \mathbf{w} = \mathbf{0} \). This constrains the filter coefficient for an arbitrary antenna and an arbitrary tab to be equal to one (here first tab at first antenna is chosen)

Eigen Beamformer

Here the goal is to calculate a projection matrix to the interference-free subspace from the space-time correlation matrix. In order to be destructive at correlator outputs, the power of interference should be significantly higher than that of the GNSS and noise signals. This makes the interference subspace be easily distinguished and estimated. A projection matrix into the interference-free subspace can be obtained by performing an Eigen value decomposition (EVD) or Singular value decomposition (SVD) of \( \mathbf{R}_i \) as

\[
\mathbf{R}_i = \begin{bmatrix} \mathbf{U}_{be}^H & \mathbf{U}_{null}^H \end{bmatrix} \begin{bmatrix} \Lambda_{be} & 0 \\ 0 & \Lambda_{null} \end{bmatrix} \begin{bmatrix} \mathbf{U}_{be} & \mathbf{U}_{null} \end{bmatrix}, \quad (9)
\]

where \( \mathbf{U}_{be} \) and \( \mathbf{U}_{null} \) are eigenvector matrices of interference and the noise-plus-GNSS signal subspaces, respectively, and \( \Lambda_{be} \) and \( \Lambda_{null} \) are corresponding eigenvalue matrices. In Equation (9), \( K \) indicates the rank of the interference subspace (without loss of generality, it is assumed that interfering signals are uncorrelated). A projection matrix into the reduced-rank interference-free subspace can be calculated as \( \mathbf{U}_{null}^H \), which is formed from \( MN-K \) eigenvectors corresponding to the \( MN-K \) smallest eigenvalues. In fact the filter gain vector \( \mathbf{w} \), which minimizes the filter output power in Equation (5) belongs to this interference-free subspace. This approach is also referred to as a blind STP since satellite signal steering vectors are not considered in the filter design. Applying this projection matrix to the received signal vector suppresses the interference; however, some satellite signals may become distorted or attenuated in this process. Eigen beamformers result in sharper nulls for interfering signals [22]; however in contrast to the power minimization approach, interference dimension \( K \) should also be determined to achieve the best performance.

3.2 Semi-distortionless STP

Semi-distortionless STP methods can be generally considered as extended versions of the MPDR beamformer for space-time processing. These methods incorporate satellite signal steering vectors in the structure of the space-time filter as a constrained optimization problem [13-16]. The same as blind STP, the array degree of freedom compared to space-only processing is increased. The optimization problem for the semi-distortionless STP MPDR beamformer can be expressed as

\[
\begin{align*}
\min_{w} & \quad w^H \mathbf{R}_i w \\
\text{s.t.} & \quad \mathbf{e}_i^H w = 1
\end{align*}
\] (10)

where \( \mathbf{R}_i \) and \( \mathbf{w} \) are defined in Equations (4) and (6) and the vector \( \mathbf{e} \) is defined as

\[
\mathbf{e}_i = \begin{bmatrix} \mathbf{a}_i^T & \mathbf{0}_i^T & \cdots & \mathbf{0}_i^T \end{bmatrix}^T
\] (11)

In this filter, in order to force the beamformer to have a fixed
group delay, only one group of tap gains with a certain delay (without loss of generality here the first group is chosen) is required to pass the satellite signal undistorted. There are also other effective semi-distortionless STP methods to reduce the induced bias error. They differ in the form of constraint, optimization and/or filter implementation, for example [11], [16], [17], [23], [24]. However, in these methods, the filter response is not necessarily linear phase and as a consequence the cross correlation functions may become asymmetric and distorted.

3.3 Distortionless STP

The output of the blind space-time filter is basically a direction-frequency dependent response. Even if the filter completely nullifies interfering signals, the non-linearity behavior of its phase response may result in distorted correlation functions, degraded acquisition and tracking performance and bias and distortion of the GNSS measurements. Although semi-distortionless methods can avoid attenuations by employing the spatial information of the satellite signals, they do not guarantee a distortionless response. To remove the non-linearity of a STAP filter phase response, cascading another time-filter, whose frequency response is the conjugate of frequency response of the STAP filter, was suggested [4]. By assigning proper filter coefficients for the cascaded filter, the resulting impulse response is symmetric and the same shift is added to all satellite pseudoranges. The structure of this filter is shown in Fig 2.

