Characterization of GNSS Measurement Distortions Due to Antenna Array Processing in the Presence of Interference Signals

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Abstract— GNSS signals are relatively weak once they are received on the earth surface and due to which they are very much vulnerable to intentional and unintentional interferences. Antenna array processing is a very efficient method for combating interference and jamming effects. Controlled Reception Pattern Antennas (CRPA) are capable of controlling the reception pattern adaptively such that interference can be mitigated by steering null in the direction of interference. In spite of having these advantages, these systems suffer from measurement distortions which in turn affect the navigation solution. Sources contributing to the measurement distortions include mutual coupling between antennas, radio frequency front-end delays, spatial filtering techniques and receiver processing methods. In this paper, the effects of mutual coupling between antennas and different array processing techniques on measurement bias are analyzed. The analysis is carried out through simulations and real data collected using Novatel 501 antennas.

Keywords— CRPA, MVDR, Beamforming, Null steering, Power minimization, Adaptive antenna processing

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS) use Direct Sequence Spread Spectrum (DSSS), which enables relatively low power signals transmitted by satellites to still be strong enough to achieve an accurate range resolution. In normal operation the signal power density at the receiver is well below the thermal noise level. Such a low power of the GNSS signals makes them susceptible to interference and multipath [1]. Interference has become major threat to GNSS operations especially in life critical applications. Interference can be broadly classified as intentional or unintentional. Intentional interferences include deliberate jamming of signals with other high power signals or GNSS like signals also known as GNSS spoofers. These spoofers mimic GNSS signals and distract the user navigation. Unintentional jammers could be due the other nearby radio transmitters such as television, radar or Ultra Wide Band (UWB) transmitters. The severity of interference on the operation of the navigation system depends on the type of interference like narrow band, wideband or pulsed interference.

An antenna array system consists of a number of closely spaced antennas and the received signals from each antenna element are then processed either spatially or temporally or as a combination of both. Here signals from different antennas are combined coherently so that the resulting receive pattern can mitigate the interference. Fixed Reception Pattern Antenna (FRPA) systems combine the signals to have a fixed receive pattern, whereas Controlled Reception Pattern Antenna (CRPA) systems can adaptively change the receive pattern based on the operating environment so that interference is mitigated successfully. There are different criteria by which one can either combine the data from different antenna elements at the pre-correlation or post correlation stage [2]. These criteria include minimizing the total output power or maximizing the signal-to-noise ratio (SNR) or minimizing the mean squared error at the output of a spatial filter. Due to their directional beam forming capabilities, signal-to-interference plus noise ratio (SINR) is improved after spatial filtering. CRPA systems are usually employed in safety critical applications like aircraft landing where anti-jamming and anti-spoofing methods are crucial for high reliability.

However, CRPA systems in the presence of Radio Frequency Interference (RFI) signals suffer from phase distortions which in turn affect the navigation solution [3-4] [5-8]. Previous research has focused on code phase and carrier phase measurement biases using the Minimum Variance Distortion-less Response (MVDR) beamforming method using patch antennas. In [3] a code phase bias of the order of one to two metres is observed in the presence of interference and mutual coupling through simulations. In [4] a carrier phase bias is observed through real data collection. It was observed that the bias is different for different satellites. In both of these analyses, Space Only Processing (SOP) is carried out on antenna signals. When Space-Time Adaptive Processing (STAP) is used, the measurements will be further distorted due to time processing [5] [7] [9]. These biases may adversely affect the carrier phase measurements, thereby not allowing resolution of ambiguities. These biases and distortions on GNSS signal measurements are not desirable for high-accuracy and high-precision applications. There are different sources for measurement distortions in CRPA applications including mutual coupling between antenna elements [10], different RF front-end delays for each receiver channel, array processing technique used or weighting algorithm, and receiver tracking strategies. When a FRPA is used, the antenna induced biases can be pre-calibrated as the beam pattern is fixed. However, considering an adaptive antenna array in the form of a CRPA, it is difficult to pre-calibrate the antenna array processing system as the system induced bias varies based on the incident signal environment.
The main objective of the paper is to analyze and characterize the bias introduced in CRPA systems using space only processing. GPS signals with Coarse/Acquisition (C/A) code are used for this analysis. The effect of mutual coupling is analyzed by performing carrier phase positioning with and without an antenna array configuration. The induced bias due to different array processing techniques such as power minimization and MVDR are evaluated through simulations. Finally, measurement biases are analyzed by collecting real data with Novatel 501 [11] antennas in a triangular array configuration.

