Interference Cancellation Using Power Minimization and Self-coherence Properties of GPS Signals

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BIOGRAPHY

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ABSTRACT

This paper presents the performance analysis of two digital beam forming techniques used in conjunction with a software GPS receiver to mitigate interference to GPS signals in interference environment. The first method is the constrained minimum power (MOP) method. The second method is the so-called self-coherence restoral (SCORE) method. Both experimental and simulation data are used in the study.

The study was performed using experiment data collected in an anechoic chamber to obtain GPS and interference signals. A two by two GPS antenna array and a four channel radio frequency front end were used to collect simulated GPS data generated using hardware-based simulator in controlled interference environment. Three types of interference signals are deployed in the experiments: FM chirp, binary phase shift key, and broadband. The interference power levels used were +20, +30, and +40 dB above GPS signal power. A software GPS receiver was used to perform acquisition of GPS signals to evaluate the performance of the beam forming algorithms. The preliminary result showed that the MOP method can effectively mitigate all three types of interference at all power levels if a single interference source is present. Experiments using multiple broadband interference sources were also analyzed and our results shown that the effectiveness of the MOP method diminishes as the interference signal power increases and ceases to function at the +40 dB level. The SCORE method does not exhibit consistent performance for the experimental data. This is consistent with our simulation results which show that for the SCORE algorithm to generate satisfactory results, sufficient number of antenna elements is necessary even if there is no interference source present. The number of antenna element is determined by the number of satellites available, as well as the number of interference sources. The experimental and simulation results are discussed in this paper.

1. INTRODUCTION

A number of methods and approached have been proposed and reported to mitigate interference for GPS receivers in interference environment. Most of these reports, however, are based on simulation results (Amin et al, 2003; Amin et al, to appear; Blazquez et al, 1999; Fante and Vacarro, 1998, 2000; Hatke, 1998; Moelker et al, 1996; Zhang et al, 2001; Zoltowski and Gecan, 1995). Recently, efforts have been made to investigate the experimental performance of the various beaming forming techniques (Liou et al., 2001; McDonald et al, 2004). In this study, two beam forming techniques, the constrained minimum power (MOP) method and self-coherence restoral (SCORE) method, were implemented to evaluate their claimed performance using experimental data collected in controlled interference environment. Simulation studies were also performed to validate the algorithms. A software GPS receiver is used to perform GPS signal acquisition of the beam former output.

The MOP method utilizes the fact that GPS signals are far beneath the thermal noise level. Minimization of total GPS receiver input power while maintaining gains along the directions of GPS satellites will suppress the interference contribution. The SCORE method is based on the known repetitive nature of the GPS signal CA code. GPS signal samples separated by integer multiples of the CA code length while within the same navigation data bit are spectrally self-coherent because of the code repetition property. Both methods have claimed pros and cons in the literature. The MOP method may work effectively on a variety of jamming sources. But it requires prior knowledge of the satellite orientations. The SCORE method does not need any satellite position information. It is, however, ineffective against interference sources that have spectral self-coherent properties. Moreover, our study showed that for the SCORE method, the number of antenna element is determined not only by the number of interference sources, but also by the number of satellites available.

Section 2 of the report will describe the experimental setup that generated the data for the study. Section 3 summaries the MOP and SCORE methods implemented in the study. The simulation results and experimental data analysis will be presented in Section 3 and 4 respectively. Section 5 concludes the summer project and discusses future works.

2. EXPERIMENTAL SETUPS

GPS signals in controlled jamming environment were collected in an anechoic chamber. Figure 1 shows the experimental setup. A two by two conventional GPS L1/L2 patch antenna array was placed in a geodesic dome as shown. The antenna elements are marked with number 1 through 4 respectively. The distance *d* from an antenna element to the center of the dome is *7* cm. Phase calibration of the antenna elements has been performed and the results were used in the beam forming algorithm (Liou et al, 2002). The distance between the elements, the size of the antenna, and the size of the geodesic dome are not drawn to proportion.

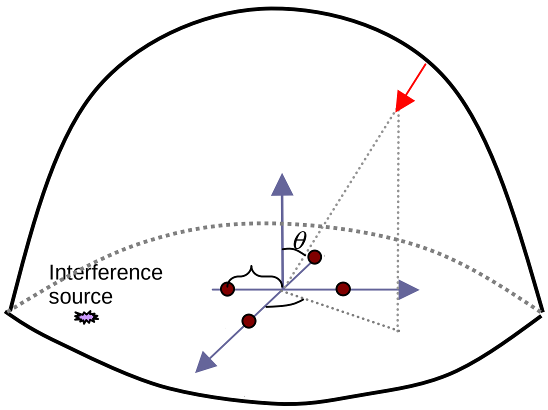


Fig. 1. Antenna elements layout and experimental setup.

Eight GPS antennas transmitting signals from a hardware-based GPS simulator were mounted on the dome to mimic a GPS constellation. Three extra antennas were placed nearby to transmit interference signals. The interference signals have three modulation schemes: a bi-phase shift key (BPSK) source with 10k and 1M modulation rates, a frequency-modulated (FM) chirp source with 1k and 10k modulation rates, and a 35 MHz-bandwidth broadband random noise. The power levels were +20, +30 and +40 dB above the GPS signals in the L1 band. We will refer to these power levels as interference to signal ratio (ISR) in the remainder of this paper. A sky plot of the GPS transmitters and the interference sources placements are shown in Figure 2. The interference sources are represented by *J1*, *J2*, and *J3*, while the numbers 4, 5, 6, 10, 13, 24, 26, and 30 represent the GPS transmitters, with the numbers representing GPS satellite ID. The azimuth angle ϕ is measured counter-clockwise from East (*x* axis) and spans 0 to 360 degrees. The rings in the plot represent inclination angles θ ranging from 0 (upward in the *z* axis direction) to 90 degrees (horizon).

A four-channel RF/IF front end is used to collect and digitize the outputs from each antenna element. Figure 3 shows the block diagram of a single channel of the RF/IF front end. The digitized outputs from each channel are stored for beam forming and software receiver processing.