The correlation function for the signal after space-time filtering, despreading and Doppler removal can be written as [4]

$$R(\tau, \alpha) = \int_{-\infty}^{\infty} H(f) p(f) e^{-j2\pi f \tau} df,$$

where $H(f)$ is the frequency response of the space-time filter defined as

$$H(f) = h^H(f) a$$

$h(f)$ is the frequency response vector of the TDLs and $a$ is the satellite signals steering vector.

Another form of distortionless STP was proposed in Reference [7]. Filter coefficients are designed such that simultaneously interference is suppressed and the filter is linear phase. For the same degree of freedom and the same length of the filter, the proposed method surpasses the two-cascaded filter approach in term of SNR characterization since more spatial temporal samples are combined to generate the filter output. However, implementation is more complex. In this approach, the distortionless filter is designed based on subspace decomposition with knowledge of the steering vectors.

In both methods, a different set of filter coefficients should be assigned to the signal of each satellite. The array gain pattern is shaped to nullify the interference signals and put the main lobe in the direction of each desired GNSS satellite while maintaining filter phase response linearity. It should be noted that the cross correlation is broadened in either case.

4. Distortionless and semi-distortionless
Space-time processing requirements

In contrast to the blind STP, distortionless and semi-distortionless methods require a calibrated array and the knowledge of the array attitude in order to calculate satellite steering vector, which is addressed in this section.

4.1 Array Calibration

Using a group of antennas operating in the near field of each other may change the phase and amplitude of the received signal at each antenna element. Unequal cable lengths, mutual coupling among array elements, antenna phase and gain mismatches and phase centre variations can affect the resulting phase and amplitude of the received signal at each antenna. Therefore, array calibration becomes a vital stage in many GNSS applications employing spatial processing.

Many array-based methods in GNSS applications require a calibrated antenna array in order to steer nulls towards undesired signals while maintaining the main lobe of the beam pattern in the direction of the desired signal.

In order to calibrate an antenna array, a common technique is to use an anechoic chamber to scan all incident signals from different angles of arrival (AOA) [25]. In GNSS applications, the GNSS signals themselves can be employed as Radio Frequency (RF) signal sources with known AOs without requiring high cost anechoic chambers for the calibration process. This approach for calibration of antenna arrays is referred to as on-site calibration (e. g. [26, 27]). The latter approach and the method proposed in [26] are considered for this research. In this method, a two-stage optimization for precise calibration is used in the form of two EVD problems. In the first stage, constant uncertainties are estimated whereas in the second stage the dependency of each antenna element gain
and phase patterns to the received signal AOA is considered for refined calibration.

### 4.2 Steering Vector Estimation

In addition to the calibrated antenna array, the array platform attitude is also needed in order to calculate array steering vectors. In doing so, two following approaches are introduced.

#### Direct approach

In this approach, the steering vector is estimated directly from its definition in Equation (2). Array configuration vectors \((z_i)\) can be easily estimated in the body frame coordinate system. However, a GNSS receiver provides steering vectors in the East-North-Up (ENU) coordinate system as a function of azimuth and elevation angles, written as

\[
P_{\text{ENU}} = \begin{bmatrix} \sin(\phi) \cos(\theta) & \cos(\phi) \cos(\theta) & \sin(\theta) \end{bmatrix}^T .
\] (14)

In order to have this vector in the body coordinate system, it is transferred as

\[
P_{\text{B}} = R_{\text{B}^{\text{ENU}}}^\theta \begin{bmatrix} P_{\text{B}} \end{bmatrix},
\] (15)