The rest of the paper is organized as follows. First a brief description of the antenna induced bias in code phase and carrier phase is given. This is followed by the methodology used to analyze the measurement bias. Next multi-antenna GPS signal simulations and measurement distortions due to different weighting algorithms are described. The test set up for mutual coupling effect on measurement biases is described and an analysis of the results is presented. The final section provides a real data collection setup and analysis of observed code phase and carrier phase measurement biases.

II. BACKGROUND AND THEORY BEHIND

An antenna array is a system where antenna elements are deployed in space and the output of each of the antenna elements is combined to form a single resulting signal. The signals from each antenna element are combined such that the resulting received beam pattern is different from individual antenna element beam patterns. In an antenna array system, properly combined signals will have better performance in terms of SINR and interference rejection capability than individual antenna signals. Antenna array processing is also known as beam forming and null steering. Beam forming employing space only processing can be thought as spatial filtering as signals are combined spatially. Here, signals from each antenna element are multiplied with complex weight computed using an adaptive algorithm such that the amplitude and phase of the signals are modified and are then combined. When it is desirable to direct beams towards desired satellites, signals are weighted such that the resulting phase will be additive. On the other hand when it is of interest to steer a null towards an interference source, the antenna element signals are weighted such that they are out of phase and the resulting receive pattern has less gain in that direction. Based on the selection of weights, beam forming can be divided into two categories:

Conventional beamforming: weights are fixed to have a fixed receive pattern.

Adaptive beamforming: weights change based on the property of the received signals and the receive pattern will be adapted accordingly.

A typical CRPA system in GPS applications is shown in Figure 1. Let \( \mathbf{x} = [x_0(t), x_1(t), x_2(t), ... x_{N-1}(t)]^T \) be the vector of input signals received from elements of the antenna array. Here, \( N \) is the number of antenna elements. In an antenna array system one of the antenna elements acts as the reference antenna. Let \( x_0(t) \) be the reference antenna signal. The signal at reference antenna is a complex baseband signal received from \( K \) different satellites and \( L \) different interference sources as shown in (1):

\[
x_i(t) = \sum_{j=0}^{K-1} r_j(t) + \frac{1}{L-1} \sum_{j=0}^{L-1} v_j(t) + \eta(t)
\]

\[ (1) \]

where \( r_j(t) \) is the complex envelope of the \( j \)th satellite signal and \( v_j(t) \) is the complex envelope of \( j \)th interference signal. \( A_j \) is the amplitude of the \( j \)th satellite signal, \( \tau_i \) is the code delay introduced by the communication channel, \( f_i \) is the Doppler frequency and \( \phi_j \) is the carrier phase.

![Figure 1: Typical CRPA system](image)

The signals received from all the antenna elements can be represented as

\[
\mathbf{x}_{ideal} = [x_0(t) \ x_1(t) \ ... \ x_{N-1}(t)]^T
\]

\[ (2) \]

\[
\mathbf{x}_{ideal} = \sum_{i=0}^{K-1} s_i r_i(t) + \sum_{j=0}^{L-1} b_j v_j(t) + \eta
\]

\[ (3) \]

where \( s_i = [s_{i,0}, s_{i,1}, s_{i,2}, ... s_{i,N-1}]^T \) is the steering vector corresponding to the \( i \)th satellite which is a function of satellite direction and antenna array manifold. Similarly, \( b_j = [b_{j,0}, b_{j,1}, b_{j,2}, ... b_{j,N-1}]^T \) is the steering vector corresponding to the \( j \)th satellite. The independent noise for each antenna element is \( \eta = [\eta_0(t), \eta_1(t), ... \eta_{N-1}(t)]^T \).

