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ABSTRACT

Jammer and interference are sources of errors in positions estimated by GNSS receivers. The interfering signals reduce signal-to-noise ratio and cause receiver failure to correctly detect satellite signals. Because of the robustness of beam-forming techniques to jamming and multipath mitigation by placing nulls in direction of interference signals, an antenna array with a set of multi-channel receivers can be used to improve GNSS signal reception. Spatial reference beam forming uses the information in the Direction Of Arrival (DOA) of desired and interference signals for this purpose. However, using a multi-channel receiver is not applicable in many applications for estimating the Angle Of Arrival (AOA) of the signal (hardware limitations or portability issues). This paper proposes a new method for DOA estimation of jammer and interference signals based on a synthetic antenna array. In this case, the motion of a single antenna can be used to estimate the AOA of the interfering signals.

I. INTRODUCTION

In recent years, research into Angle Of Arrival (AOA) estimation has attracted significant attention for applications such as radar, sonar, mobile communications and position estimation. GNSS AOA techniques typically utilize arrays of multiple antennas to measure the direction of incoming signals from several locations. Multipath and interference are the main sources of errors in positions estimated by GNSS signals. The interfering signals reduce the signal to noise ratio (SNR) and cause receiver failure to detect correctly satellite signals. On the other hand, multipath distorts correlation peaks and affects discriminators performance in Delay Lock Loops (DLL). Because of the robustness of beam-forming techniques to jammer and
multipath, an antenna array with a set of multi-channel receivers can be used to improve GNSS signal reception. Advantages of AOA estimation and beam-forming to improve GNSS signals measurement accuracy have been investigated by many authors (Brown & Gerein 2001, Fu et al 2003, Zoltowski & Gecan 1995). For the purpose of interference mitigation to assist GNSS accuracy, the use of adaptive antenna arrays can be practical. With adaptive antenna array algorithms, it is possible to design a beam-former to place nulls in directions of interfering signals. Spatial reference beam-former uses the AOA information contained in the incoming signals to synthesize beam steering to the desired signal and put nulls toward the interferers. Therefore, for effective jammer and interference signals cancellation, it is important to estimate the angle of arrival of those sources correctly. The capability of AO A techniques such as the MUSIC algorithm (Schmidt 1986) to determine the number of multipath contribution depends on the number of array elements and the aperture of antenna array. Therefore, in sub-space AOA estimation algorithms the number of array elements is a limitation factor, which has a direct effect on the performance of AOA estimation and restricts applicability of DOA estimation (practical requirements with respect to size and weight of the antenna array). In some particular applications such as position estimation with a handheld GNSS receiver, the size and shape of the antenna array limit the applicability of AOA estimation. In order to overcome the limitations of the conventional antenna arrays, a method to synthesize the antenna array with a single antenna is proposed herein. Instead of using multiple antennas with a multi-channel receiver, which increases cost and complexity of receiver designs, an antenna array can be synthesized by moving a single antenna in an arbitrary direction. For example, an Uniform Circular Array (UCA) can be synthesized by placing an antenna on a rotating arm, which is controllable with a PC. The AOA estimation method based on synthetic antenna arrays has numerous military and civilian applications (in commercial application, the synthetic array concept can be implemented in handheld receivers to enhance signal reception). In this case, just by moving a single antenna, the AOA of an incoming signal can be determined. This application can be useful to enhance GNSS accuracy in urban environments. Estimating the AOA with MUSIC assumes that the antenna array manifold (phase, gain, and element spacing) is completely known, which is not known in the synthetic array concept. During the data collection, a handheld receiver is moved in an arbitrary direction to take spatial samples while continuously sampling the jammer signal. In order to estimate trajectory of synthetic array, auxiliary sensors called inertial measurement units (IMU), which consist of accelerometers and gyroscopes have been used. In direction finding with moving antennas, a synthesized array does not have a unique shape. With the purpose of exploiting the MUSIC algorithm, an interpolated technique can be used with an arbitrary array shape (Friedlander 1992, 1993). The spatial resolution of AOA estimation depends on the number of elements in the antenna array. This paper presents the AOA estimation results of an interference signal with a moving antenna array along a circular path to produce a synthetic array. An IMU is used to estimate the trajectory of the circular array. The block diagram of AOA estimation with a synthetic array is shown in Figure 1. The AOA of a point source jammer with a moving antenna has been used in electronic countermeasures for several decades. However, application to GNSS can be considered here. In addition, a fixed mechanical motion of the antenna has been tested but the eventual novelty will be the arbitrary motion of the antenna (e.g. Jong & Herben 1999).