In Equation (14), \(R_{\text{B}^{\text{ENU}}}^\theta\) is a transformation matrix from the body frame coordinate to the ENU coordinate system defined as

\[
R_{\text{B}^{\text{ENU}}}^\theta = \begin{bmatrix} \cos(\phi) \cos(\theta) & -\sin(\phi) \cos(\theta) & \sin(\phi) \sin(\theta) \\ \sin(\phi) \cos(\theta) & \cos(\phi) \cos(\theta) & -\sin(\phi) \sin(\theta) \\ -\cos(\phi) & \sin(\phi) & 0 \end{bmatrix}.
\] (16)

in which \(r, p\) and \(y\) refer to the roll, pitch and yaw (heading) angles, respectively. To obtain these angles, one approach is to employ a GNSS/INS receiver consisting of an inertial measurement unit (IMU) [26,27]. A GNSS/INS unit can provide attitude information and hence the transformation matrix can be obtained. In this approach, the steering vectors of all satellites regardless of the signal quality and availability can be obtained as long as the azimuth and elevation angles of those satellites, either from the receiver or from external sources and attitude parameters, are available.

#### Indirect approach

The steering vector can be also obtained by measuring phase differences of the received signals at the antenna array elements. In contrast to the direct approach, this approach does not need any external information but requires signal acquisition and tracking. However, in challenging environments such as harsh multipath environments or in the presence of interference and jamming some signals may not be available.

Steering vector estimation in a jammed environment for attitude determination was studied in [28]. In this paper it is assumed that the spatial covariance matrix is positive definite and invertible which may not be the case in all interference scenarios where the covariance matrix becomes ill-conditioned.

Another approach to deal with steering vector estimation in the presence of interference was studied in [7]. It was shown that the estimation of the signal steering vector from the interference-removed signals is an under-determined problem and it was shown that extracting the spatial information from the projected signals might not be possible but might be partially done for some signals. In fact, some of the array DOF information is used to remove interfering signals. Therefore, in this paper attitude parameters were first estimated considering satellites that could be acquired. By using attitude parameters, satellite azimuth and elevation angles from ephemeris data, similar to the direct approach, the steering vector of all satellite signals can be then accurately calculated.

### 5. Experimental Results

Due to frequency regulations, outdoor radio frequency (RF) power transmission in the GNSS frequency bands is prohibited. Therefore, special considerations have to be taken into account while testing the performance of anti-interference techniques. Some previous work has suggested combining interference signals to GNSS signals through wires. However, for an array antenna, this type of test requires many combiners, cables and connectors. Moreover, control on GNSS and interfering signals’ AOA would be difficult. Herein for testing and evaluating the performance of the previously discussed methods, interference has been generated in software and added to the digitized GNSS samples.

The test set up and data collection environment are shown in Fig 3. GPS L1 C/A signals were collected using a six-element antenna array. The data collection was performed in a parking lot with an open view of satellites. A circular trajectory was driven for the calibration process to receive signals from various directions (Fig 3a). The antenna array was mounted on the top of a vehicle (Fig 3b) and the six antenna elements were connected to the phase coherent six-channel Fraunhofer/TeleOrbit RF front-end (Fig 3c). The received signals were then down converted, digitized and stored for post processing. The sampling frequency was \(Fs=20\) MHz. Moreover, a NovAtel SPAN™ LCI system, which includes a GNSS/INS receiver and a tactical grade IMU was used as a reference. IMU measurements were sent to the receiver where a coupled GNSS/INS position, velocity and attitude solution was generated at a rate of 200 Hz [29]. Raw GPS data was also collected under Line of Sight (LOS) condition using a base station receiver (fixed on the rooftop of a building located on the campus of the University of Calgary) to enable differential positioning. The data collected by SPAN and the base station file were then fed to the NovAtel Inertial Explorer® post-processing software to produce accurate reference orientation angles (the estimated standard deviations for position in each direction are better than 5 cm and the estimated standard deviations for attitude parameters are better than 0.1 degree).
Data collection scenario and setup. Satellite visibility during data collection is shown in Fig 4. Pseudorandom noise (PRN) codes, elevation and azimuth angles of the satellites are shown in Table 1. At the time of the data collection, there were 10 observable GPS signals. The precise antenna array calibration method proposed in [26] was employed. An open source MATLAB-based single antenna software receiver [30] was further developed for multi-antenna receiver processing where the acquisition, tracking, and position solution parts of the original software were modified. In the software receiver, only the satellite signals received at the array reference antenna were acquired, tracked and used for positioning. The locally generated signals obtained from processing the signal of this antenna branch were used to measure the relative phase and amplitude values of the signals at other antennas. Therefore, the estimated discriminator outputs at different antennas differ only in phase and amplitude [7].