Equation (4) is the ideal model for an antenna array system. However, in practice there are other factors which need to be incorporated into the model. In actual cases, some part of the incident signal energy is reradiated back from the antenna surface. Thus, when antennas are placed close to each other with a half wavelength distance between adjacent pairs, the reradiated energy will affect the signal reception of the rest of the antennas. This effect is known as mutual coupling and it has to be taken care of in practical applications. The effect of mutual coupling depends on the type of antennas. Survey grade antennas will have less mutual coupling effect as compared to patch antennas. Also the RF front-end delays might be different for different channels. Here it is assumed
that different channels of the RF front-end are ideal and only mutual coupling effect is incorporated into the model. The received signal can be written as

$$x = \sum_{i=0}^{K-1} C_s i_r(t) + \sum_{j=0}^{L-1} C b j_r(t) + \eta$$  \hspace{1cm} (5)

C is a Hermitian mutual coupling matrix and can be represented as

$$C = C_{0,0} \quad C_{0,1} \quad \cdots \quad C_{0,N-1}$$

$$\vdots \quad \vdots \quad \ddots \quad \vdots$$

$$C_{N-1,0} \quad C_{N-1,1} \quad \cdots \quad C_{N-1,N-1}$$

(6)

The output of the antenna array system is the weighted sum of signals from each antenna element and can be expressed as

$$y = w^H x.$$  \hspace{1cm} (7)

Here $$w = [w_0 \quad w_1 \quad \cdots \quad w_{N-1}]^T$$ is the weight vector used to combine antenna signals. This weight vector could be specific to a particular Pseudo-Random Noise (PRN) depending on the beamforming technique. In order to analyze the distortion in the measurements, the effect of antenna array processing on correlator output is considered from where the measurements are generated. The correlator output for a specific PRN can be written as

$$q_i(\Delta \tau_i, \Delta \varphi_i) = \frac{1}{T_{coh}} \int_0^{T_{coh}} w_i^H C_s i_r(t) c_i(t-\tau_i) \exp\{-j\Delta \varphi_i\} \text{d}t$$  \hspace{1cm} (8)

$$q_i(\Delta \tau_i, \Delta \varphi_i) = w_i^H C_s \frac{A}{2} R(\Delta \tau_i) \text{sinc}(2\pi f_d t \pm \Delta \varphi_i) + \eta_i$$  \hspace{1cm} (9)

where

$$q_i(\Delta \tau_i, \Delta \varphi_i) : \text{cross-correlation output from the receiver for } i^{th} \text{ satellite}$$

$$T_{coh} : \text{coherent integration period}$$

$$R(\Delta \tau_i) : \text{autocorrelation function with delay } \tau_i$$

$$\Delta f : \text{Doppler frequency}$$

$$\Delta \varphi_i : \text{carrier phase}$$

$$\eta_i : \text{independent identically distributed noise}$$

$$w_i : \text{weight vector corresponding to } i^{th} \text{ satellite}$$

As shown in (9), the correlator output is a function of complex weights and the mutual coupling matrix. These correlator outputs are used in code and carrier tracking loops and measurements are generated. So the measurements generated are also a function of complex weights and mutual coupling.

In this paper two weighting algorithms are analyzed:

A. Power minimization

Power minimization works based on the statistics of the received data to place a deep null in the direction of interference and try to maintain a uniform beam pattern in other directions. This method does not require a priori information of the angular directions of the desired signal and interference. For the present analysis, the Singular Value Decomposition (SVD) based projection method is used to perform null steering [12-13].

The cross covariance matrix R of the antenna array received signal is given by

$$R = E\{xx^H\}$$  \hspace{1cm} (10)

The covariance matrix is a positive definite matrix; therefore it has an Eigen decomposition given as

$$R = EAE^H$$  \hspace{1cm} (11)

Assuming that the interference power is much higher than the GPS signal power then interference is dominating in the overall cross covariance matrix. As the GPS signal is buried under the noise, signal and noise are treated as one subspace. The signal plus noise subspace will be orthogonal to the interference subspace. If V is the interference subspace, then the projection matrix P orthogonal to V is given by

$$P = I - V(V^H V)^{-1} V^H$$  \hspace{1cm} (12)

The interference free output is obtained by projecting the input signal onto this projection matrix.

B. MVDR

The MVDR technique minimizes the output power subject to a unity gain constraint in the direction of the desired signal. The optimal weight vector is obtained as

$$w_i = R^{-1}_{\eta,\eta} s_i^H (s^H_i R_{\eta,\eta}^{-1} s^H_i)^{-1}$$  \hspace{1cm} (13)

where $$R_{\eta,\eta}$$ is the spatial correlation matrix of the undesired signals and $$s_i$$ is the steering vector corresponding to the $$i^{th}$$ satellite.