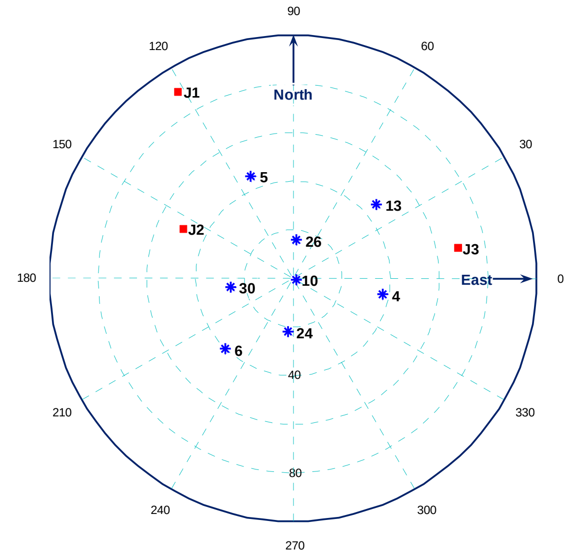


Fig. 2. Sky view of satellites and interference sources in the experimental setup

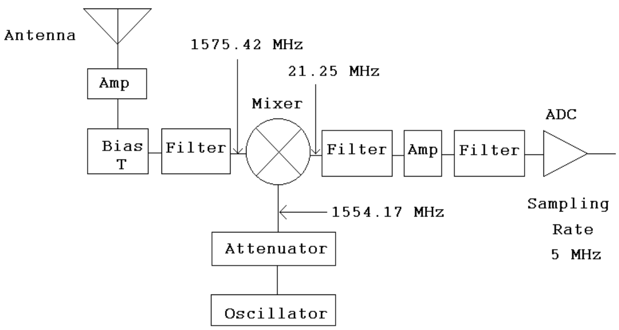


Fig. 3. Block diagram of a single channel GPS receiver RF/IF front end

3. BEAM FORMING ALGORITHMS

A simple spatial adaptive processor as shown in Figure 4 is used in this study. Inputs from the antenna elements (x_k, $k=1,\ldots K$) are applied with weight (w_k, $k=1,\ldots K$) and combined to generate an output y.

$$y=\sum_{k=1}^{K} w_k x_k = w^H x, \qquad (1)$$

where,

$$w=\begin{bmatrix} w_1 & w_2 & \cdots & w_K \end{bmatrix}^T, x=\begin{bmatrix} x_1 & x_2 & \cdots & x_K \end{bmatrix}^T.$$

Beam forming algorithms are designed to generate a set of optimized weight w, so that y is a much improved version of the input signal x in that the interference signals are suppressed, while the GPS signals are enhanced.

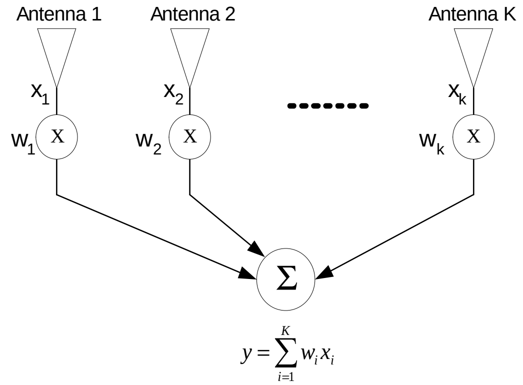


Fig. 4. Schematics of a K-element antenna array spatial adaptive processor

3.1. MULTI-ANTENNA ELEMENTS GPS RECEIVER INPUTS

The signal impinging on an antenna element is the collection of inputs from all GPS signals in direct view of the antenna, their multipath and interferences, and noise:

$$x_k=\sum_{p=1}^{P} g_p a_{kp}(\theta_p,\phi_p)+\sum_{q=1}^{Q} v_q b_{kq}(\theta_q,\phi_q)+n_k \qquad (2)$$

where,

P: Number of GPS signals received by the antenna.

Q: Number of interference (including multipath) signals received by the antenna.

θ_p, ϕ_p: The p^{th} GPS satellite inclination and azimuth angle.

a_{kp}, b_{kq}: The k^{th} antenna spatial phase delay factor for a signal arrival from a specified direction.

v_q: The q^{th} interference signal at the reference location.

θ_q, ϕ_q: The q^{th} interference source inclination and azimuth angle.

$n_k(t)$: Noise component for the k^{th} antenna.

$g_p(t)$: The p^{th} GPS satellite signal received at a reference location.

$$g_p = A_p e^{j(2\pi f_p t+\varphi_p)} \sum_{n=-\infty}^{\infty} h_p(n) u_p(t-nT_c) \qquad (3)$$

In Equation (3), $f_p = f_{L1}+f_{Dp}$ is the GPS signal carrier frequency, f_{L1} is GPS satellite L1 band center frequency, f_{Dp}, A_p, φ_p, h_p, and $u_p(t\text{-}nT_c)$ are the satellite signal Doppler frequency, amplitude, carrier phase, navigation data, and CA code with chip duration T_c.

Equation (2) can be written in a more compact form:

$$x = as + bv + n \qquad (4)$$

where,

$$s=\begin{bmatrix} g_1 & g_2 & \cdots & g_P \end{bmatrix}^T, v=\begin{bmatrix} v_1 & v_2 & \cdots & v_Q \end{bmatrix}^T,$$

$$n=\begin{bmatrix} n_1 & n_2 & \cdots & n_K \end{bmatrix}^T,$$

$$a=\begin{bmatrix} \vec{a}_1 & \vec{a}_2 & \cdots & \vec{a}_P \end{bmatrix}, b=\begin{bmatrix} \vec{b}_1 & \vec{b}_2 & \cdots & \vec{b}_Q \end{bmatrix}.$$

$\vec{a}_p$ ($p=1, \ldots, P$) and $\vec{b}_q$ ($q=1, \ldots, Q$) are the spatial signatures (also called steering vector or directional vector) of GPS signal source p and interference source q respectively. Assuming all signals are from far field sources and that the time it takes for a signal to travel between array elements is much smaller than the inverse of the receiver bandwidth, the spatial signature for a GPS satellite is:

$$\vec{a}_p = \begin{bmatrix} a_{1p} \\ a_{2p} \\ \vdots \\ a_{Kp} \end{bmatrix} = \begin{bmatrix} e^{j2\pi f_p \tau_{1p}} \\ e^{j2\pi f_p \tau_{2p}} \\ \vdots \\ e^{j2\pi f_p \tau_{Kp}} \end{bmatrix} \tag{5}$$

where, $\tau_{kp} = \hat{g}_p \cdot (\vec{r}_k - \vec{r}_0)/c$, $\hat{g}_p$ is the unit vector pointing from the p^{th} signal source toward the k^{th} antenna, $\vec{r}_k$ and $\vec{r}_0$ are position vectors of the k^{th} antenna and the reference location, respectively, and c is the speed of light. For the 4-element antenna shown in Figure 1, if antenna element 1 location is the reference location, then the steering vector associated with a particular signal source p is:

$$\vec{a}_p = \begin{bmatrix} 1 \\ e^{j2\pi f_p \sin\theta_p (\cos\phi_p - \sin\phi_p) d/c} \\ e^{-j2\pi f_p \sin\theta_p (\cos\phi_p + \sin\phi_p) d/c} \\ e^{-j4\pi f_p \sin\theta_p \sin\phi_p d/c} \end{bmatrix} \tag{6}$$