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Table 1 PRNs used during test and corresponding azimuth and elevation angles

<table>
<thead>
<tr>
<th>PRN</th>
<th>Azimuth (degree)</th>
<th>Elevation (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>310</td>
<td>29</td>
</tr>
<tr>
<td>04</td>
<td>284</td>
<td>52</td>
</tr>
<tr>
<td>11</td>
<td>289</td>
<td>37</td>
</tr>
<tr>
<td>14</td>
<td>140</td>
<td>83</td>
</tr>
<tr>
<td>18</td>
<td>105</td>
<td>24</td>
</tr>
<tr>
<td>19</td>
<td>239</td>
<td>18</td>
</tr>
<tr>
<td>22</td>
<td>104</td>
<td>59</td>
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<tr>
<td>24</td>
<td>41</td>
<td>19</td>
</tr>
<tr>
<td>31</td>
<td>170</td>
<td>17</td>
</tr>
<tr>
<td>32</td>
<td>284</td>
<td>41</td>
</tr>
</tbody>
</table>

Three interference scenarios are considered and the parameters are shown in Table 2. Eigen beamformer as a blind STP, STP MPDR as a semi-distortionless and distortionless STP introduced in Reference [4] are selected for interference mitigation.

Table 2 Interference scenarios.

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>One CW Interference, $I/N_0=90$ dB-Hz. Azimuth (degree) [270] Elevation (degree) [5.6] frequency offset (Hz)[500] TDL=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2</td>
<td>One CW &amp; One Wideband, $I/N_0=90$ dB-Hz for each Azimuth (degree) [270, 180] Elevation (degree) [5.6, 9.7] frequency offset (Hz) [500 1500] TDL=6</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Six CW Interference, $I/N_0=88$ dB-Hz for each Azimuth (degree) [270, 180, 330, 120, 15, 60] Elevation (degree) [5.6, 9.7, 3.1, 4.7, 6.2, 7.5] frequency offset (Hz) [500 1500 2500 3500 4500 5500] TDL=6</td>
</tr>
</tbody>
</table>
In the first test, Scenario 2 is considered and array gain patterns for the blind, semi-distortionless and distortionless STP beamformers are displayed for three GPS signals in Fig. 5. For the blind STP array, the gain pattern is calculated once for all signals while for the other two methods, the array gain is different for each PRN. Deep nulls are placed in the direction of the interference signals in all cases; however, since the steering vectors of the satellite signals have not been employed in the blind STP processor, some of the desired signals are also unintentionally attenuated. For the case of semi-distortionless and distortionless STP methods, the filter coefficients are determined to not only nullify the interference but also steer the main lobe of the array gain pattern into the direction of the desired signal. The array gain patterns do not show considerable difference between semi-distortionless and distortionless cases. Based on Equation (13) the gain pattern (in dB) for a space–time filter is calculated as

$$\text{ArrayGain} = 10 \log \left( |h^T(\hat{f})a|^2 \right)$$

In fact, this gain pattern determines the space-time filter gain as a function of frequency, azimuth and elevation angles.

In order to obtain an actual sense of the improvement achieved, Fig 6 compares $C/N_0$ values of these beamformers for the same 5 s interval of received satellite signals. Average $C/N_0$ values are also shown in the figure. Since some PRNs are located close to the main lobe of the gain pattern in the blind filter, their $C/N_0$ values are comparable with the semi-distortionless and distortionless STP while for the rest of PRNs improvement is significant. In addition, PRNs 19, 24 and 31 were significantly attenuated and denied after blind filtering but they could be acquired and tracked by employing the distortionless and semi-distortionless STP filtering.