III. METHODOLOGY

In the antenna array processing method, one of the antenna elements is considered as the reference antenna. In the test experiment, as interference is added either in software or using a hardware interference generator after receiving the signals from each antenna, the reference antenna signal can be used to evaluate the performance of the array. A differential technique is used to evaluate the code and carrier phase measurements. Double differencing between the reference antenna data and array combined data acts as a zero base line. This is basically because the steering vector will be constructed with respect to a reference antenna position and the effective antenna array position will be the same as the reference antenna. The resulting double difference ideally should have a zero mean if the antenna induced bias is zero. The intermediate frequency
(IF) data is processed using the GSNRx™ software receiver developed by the PLAN Group of The University of Calgary [14]. In this study antenna signals are combined before correlation. The data from different antennas are combined at the sample level using MATLAB™ based software. This combined data is then processed using the software receiver to generate code phase and carrier phase measurements.

The filtered pseudorange can be expressed as

\[ P_{\text{array}} = c d \tau = p + d \rho + c (d t - d T) + d_{\text{iono}} + d_{\text{tropo}} + \rho_{\text{bias}} + \varepsilon_p \]  \hspace{1cm} (14)

Here \( \rho \) is the true range, \( d \rho \) is the orbital error, \( dt \) and \( dT \) are satellite and receiver clock errors, \( d_{\text{iono}} \) is the ionosphere delay, \( d_{\text{tropo}} \) is the troposphere delay, \( \varepsilon_p \) is the receiver noise and \( \rho_{\text{bias}} \) is the bias introduced by the antenna array processing.

The pseudorange for reference antenna without interference can be expressed as

\[ P_{\text{ref}} = c d \tau = p + d \rho + c (d t - d T) + d_{\text{iono}} + d_{\text{tropo}} + \varepsilon_p \]  \hspace{1cm} (15)

The single difference between the reference antenna pseudorange and array combined pseudorange is

\[ \Delta P = P_{\text{ref}} - P_{\text{array}} = c \Delta d T + \rho_{\text{bias}} + \varepsilon_{\Delta \rho} \]  \hspace{1cm} (16)

The measurements differencing between the reference antenna and the antenna array combined signal acts like a zero baseline. Due to this, the atmospheric errors are cancelled completely during single differencing between receivers. The clock bias is common across satellites and can be removed by performing a double difference as

\[ \Delta \nu P = \rho_{\text{bias}} + \varepsilon_{\Delta \nu \rho} \]  \hspace{1cm} (17)

After double differencing, the code noise and pseudorange bias will remain. The code noise standard deviation depends on receiver tracking strategies like chip spacing and the discriminators used and it should be ideally zero mean. Hence, one can estimate the pseudorange bias introduced by the antenna array processing. Here it is assumed that the multipath effect is small as compared to the bias due to the antenna array processing. Similar to pseudorange measurement bias estimation, the carrier phase measurement bias can also be estimated by performing double differencing between the reference antenna and array combined carrier phase measurements. Double differenced carrier phase measurements are obtained as

\[ \Delta \nu \phi = \Delta \nu N_{dd} + \phi_{\text{bias}} + \varepsilon_{\Delta \nu \phi} \]  \hspace{1cm} (18)

The double differenced ambiguity is removed by estimating the constant integer in the double differenced measurements.

**IV. SIMULATION RESULTS**

For simulation studies, multi-antenna signals are generated using software written in MATLAB™. The procedure for generating multi-antenna signal is as follows:

- A hardware GPS signal generator (GSS7700) is used to generate error free GPS signals, and IF data samples are collected using a National Instrument (NI) data acquisition system. The hardware simulator is capable of generating GPS signals without any errors like multipath and atmosphere. This allows the generation of more reliable multi-antenna signals where there is no adverse effect of multipath.
- Process the collected IF data using the MATLAB™ software to generate the replica signals for each PRN. Replica signals have carrier, code and data bits embedded in them.
- Generate the steering vector using fixed elevation and azimuth angles of the satellites and the relative position of each of the antennas with respect to the reference antenna.
- The replica signals of each PRN are then multiplied with the steering vector to generate multi-antenna signals.
- In antenna array processing, it is assumed that noise across antenna elements is independent. Thus independent noise is added to each of the antenna element signals.