A 9-element antenna array is used in simulation studies. The 9-element antenna array assumed the layout as shown in Figure 5. The steering vector for this antenna array layout is:

$$\vec{a}_p = \begin{bmatrix} e^{-j2\pi f_p \sin\theta_p (\cos\phi_p - \sin\phi_p) d/c} \\ e^{-j2\pi f_p \sin\theta_p \cos\phi_p d/c} \\ e^{-j2\pi f_p \sin\theta_p (\cos\phi_p + \sin\phi_p) d/c} \\ e^{j2\pi f_p \sin\theta_p \sin\phi_p d/c} \\ 1 \\ e^{-j2\pi f_p \sin\theta_p \sin\phi_p d/c} \\ e^{j2\pi f_p \sin\theta_p (\cos\phi_p + \sin\phi_p) d/c} \\ e^{j2\pi f_p \sin\theta_p \cos\phi_p d/c} \\ e^{j2\pi f_p \sin\theta_p (\cos\phi_p - \sin\phi_p) d/c} \end{bmatrix} \tag{7}$$

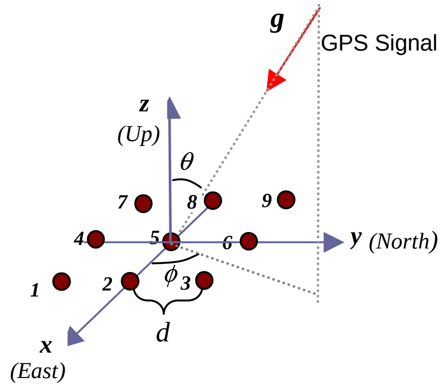


Fig. 5. Layout of a 9-element antenna array used in simulation study.

3.2. MOP METHOD

Assuming that GPS signals, interferences, and noise are uncorrelated, the total combined average beam-former output signal power is:

$$E\{|y(t)|^2\} = w^H R_x w = w^H (R_s + R_V + R_n) w \tag{8}$$

where, $R_x = E\{xx^H\}$, $R_s = E\{SS^H\}$, $R_V = E\{VV^H\}$, and $R_n = E\{nn^H\}$ are the expected correlation matrix for the total input signal, GPS signals, interferences, and noise respectively. In the MOP method, the weight vector w is obtained by minimizing the total output power given by (8), while constrain the gain along the direction of known satellites:

$$\min_w w^H R_x w \qquad \textit{subject to} \;\; w^H a_p = 1 \tag{9}$$

The solution that satisfies (9) is (Godara, 2004):

$$w = R_x^{-1} a (a^H R_x^{-1} a)^{-1} \tag{10}$$

where a contains the spatial signature for those satellites whose directions are known and whose signals are of interests to the user. Zoltowski and Gecan (1995) pointed out that the constraints applied in the optimization process consume the limited number of degrees of freedom associated with a phased array. It may provide up to K-P spatial nulls to cancel interference where K is the total number of antenna elements and P is the total number of GPS signal sources. As can be seen from the analysis results to be presented in Section 5, this is truly the case for the array used in this study.

3.3. SCORE METHOD

The SCORE method was proposed by Agee et al (1990) and was applied to GPS interference cancellation by Sun and Aimin (to appear). The SCORE method explores the unique characteristics of a class of signals that are *spectrally self-coherent*, ie, the correlation between a signal $s(t)$ and its frequency-shifted version for some time lag is non-zero:

$$\rho_s^{\beta}(\tau) = \frac{< s(t)s^*(t-\tau)e^{-j2\pi\beta t} >_{\infty}}{\sqrt{< |s(t)|^2 >_{\infty} < |s^*(t-\tau)e^{-j2\pi\beta t}|^2 >_{\infty}}} = \frac{R_s^{\beta}(\tau)}{R_s(0)} \neq 0 \quad (11)$$

where the notation $\langle \bullet \rangle_{\infty}$ represents infinite time averaging operation. The function $\rho_s^{\beta}(\tau)$ is referred to as the *spectral self-coherence function* of $s(t)$. $R_s^{\beta}(\tau)$ and $R_s(0)$ are the *cyclic autocorrelation* function and autocorrelation function of $s(t)$ respectively. The SCORE algorithms aims at obtaining optimized weight vector w that maximize the cyclic components of a receiver input. If the interference and noise at a GPS receiver are not spectrally self-coherent at frequency separation β, the cyclic autocorrelation of the receiver input x is:

$$R_x^{\beta}(\tau) = |a|^2 R_s^{\beta}(\tau) + |b|^2 R_v^{\beta}(\tau) + R_n^{\beta}(\tau) = |a|^2 R_s^{\beta}(\tau) \quad (12)$$

The CA code of GPS signals $u_p(t-nT_c)$ as shown in Equation (3) has a chip duration of $T_c = 977$ ns and the code period T is *1* ms. The GPS navigation data has a data rate of *50* Hz. As a result, the CA code repeats itself *20* times within one navigation data bit. Within the same navigation data bit, a GPS satellite signal is spectrally self-coherent without frequency separation. The collection of all GPS satellite signals at a receiver input is also spectrally self-coherent without frequency separation. Because of this property, Sun and Aimin (to appear) developed a self-coherent beam former for GPS interference mitigation. Two set of inputs are used in their processor: the direct input x from the antenna array, and a delayed version of the input $x(t-mT)$ where m is an integer. The direct input x is applied with a set of weight w to generate an output y, while the delayed input $x(t-mT)$ is applied with another set of weight w' to generate a reference output y'. The difference between y and y', e, is minimized to generate optimized weight w'. This minimization is done in the least-square sense. The main beam former generates weight w by maximizing the correlation between y and y':

$$F(w,w') = \frac{|R_{yy'}|^2}{R_y R_{y'}} \quad (13)$$

$$R_{yy'} = E\{yy'\} = w^H R_x(mT)w \quad (14)$$

$$R_y = E\{yy\} = w^H R_x(0)w \quad (15)$$

$$R_{y'} = E\{y'y'\} = w'^H R_x(0)w' \quad (16)$$

$R_x(mT)$ denotes the correlation of x with its mT time delayed version and $R_x(0)$ is the auto-correlation function of x. Assuming that interference and noise are uncorrelated between themselves and their mT time delayed version, then $R_x(mT) = R_s$. Maximizing $F(w,w')$ is therefore the maximization of total GPS signal output.