The results for this scenario and the other two interference scenarios are listed in Table 3. Compared to the blind STP, the number of acquired PRNs is larger for semi-distortionless and distortionless STP beamformers. It can be seen that $C/N_0$ values for distortionless STP are lower compared to the semi-distortionless STP. This is due to the fact that distortionless STP methods do not just steer the main lobe of the array beam pattern toward the direction of the received signal; a constraint is also applied to maintain the linearity of the filter phase response. In Scenario 3, although the average $C/N_0$ value for the blind STP is larger compared to the distortionless STP, the number of acquired satellites is lower.

### Table 3: $C/N_0$ comparison between different STP methods

<table>
<thead>
<tr>
<th>STP Method</th>
<th>Scenario1</th>
<th>Scenario2</th>
<th>Scenario3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blind</td>
<td>47.5/8</td>
<td>48.5/7</td>
<td>40.3/5</td>
</tr>
<tr>
<td>Semi-distortionless</td>
<td>51.3/10</td>
<td>49.9/10</td>
<td>41.7/10</td>
</tr>
<tr>
<td>Distortionless</td>
<td>50.5/10</td>
<td>48.8/10</td>
<td>36.4/7</td>
</tr>
</tbody>
</table>

In Fig. 5 Normalized antenna array gain patterns at the interference frequency for PRNs 1, 18 and 19 employing (a) blind STP (b) semi-distortion STP (c) distortionless STP
In order to quantify the errors due to CCF misshaping and attenuation for different STP methods, the metric introduced in Reference [18] is employed. In a typical GNSS receiver, the Prompt (P) value of the correlator is decided based on the placement of the Early (E) and Late (L) correlator branches. Any distortion on the correlation function results in a positive or negative offset compared to a clean undistorted peak (Fig. 7). The metric employed measures the offset in distance (in units of m) that is due only to CCF misshaping; the bias values that may be different across satellites are not characterized. The effects of those biases are evaluated later in the position domain errors.

CCF misshaping for three signals (PRNs 4, 18 and 22) using the metric introduced in Reference [18] for the interference scenario I and for three STP approaches were performed. The metric is applied to CCFs extracted at the tracking stage. Root mean squares (RMS) values of a 10 s observation period in static mode are reported in Table 4. The number of acquired PRNs is also shown in this table. Results show that RMS values for blind STP are on the average higher and the acquired satellites are lower. Results also show slightly less distortion in the semi-distortionless STP compared to the distortionless STP. This highlights the fact that this metric does not characterize all three types of STP error. In fact, as mentioned before, measurement biases cannot be evaluated by using only this metric or the $C/N_0$ value. Measurement biases due to the STP, if they are different, can be a significant error source in the position domain. By comparing the results for three STP methods in the position domain, their performance considering all types of error can be better evaluated.

Table 4: CCF distortion evaluation using the distortion metric for PRNs 4, 18 and 22

<table>
<thead>
<tr>
<th>STP method</th>
<th>RMS (m)</th>
<th>Number of tracked PRNs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blind</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>Semi-distortionless</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Distortionless</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

In order to quantify the errors due to CCF misshaping and attenuation for different STP methods, the metric introduced in Reference [18] is employed. In a typical GNSS receiver, the Prompt (P) value of the correlator is decided based on the

![Fig. 6](image)

**Fig. 6** (a) Measured $C/N_0$ for after employing (a) blind STP filtering (b) semi-distortionless STP (c) distortionless STP

![Fig. 7](image)

**Fig. 7** CCF distortion metric [18]
Table 5 lists errors in the ENU coordinate system for or a simple (Scenario 1) and a harsh interference scenario (Scenario 3) employing distortionless, semi-distortionless and blind STP using GPS L1 C/A signals. For Scenario 1, the amount of position errors is almost the same among different STP methods. Distortionless and semi-distortionless STP methods slightly outperform the blind STP in terms of number of tracked satellite signals and DOP enhancement. In the harsh interference scenario, the blind STP has the worst results in terms of number of tracked satellites and position accuracy, as expected. Although distortionless STP has the smaller number of tracked satellites compared to the semi-distortionless STP, it yields significantly better results in the position domain.