Carrier-to-noise ratios for all satellites are maintained at 42 dB-Hz. It is assumed that the antennas are isotropic and there is no mutual coupling between them. Also RF front-end delays are assumed to be same for all antenna elements. The sky plot of all the satellites simulated is shown in Figure 2. The zero baseline analysis is performed on GSNRx™ generated pseudorange and carrier phase measurements beforehand to ensure that the software receiver does not introduce any bias in the measurements. Narrow correlator with a 0.1 chip spacing and a coherent early-late discriminator is used in the software receiver for analysis. A bias analysis is carried out in two scenarios. In one scenario, the direction of the interference is kept constant and the power of the interference is varied. In the other scenario, the power of the interference is kept constant and the direction of interference is varied.

![Figure 2: Sky plot of simulated satellites](image)
The effectiveness of the power minimization algorithm depends on the power of interference, i.e. the higher the power, the better the interference rejection. The effect of different interference powers on the measurement distortion is studied through simulations. Table 1 shows the interference type and different powers of interference used. For the entire simulation period, both the satellite signals and interference directions are kept constant.

### TABLE 1: SIMULATION DATA PARAMETERS

<table>
<thead>
<tr>
<th>Interference type</th>
<th>Continuous wave @ IF frequency (420 kHz) from Elevation = 5° Azimuth = 5°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference power (JNR in dB)</td>
<td>P1 45</td>
</tr>
</tbody>
</table>

Even though the interference direction is not changed during the simulation period, in order to have adaptive nature, weights are computed every 20 ms. Since the maximum coherent integration time is 20 ms in the software receiver which processes the simulated data, the weight computation time is chosen as 20 ms. The magnitude and phase of the complex weights computed depend on the interference power and they become noisier when the latter decreases. This will have an impact on the cross-correlation function of the satellite signals and in turn on the measurements. When the interference power is very low the weights computed are erroneous and will have more impact on measurements.

The time series plot of the double differenced pseudorange measurements is shown in Figure 3. Due to power minimization combining, the double differenced pseudorange measurement noise is increased and also the measurement is biased. The induced biases for different powers of interference are shown in Table 2. Pseudorange biases of the order of 6 cm to 45 cm are observed based on the interference power. Similarly carrier phase biases up to 1.7 cm are observed when the interference power is low.

Since isotropic antennas are considered for simulation, the measurement distortion can be characterized only because of the combining technique. Even though interference and satellite signal directions are the same, the biases induced into measurements are different for different powers. It is observed that when the interference power is high enough, the PRNs which are in the direction of the interference incur more distortion. When the power is low as in the case of P3, most of the PRNs measurements are distorted, as can be observed in Table 2.

Similar to code phase measurement errors, carrier phase measurement errors for different powers of interference are shown in Figure 4. For higher interference power, the biases observed are less, but when the interference power is lower as in the case of P3, the carrier phase measurement distortion can be seen. This can be attributed to the noisier complex weights computed during low interference power.

### TABLE 2: MEASUREMENT BIASES DUE TO POWER MINIMIZATION FOR DIFFERENT INTERFERENCE POWERS

<table>
<thead>
<tr>
<th>PRN</th>
<th>Pseudorange bias (cm)</th>
<th>Carrier phase bias (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>-22</td>
<td>-1.2</td>
</tr>
<tr>
<td>P2</td>
<td>-15</td>
<td>-0.5</td>
</tr>
<tr>
<td>P3</td>
<td>37</td>
<td>-1.0</td>
</tr>
<tr>
<td>PRN22</td>
<td>11</td>
<td>0.6</td>
</tr>
<tr>
<td>PRN27</td>
<td>-6</td>
<td>0.2</td>
</tr>
<tr>
<td>PRN28</td>
<td>-7</td>
<td>0.2</td>
</tr>
<tr>
<td>PRN26</td>
<td>-11</td>
<td>0.3</td>
</tr>
<tr>
<td>PRN5</td>
<td>24</td>
<td>0.3</td>
</tr>
<tr>
<td>PRN12</td>
<td>-14</td>
<td>0.3</td>
</tr>
<tr>
<td>PRN15</td>
<td>-15</td>
<td>0.3</td>
</tr>
<tr>
<td>PRN17</td>
<td>29</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

2) Minimum variance distortionless response

With the same simulated data, MVDR beam forming is performed and analyzed for possible measurement distortions. As data is simulated using known signal directions, calibration of antenna elements is not required. The steering vector can be
constructed based on the known signal directions. The time series plot of the double differenced pseudorange error is shown in Figure 5. It is observed that the MVDR algorithm does not introduce any bias into the measurements. Since one can constrain the receive pattern to have unity gain in the direction of satellite signals, MVDR provides a distortion-less response even in the case of interference. This can be attributed to bias free measurements.