Substituting (14), (15), and (16) into (13) and solve for the optimization problem, the desirable weight vector w is the eigenvector corresponding to the largest eigenvalue of the generalized eigenvalue problem:

$$R_x w = \lambda_{\max} R_x(mT) R_x^{-1} R_x^H(mT) w \quad (17)$$

MatLab is used to implement both the MOP and the SCORE algorithm. The correlation matrix R_x and $R_x(mT)$ are calculated using multiple blocks of digitized GPS input data. This is necessary to reduce the impact of possible navigation data bits transition within an input data block or its delay version. Figure 6 explains the general idea of the multiple data block selection. Each block contains exactly one CA code period of data. If Data Block 2 which contains a navigation data bit transition is used to calculate the correlation functions, the self-coherence property of the signal will be non-existence or greatly reduced. Since navigation data transition occurs no more than once in every twenty blocks of data, using the averaged correlation results of twenty blocks of data and their corresponding delayed blocks will lessen the impact of the navigation data bit transition.

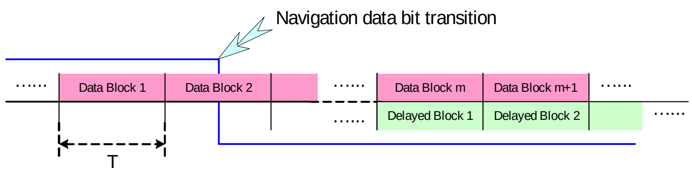


Fig. 6. Data Block Selection for SCORE Algorithm

4. EXPERIMENTAL DATA ANALYSIS

A total of 33 sets of experimental data containing GPS and interference signals were taken for this study. The following subsections will present the results of the MOP and SCORE beam forming algorithms and software receiver acquisition performance based on the experimental data processing.

4.1. MOP METHOD

Among the 33 sets of experimental data, there are 6 sets containing single FM chirp, 6 sets containing single BPSK, and 21 sets containing single and multiple broadband interference sources. Figures 7 through 14 summarize the beam forming and receiver acquisition results of these experimental data. Figure 7, 9, 11, and 13 compares the average number of successful GPS signal acquisition in the presence of FM chirp, BPSK, single broadband, and multiple broadband interference sources respectively, while Figure 8, 10, 12, and 14 compares the post-acquisition signal to noise ratio for the successfully acquired signals. It is evident from these figures that the MOP method worked effectively to cancel FM chirp and BPSK interferences at all interference power levels tested. The method is also functional to some degrees when dealing with single broadband jamming source. For multiple broadband jamming sources, its performance degrades considerable at the 30 and 40 dB ISR levels.

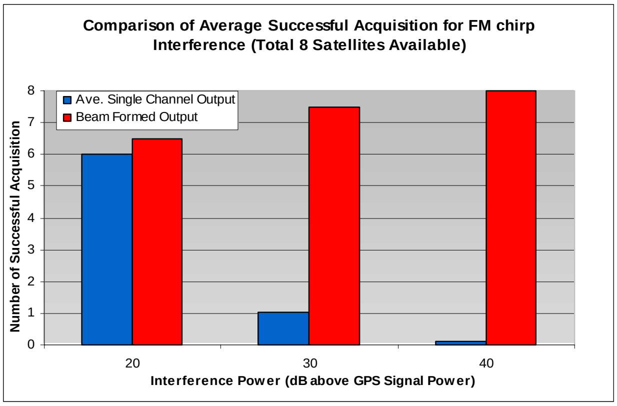


Fig. 7. Average number of successful GPS signal acquisition in the presence of FM chirp interference

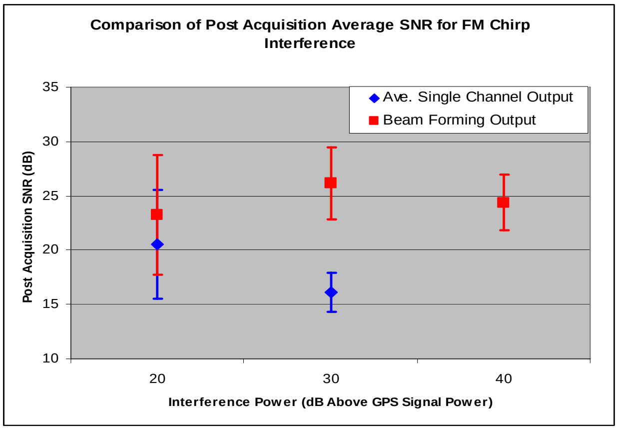


Fig. 8. Average post-acquisition GPS signal to noise ratio in the presence of FM chirp interference

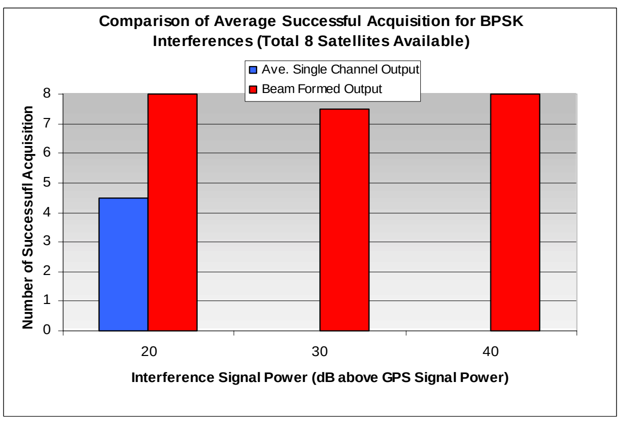


Fig. 9. Average number of successful GPS signal acquisition in the presence of BPSK interference.

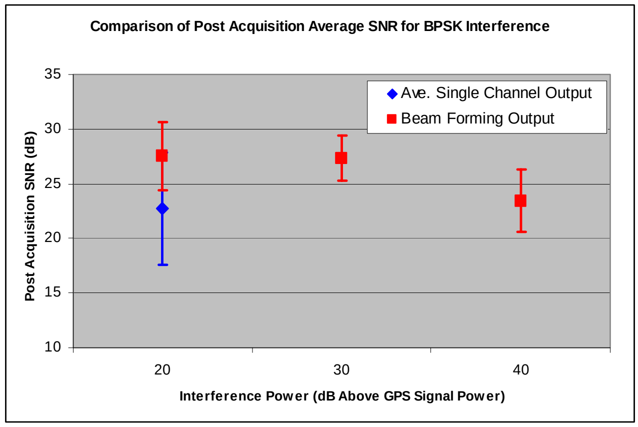


Fig. 10. Average post-acquisition GPS signal to noise ratio in the presence of BPSK interference

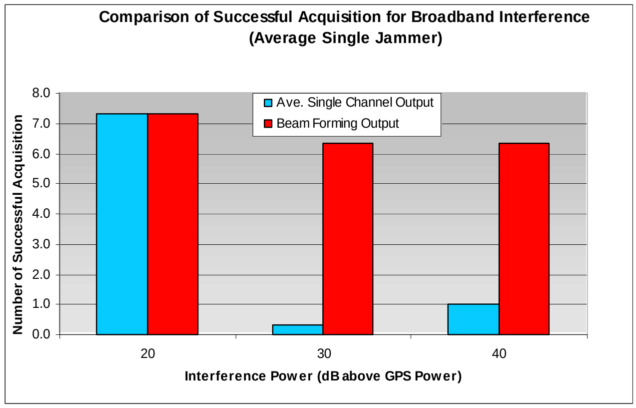


Fig. 11. Average number of successful GPS signal acquisition in the presence of one broadband interference.