In Table 4, the results for the MPDR beamformer which is based on space only processing are also shown. For the MPDR beamformer, the array DOF, indicating the number of unwanted signals that can be nullified, is equal to the number of antenna elements minus one. Since this beamformer is only based on spatial processing, CCFs and position solutions do not experience any distortion due to time filtering. Results in Table 5 verify the fact that the MPDR beamformer can suppress the one-jammer scenario without generating significant ENU errors but is not able to mitigate six uncorrelated narrowband interference signals. Results show that the distortionless STP filter not only provides extra DOF for narrowband interference mitigation (compared to MPDR) but also keeps the CCFs less distorted and biased. Therefore its positioning performance is considerably better than that of the other STP methods.

### 6. Conclusions

Three different types of STP methods were studied. These methods were compared in terms of implementation complexity and performance. Advantages and disadvantages of each technique were studied and evaluated through several analyses. Blind STP has the advantage of low implementation complexity. Since blind STP does not require any information of GNSS signals, it can be implemented independently of the receiver. The semi-distortionless and distortionless methods require multi-antenna receivers; however they outperform blind STP in terms of position accuracy. Using these techniques, a greater number of satellite signals can be acquired and less distortion occurs. The distortionless STP resulted in less distortion and bias on pseudorange measurements and consequently provides more accurate position and timing solutions. Experimental results also showed that the positioning performance of the distortionless STP is considerably higher than that of the blind and semi-distortionless STP in harsh interference environments. In general, the improvement obtained with these methods depends on the interference scenario, antenna array configuration, number of taps in TDLs, calibration accuracy, power and direction of GNSS and interference signals, DOP.

Future work will focus on the design of an approach to adaptively nullify interference signals to allow the proposed receiver to operate in dynamic modes.

<table>
<thead>
<tr>
<th>10 s of data in the static mode</th>
<th>Scenario 1</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blind STP</strong> ENU error (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>-0.9</td>
<td>686</td>
</tr>
<tr>
<td>N</td>
<td>3.5</td>
<td>5627</td>
</tr>
<tr>
<td>U</td>
<td>2.5</td>
<td>3085</td>
</tr>
<tr>
<td><strong>MPDR</strong> ENU error (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>-1.5</td>
<td>NA</td>
</tr>
<tr>
<td>N</td>
<td>1.7</td>
<td>NA</td>
</tr>
<tr>
<td>U</td>
<td>1.3</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Semi-distortionless STP ENU error (m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>-1.3</td>
<td>-35.4</td>
</tr>
<tr>
<td>N</td>
<td>-3.6</td>
<td>-56.7</td>
</tr>
<tr>
<td>U</td>
<td>3.2</td>
<td>-203</td>
</tr>
<tr>
<td><strong>Proposed Distortionless STP</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENU error (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>-1.3</td>
<td>-8.7</td>
</tr>
<tr>
<td>N</td>
<td>1.5</td>
<td>-17.9</td>
</tr>
<tr>
<td>U</td>
<td>3</td>
<td>-23.8</td>
</tr>
</tbody>
</table>

| **Number of tracked PRNs**      |            |            |
| **Blind STP**                   | 8          | 5          |
| **MPDR**                        | 10         | NA         |
| **Semi-distortionless STP**      | 10         | 10         |
| **Distortionless STP**          | 10         | 7          |
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References


Biography

Saeed Daneshmand holds a Ph.D. degree in Geomatics Engineering from the University of Calgary. Since May 2013 he has been a senior research associate/post-doctoral fellow in the PLAN Group. His research interests are in the area of software receivers and signal processing for GNSS.

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Gérard Lachapelle, Professor Emeritus, has been involved in a multitude of GNSS R&D projects since 1980, ranging from RTK positioning to indoor location and signal processing enhancements, first in industry and since 1988, at the University of Calgary.