**B. Effect of different interference directions on measurement biases**

Effect of different interference directions on measurement biases is analyzed through simulations. The interference type and different directions of interference are shown in Table 3.

<table>
<thead>
<tr>
<th>Interference type</th>
<th>Continuous wave @ IF frequency (420 kHz) at JNR of 45 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference direction</td>
<td>D1 (5°, 5°)</td>
</tr>
</tbody>
</table>

1) **Power minimization algorithm**

Biases observed in code phase and carrier phase measurements when interference directions are changed are shown in Table 4. It can be observed from the table that PRNs whose directions are near the interference suffer more distortions as compared to others. For example, when the interference direction is D1, PRN 28 (elevation 16°, azimuth 71°) suffers more distortion. Similarly for D2, PRN 27 (elevation 16°, azimuth 127°) whose direction is close to interference suffers more distortion. During D3, PRN 05 (elevation 20°, azimuth 260°) has more distortions in the measurements.

<table>
<thead>
<tr>
<th>PRN</th>
<th>Code phase bias (cm)</th>
<th>Carrier phase bias (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1</td>
<td>D2</td>
</tr>
<tr>
<td>22</td>
<td>-22</td>
<td>-9</td>
</tr>
<tr>
<td>27</td>
<td>-15</td>
<td>-45</td>
</tr>
<tr>
<td>28</td>
<td>37</td>
<td>30</td>
</tr>
<tr>
<td>26</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>-6</td>
<td>6</td>
</tr>
<tr>
<td>05</td>
<td>-9</td>
<td>-12</td>
</tr>
<tr>
<td>17</td>
<td>16</td>
<td>26</td>
</tr>
</tbody>
</table>

2) **Minimum variance distortionless response**

Similar to different interference powers, different interference directions do not introduce any bias in the measurements when the MVDR algorithm is employed.

V. FIELD TEST RESULTS

Real data is now analyzed for possible measurement distortion due to mutual coupling between antennas and various beamforming techniques. In the first section the effect of mutual coupling is analyzed through experimental results.

A. **Effect of mutual coupling on measurement distortion**

As stated earlier mutual coupling exists when antennas are placed close to each other and this affects GPS measurements. Commercial grade antennas, namely Novatel 501 units, are
used to understand the effect of mutual coupling. The antennas are arranged in a triangular array configuration.

The antennas are placed on the rooftop of the CCIT building on the campus of The University of Calgary where relatively low multipath occurs. The antennas are placed on a wooden platform to have less effect due to reflected signals and several metres above the base to reject reflected signals. The data is collected in three modes. In one mode, only the reference is mounted on the platform and data is collected for a few hours. In the second mode, all three antennas are mounted on the platform and only the reference antenna is powered while data is collected from it. In the third mode, all three antennas on the platform are powered and data is collected using the reference antenna. In the second and third mode, all the three antenna placements were the same. In all the modes, data is also collected from a base station located 10 m away from the antenna array (referred to as the rover in the sequel).

The data collected using Novatel ProPak-V3 receivers is processed using an open source program package for GNSS positioning i.e., RTKLIB™ (http://www.rtklib.com/). This software provides carrier phase-based positions using base station and rover data. The software is capable of solving the integer ambiguities and provides fixed solutions. A quality flag indicating the ambiguity resolution status is available to show the position accuracy. The position solution quality is shown by. Fixed solutions have a quality flag of 1. Before performing the tests, in order to ensure that the measurement noise of Novatel receivers under test are within specifications, zero baseline tests were conducted between the receivers.

<table>
<thead>
<tr>
<th>TABLE 5: RMS POSITION ERRORS OF REFERENCE ANTENNA IN SINGLE AND ARRAY MODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Mode 1: Reference antenna in single antenna configuration without other two antennas</td>
</tr>
<tr>
<td>Mode 2: Reference antenna in array antenna configuration without powering other two antennas</td>
</tr>
<tr>
<td>Mode 3: Reference antenna in array antenna configuration after powering other two antennas</td>
</tr>
</tbody>
</table>

The reference antenna of the array is kept in a known surveyed location so that position solution can be compared with the known position for possible distortion. The position error spread for all the three configurations is shown in Figure 7. It is observed that in all the three test configurations, RTKLIB™ is able to resolve the ambiguities and provide fixed solutions, as expected.