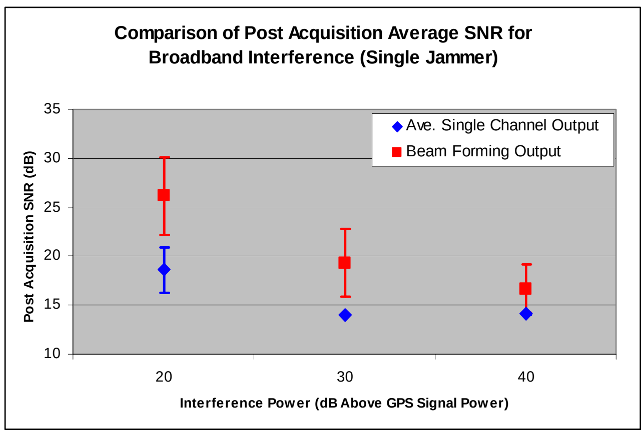


Fig. 12. Average post-acquisition GPS signal to noise ratio in the presence of one broadband interference.

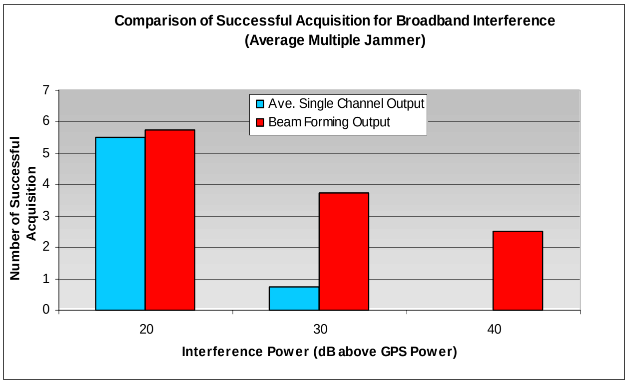


Fig. 13. Average number of successful GPS signal acquisition in the presence of multiple broadband interferences.

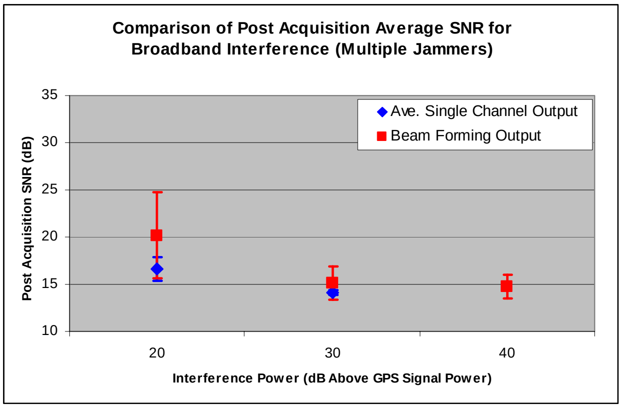
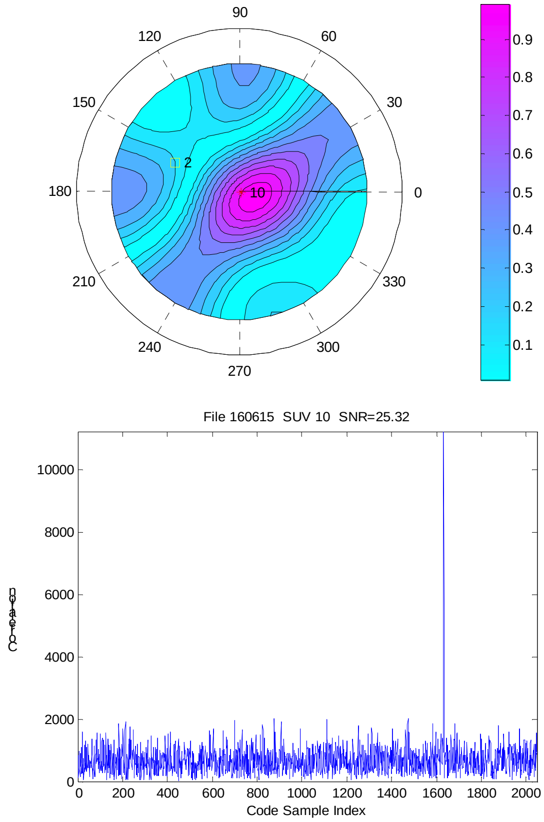


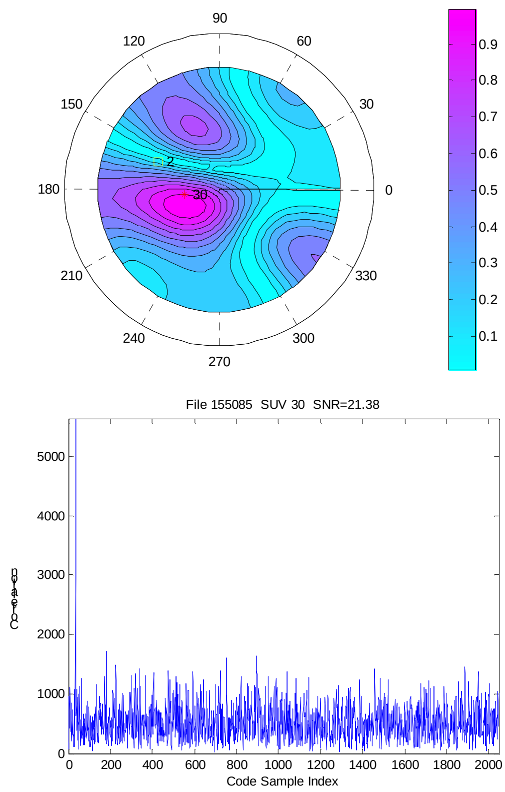
Fig. 14. Average post-acquisition GPS signal to noise ratio in the presence of multiple broadband interferences.

The following groups of figures (Figure 15 (a)-(f)) show some examples of the antenna gain pattern and receiver acquisition results. Figures 15 (a), (b), and (c) show the examples using single beam constraint for data containing single FM chirp, BPSK, and broadband interference respectively. The interference to signal power ratio are at 40 dB for all three examples. Figure 15 (d) and (e) shows the results using single satellite beam constraint for data containing two and three broadband interference sources with ISR =40 dB respectively. In Figure 15 (f), a single broadband interference sources with ISR=40 dB is included in the data and two satellites are used to constraint the beam forming algorithms.

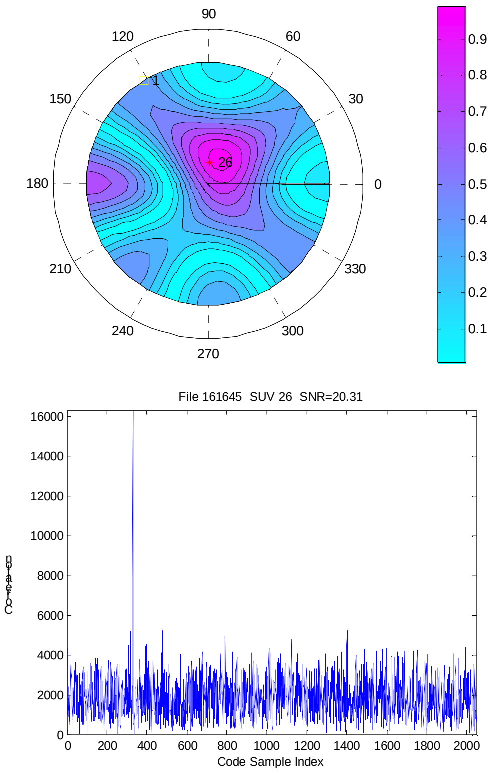
Additional processing is performed for two and three beam constraints using the MOP method. The general conclusion is that post-acquisition signal to noise ratio of satellites using two-beam constraints is compatible with that using single beam constraint, while the three-beam constraints cannot generates satisfactory weighted output.



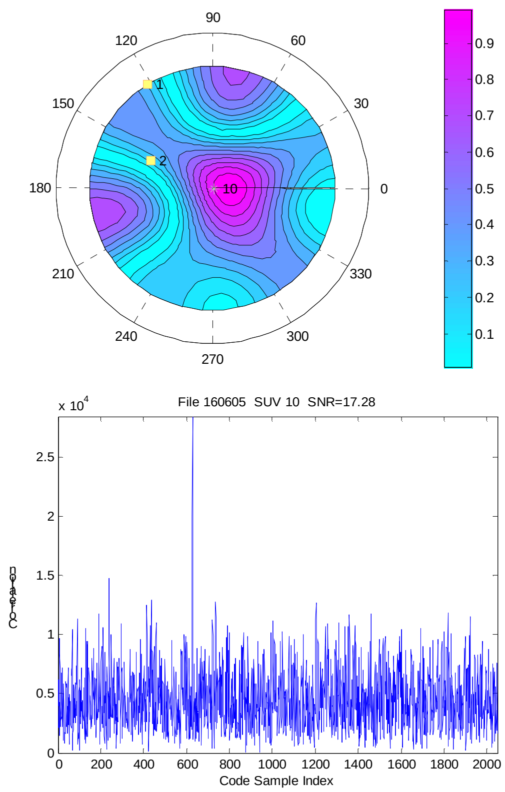
(a)



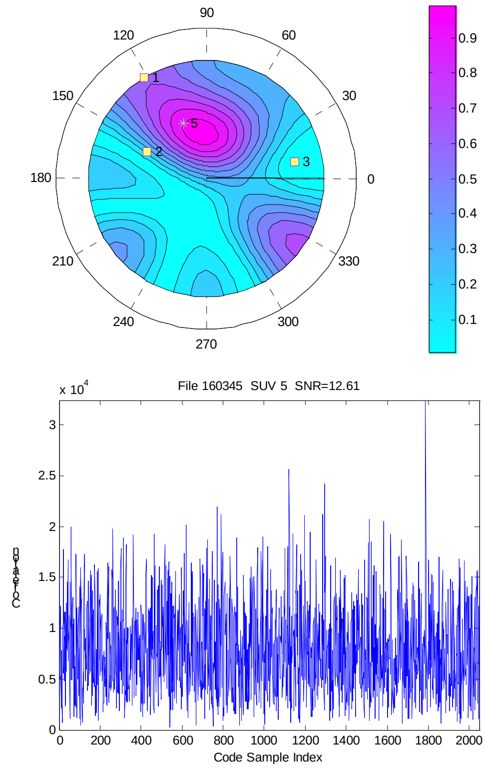
(b)


File 161645 SUV 26 SNR=20.31
Code Sample Index

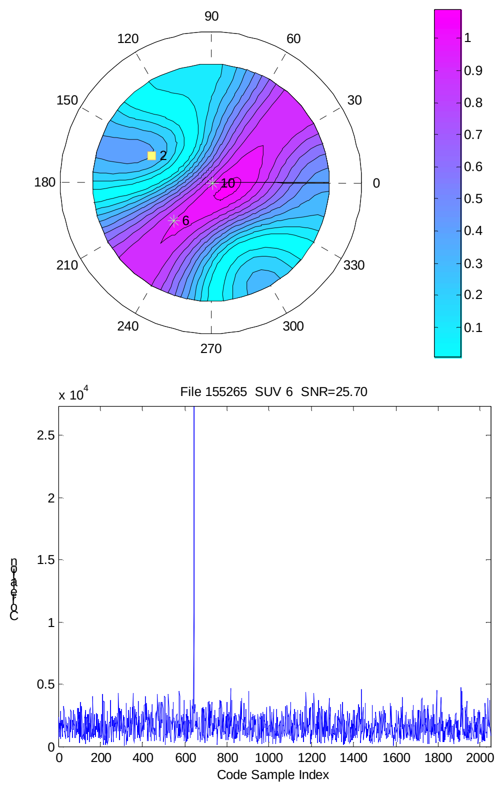
(c)

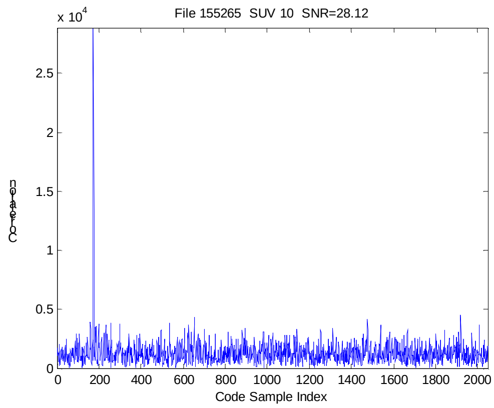

File 160605 SUV 10 SNR=17.28
Code Sample Index

(d)


File 160345 SUV 5 SNR=12.61
Code Sample Index

(e)