The RMS position errors for all the three configurations are shown in Table 5. One can observe that there are no significant RMS position error differences between the three configurations. In mode 1, as a single antenna is used, one can expect low RMS position errors due to the very close base station. On the other hand, in mode 2 and 3, antennas are configured in an array fashion and a mutual coupling effect exists between them. Even in these two modes, RMS position errors are lower and are in a good agreement with that of the single antenna mode. With successful integer ambiguity resolution and less RMS position errors, one can conclude that Novatel 501 antennas suffer less mutual coupling effects.

B. Code and carrier phase distortions

The data collection setup is shown in Figure 8. The antennas configured in a triangular array are used for data collection. The antennas are kept on the rooftop and signals are sent indoors through cables. In order to avoid additional biases due to differences in cable lengths, zero baseline tests across different cable lengths were performed to compensate for the differences in length. Continuous wave interference is generated using a function generator and combined with each antenna signal using a combiner. The combined signal is sampled and stored using a NI data acquisition system capable of collecting 3 channel data simultaneously. Beam forming and null steering is performed on the collected data at sample level and processed using GSNRx™ to generate measurements. Antenna A1 (as shown in Figure 8) is considered the reference antenna and interference free signal is collected from this antenna using another NI data acquisition system. For both systems same clock is used to have sample level synchronization. The reference antenna signal is also processed using software receiver to generate measurements. The interference settings and other parameters used during data collection are tabulated in Table 6.
### TABLE 6: FIELD DATA COLLECTION SETTINGS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jamming to noise ratio</td>
<td>25 dB</td>
</tr>
<tr>
<td>Intermediate frequency</td>
<td>420 kHz</td>
</tr>
<tr>
<td>Interference type</td>
<td>Narrow band, continuous wave at 620 kHz</td>
</tr>
<tr>
<td>Data duration</td>
<td>300 seconds with initial 50 seconds no interference</td>
</tr>
<tr>
<td>RF front end bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>10 MHz</td>
</tr>
</tbody>
</table>

### TABLE 7: CODE PHASE AND CARRIER PHASE MEASUREMENT BIASES FOR DIFFERENT PRNs USING FIELD DATA WITH THE POWER MINIMIZATION ALGORITHM

<table>
<thead>
<tr>
<th>PRN</th>
<th>(azimuth, elevation) in degrees</th>
<th>Code phase bias (m)</th>
<th>Carrier phase bias (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>(287°,68°)</td>
<td>-0.98</td>
<td>-3.04</td>
</tr>
<tr>
<td>8</td>
<td>(273°,38°)</td>
<td>-0.33</td>
<td>-0.57</td>
</tr>
<tr>
<td>9</td>
<td>(276°,27°)</td>
<td>0.11</td>
<td>0.38</td>
</tr>
<tr>
<td>10</td>
<td>(253°,31°)</td>
<td>-1.28</td>
<td>-0.95</td>
</tr>
<tr>
<td>13</td>
<td>(157°,63°)</td>
<td>1.89</td>
<td>-3.23</td>
</tr>
<tr>
<td>23</td>
<td>(147°,28°)</td>
<td>0.44</td>
<td>0.76</td>
</tr>
<tr>
<td>27</td>
<td>(82°,34°)</td>
<td>1.45</td>
<td>4.37</td>
</tr>
<tr>
<td>19</td>
<td>(276°,27°)</td>
<td>-0.22</td>
<td>1.14</td>
</tr>
</tbody>
</table>

1) **Power minimization algorithm**

Weights are computed every 20 ms and used to combine the antenna signals at sample level. As interference is added through the signal generator, its direction is fixed.