File 155265 SUV 6 SNR=25.70
Code Sample Index

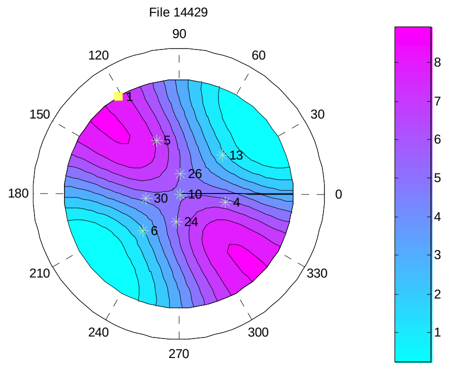


(f)

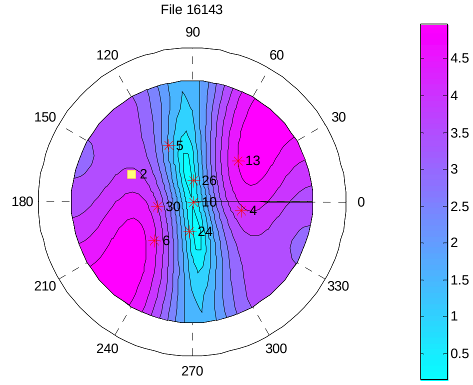
Fig. 15 (a)-(f). Antenna gain patterns and receiver acquisition results for experimental data collected using a 4-element antenna array. The results are obtained using MOP method.

4.2. SCORE METHOD

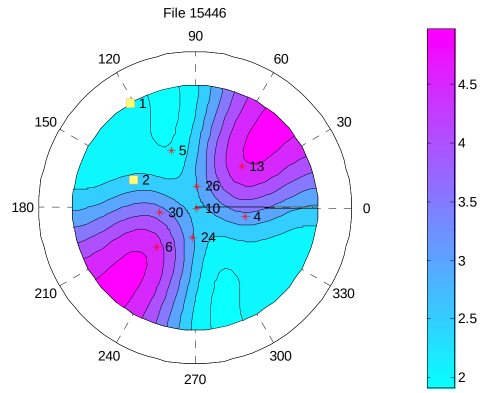
The SCORE method did not generate outputs that lead to consistent acquisition results. Figure 16 shows four sample antenna gain pattern generated for data containing a variety of interference sources. Figure 16(a), (b), (c), and (d) show results for data containing a single interference source with ISR=20 dB, a single interference source with ISR=40 dB, two interference sources with ISR=40 dB each, and three interference sources with ISR=30 dB each, respectively. Broadband interference sources are contained in all four data files. It is evident from these plots that the SCORE beam forming algorithm places nulls in an inconsistent manner in the patterns. We believe that this is the consequence of having a total of eight satellites in the experimental setups while only 4 antenna elements are used to collect the data. The number of degree of freedoms associated with the 4 antenna array elements is not sufficient to handle the number of signal sources contained in the data.



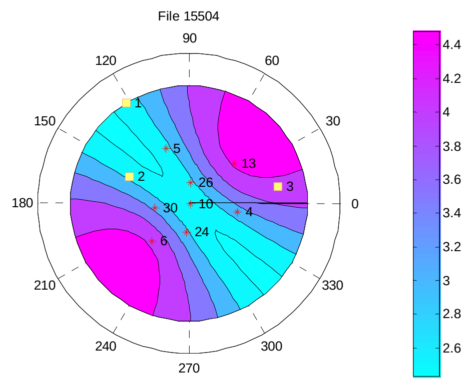
(a)



(b)



(c)



(d)

Fig. 16 (a)-(d). Antenna gain pattern for experimental data collected using a 4-element antenna. SCORE algorithm is used to obtain the results.

5. SIMULATION RESULTS

To validate some of the observations made from the experimental data processing, simulation inputs containing GPS signals and noise only are generated to test the beam forming algorithm performance in this project. Inputs from two different antenna arrays are simulated. Both MOP and SCORE are used to process the simulated inputs and will be discussed in the following two subsections.

5.1. MOP METHOD

Figure 17 shows two example antenna gain patterns generated for an input signal that contains all eight satellites shown in Figure 2 using the MOP method. A 4-element antenna is used in the simulation. A single beam constraint is applied in both cases. The figure shows that MOP method is indeed capable of generating a well defined beam towards the given satellite direction.

The performance of the MOP method degrades as the number of beam constraints increases. This is evident as shown in Figure 18 where 3-beam constraints and 8-beam constraints are applied for the 4-element antenna input.

The number of antenna elements increases the degree of freedom of the MOP beam former. Figure 19 is generated using the same simulated input as that of Figure 18 and applied to a 9-element planar-layout antenna array. Comparison of Figure 19 with Figure 18 shows clearly the improvement of the beam forming algorithm performance due to the increase in the number of antennas.

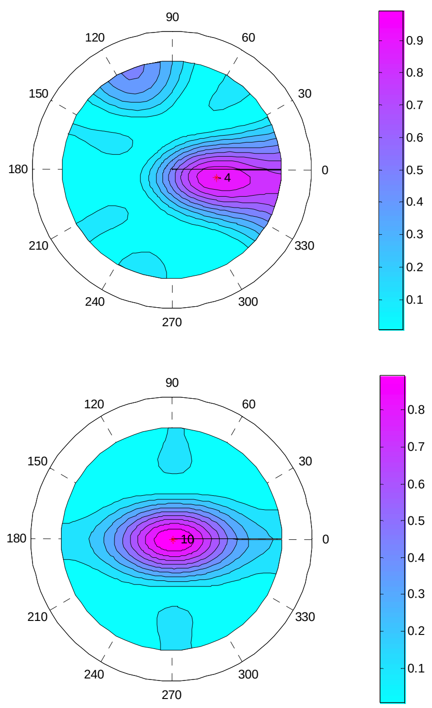


Fig. 17. Simulated antenna gain pattern using 4-element antenna and MOP algorithm for single satellite, no interference source scenarios.

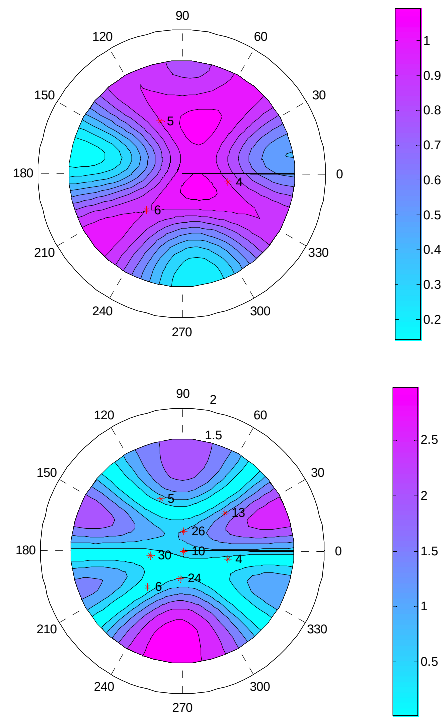


Fig. 18. Simulated antenna gain pattern using 4-element antenna and MOP algorithm for multiple satellites, no interference scenarios.

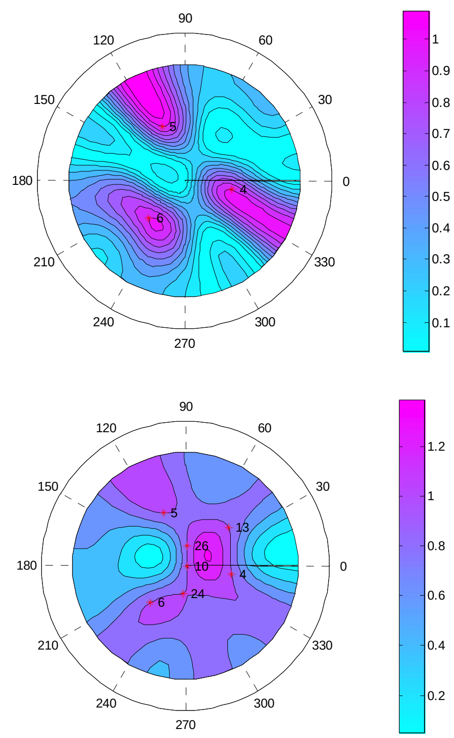


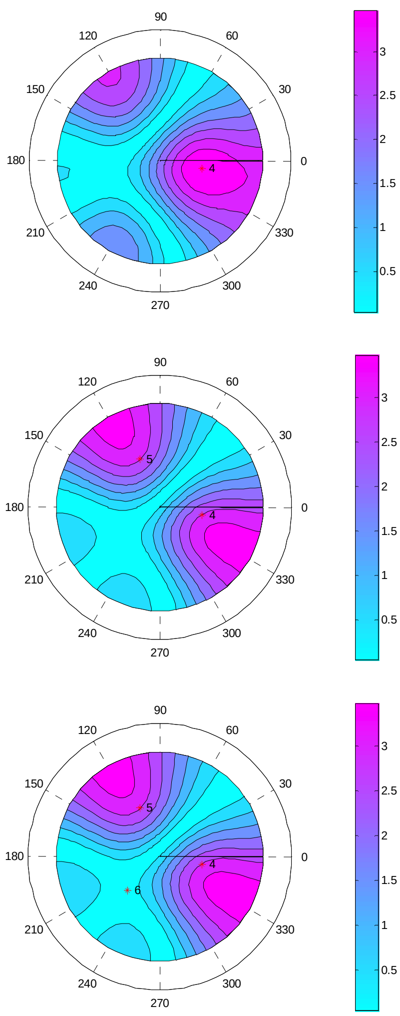
Fig. 19. Simulated antenna gain pattern using 9-element antenna and MOP algorithm for multiple satellites, no interference scenarios.

5.2. SCORE METHOD

Figure 20 shows the antenna gain patterns generated using SCORE algorithm. The input signals for the four patterns contain one, two, three and eight GPS signals respectively. The antenna array used for the simulation has 4-elements. The SCORE algorithm generates satisfactory results for one and two satellite scenarios. For the three and eight satellite scenarios, the algorithms can not operate optimally.

The performance of the SCORE algorithm does improve as the number of antenna elements increases. Figure 21 is the result of using a 9-element antenna array for the same simulation signals used to generate the last two patterns shown in Figure 20.

The addition of interference sources in the input signal will further influence the beam pattern. Future simulation will be conducted to study this problem.



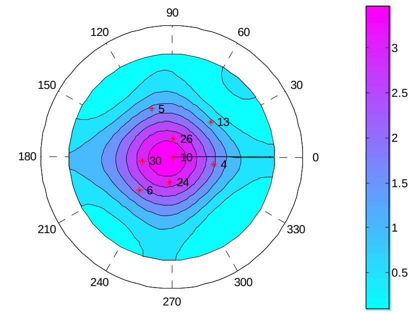


Fig. 20. Simulated antenna gain pattern using 4-element antenna and SCORE algorithm for single and multiple satellites, no interference scenarios.

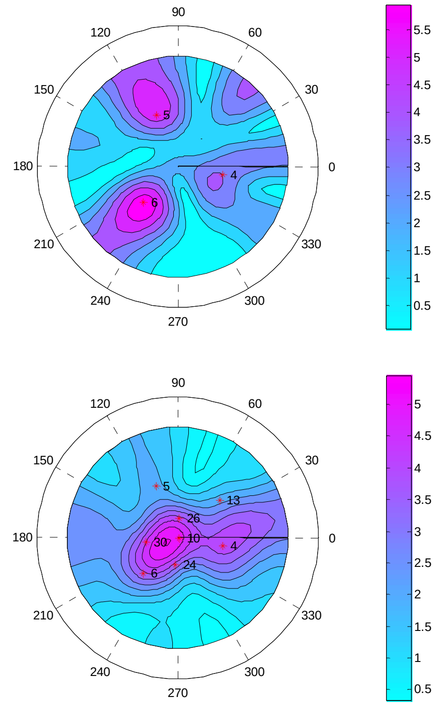


Fig. 21. Simulated antenna gain pattern using 9-element antenna and SCORE algorithm for multiple satellites, no interference scenarios.

6. CONCLUSIONS AND FUTURE WORKS

This paper presented results of integrating two digital beam forming algorithms, MOP and SCORE, with a software GPS receiver to study the effectiveness of the beam forming algorithms. Both experimental and simulation data are used to test and evaluate the performance of these algorithms. The software GPS receiver is used to perform signal acquisition of the beam former output. Our study showed that MOP can be an effective interference cancellation technique when satellite signal angle of arrival is known and when enough degrees of freedom are available. Our experimental results show that the MOP method works with all 3 types of interference sources with ISR up to 40 dB.

Our experience with the SCORE method suggests that it requires large numbers of antenna elements when the number of available satellites is large. It will produce erroneous results if interference also has spectrally self-coherent properties. Because of its sensitivity to the special spectral self-coherent properties of the CA code, it may be used for ground-based interference identifications.

The study shows that integrating beam forming algorithm with Software GPS receiver can provide a powerful means to develop anti-jam receivers.

For future works, more experiments involving different types of antenna elements, antenna layout configurations, more receiver input channels, interference and satellite configurations, interference types and ISR levels should be carried out. Additional simulation works need to including interference sources. Analysis using tracking and position calculations will also be investigated in the future.

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