### Figure 8: Test setup for field data collection using three antennas

![Test setup for field data collection using three antennas](image)

### Figure 9: Double differenced pseudorange errors for all visible PRNs using the power minimization algorithm

![Double differenced pseudorange errors for all visible PRNs using the power minimization algorithm](image)

### Figure 10: Double differenced carrier phase errors for all visible PRNs using power minimization algorithm

![Double differenced carrier phase errors for all visible PRNs using power minimization algorithm](image)

Double differenced pseudorange and carrier phase measurements for all the visible PRNs are shown in Figure 9 and 10. The plot shows measurement distortions before and after interference addition. The biases induced in code phase and carrier phase measurements during interference are tabulated in Table 7. Significant biases up to 1.89 m in pseudorange measurements and up to 3.23 cm in carrier phase measurements are observed in the presence of interference. As the power minimization algorithm blindly puts null in the direction of interference without taking care of satellite signal directions, measurements are distorted. The measurement bias induced is different for different PRNs and also depends on the interference environment. This makes it difficult to have a calibration table for bias correction.
2) **MVDR algorithm**

For the same data collected using three antennas, MVDR beamforming is performed and double differenced pseudorange and carrier phase measurements are analyzed. With the MVDR algorithm, one needs a calibrated antenna system so that the steering vector can be constructed. One antenna signal is tracked and the corresponding delay and frequency are used to decode the other antenna signals [15]. The phase differences between antenna elements for a particular satellite are used to construct the steering vector for that satellite. The phase difference between antenna elements includes the phase due to actual satellite signal direction as well as the calibration phase. Interference free signals of antenna elements are used to construct the steering vector as interference may affect the phase and the constructed steering vector will be erroneous. Also it is assumed that the multipath effect on received signals is minimal. With the MVDR algorithm, as direction of the satellite signal is taken into consideration, one can expect no bias in the measurements.

Double differenced pseudorange measurements are shown in Figure 11 and, as expected, are distortions free. Similarly, double differenced carrier phase measurements shown in Figure 12 are also distortion free. The code phase and carrier phase biases observed for different PRNs are listed in Table 8.

![Double differenced pseudorange measurements](image)

**Figure 11:** Double differenced pseudorange errors for all visible PRNs using the MVDR algorithm

**TABLE 8: CODE PHASE AND CARRIER PHASE MEASUREMENT BIASES FOR DIFFERENT PRNs USING FIELD DATA WITH THE MVDR ALGORITHM**

<table>
<thead>
<tr>
<th>PRN</th>
<th>(azimuth, elevation) in degrees</th>
<th>Code phase bias (m)</th>
<th>Carrier phase bias (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>(287.68°)</td>
<td>0.07</td>
<td>-0.1</td>
</tr>
<tr>
<td>8</td>
<td>(273.38°)</td>
<td>0.13</td>
<td>-0.1</td>
</tr>
<tr>
<td>9</td>
<td>(276.27°)</td>
<td>-0.10</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>(253.31°)</td>
<td>0.08</td>
<td>-0.1</td>
</tr>
<tr>
<td>13</td>
<td>(157.63°)</td>
<td>0.07</td>
<td>-0.1</td>
</tr>
<tr>
<td>23</td>
<td>(147.28°)</td>
<td>-0.07</td>
<td>0.1</td>
</tr>
<tr>
<td>27</td>
<td>(82.34°)</td>
<td>0.29</td>
<td>0.1</td>
</tr>
<tr>
<td>19</td>
<td>(276.27°)</td>
<td>0.33</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**VI. CONCLUSION**

Antenna array processing in the form of a CRPA induces measurement distortions in the presence of electronic interference. Distortions in code and carrier phase measurements were investigated herein with simulated and real data. There are number of possible reasons for antenna array induced biases such as mutual coupling between the antenna elements, RF front-end delays and spatial filtering techniques. GPS signals were simulated for a multi-antenna configuration and the induced biases in code and carrier phase measurements due to power minimization and the MVDR algorithm were analyzed. It was observed that the power minimization algorithm induces measurement biases as the algorithm does not have any constraints on the desired signal directions. A bias of up to 0.5 m as observed in the code phase measurements and up to 1.5 cm in the carrier phase measurements when the interference power was lower. However, the MVDR algorithm, which uses the desired signal direction to change the receive pattern, did not induce any bias in the measurements. Effects of mutual coupling and array processing techniques on measurements were analyzed through field tests. Successful ambiguity resolution and carrier phase RMS position errors were analyzed in single antenna and antenna array configurations. There is a close agreement between the positions errors with a single antenna configuration and an array configuration, indicating that the Novatel 501 antennas have relatively low mutual coupling effects on measurements. The real data collection results also revealed that the MVDR algorithm does not introduce any bias in the measurements. But the power minimization algorithm distorts measurements with a code phase bias up to 1.5 m and a carrier phase bias up to 4 cm. Further investigations and tests
are being carried out under different environments and using different numbers of antenna elements.

REFERENCES