The paper is organized as follows. In Section II, signals models of GPS signals, interference and noise are described. The synthetic array concept is described in Section III. Then AOA estimation algorithms for UCA are shown in Section IV. Trajectory estimation is defined in Section V. Practical considerations and experimental results are presented in Section VI. Finally, conclusions are given in Section VII.

II. SIGNAL MODEL

The received signal at the antenna array is composed of three components: GPS signal, jammer and interference, and receiver noise. Assume \( N \) narrow-band (partial of full correlated) reflected GPS signals and \( N_I \) interference signals impinging on an array with \( M \) sensors. The output of the stationary array can be represented by

\[
x(t) = \sum_{i=0}^{N} a_{i \text{GPS}} s_{i \text{GPS}}(t) + \sum_{k=1}^{N_I} a_{k \text{I}} s_{k I}(t) + n(t) \quad (1)
\]
where \( s_i(t) \) is the complex phase and gain of the signal, \( f_d \) is the Doppler frequency, \( p \) is the navigation data, \( n(t) \) is the zero mean stationary additive noise which is independent form sensor to sensor, and \( D \) is the C/A PN code (Seco & Rubio 1997). \( a_{GPS} \) and \( a_i \) are the GPS and interference steering vector, respectively. The steering vector of an uniform circular array (UCA) can be written as (Mathews & Zoltowski 1994):

\[
a(\xi, \varphi) = \left[ e^{j\xi \cos(\varphi - \gamma)}, e^{j\xi \cos(\varphi - 2\gamma)}, \ldots, e^{j\xi \cos(\varphi - (M-1)\gamma)} \right]
\]

\( \xi = 2\pi r (\sin \vartheta) / \lambda \).

where \( \varphi \) and \( \vartheta \) are the azimuth and elevation angle, respectively, and \( \gamma_m = 2\pi m / M \) is the position of the \( n \)th element of the array. \( r \) is the radius of the circular array, and \( \lambda \) is the wavelength of the incoming signal.

The received signal model can be succinctly represented as

\[
X(t) = A_{GPS} S_{GPS} + A_I s_I + N(t)
\]

where \( A_{GPS} \) and \( A_I \) are \((M \times N+1)\) and \((M \times N_0)\) steering matrices and \( X(t) \) and \( N(t) \) are \( M \times 1 \) received signal and noise vectors. The spatial covariance matrix of the array outputs is

\[
R = E[x(t)x^H(t)] = A_{GPS} R_{GPS} A_{GPS}^H + A_I R_I A_I^H + \sigma^2 I
\]

where \( R_{GPS} \) and \( R_I \) are the GPS source covariance matrix and interference signals respectively, and \( \sigma^2 \) is the noise variance. Signal and noise are assumed independent. Because the GPS signals before despooling are well below the noise floor, the correlation matrix of the received signal can be written as (Zoltowski & Gecan 1995):

\[
R = E[x(t)x^H(t)] = A_I R_I A_I^H + \sigma^2 I
\]

\[
= \sum_{i=1}^{N_1} \lambda_i v_i v_i^H + \sigma^2 \sum_{i=N_1+1}^{M} \lambda_i v_i v_i^H
\]

It has been assumed that \( N_1 < M \). Any Eigen- decomposition AOA estimation algorithm can be applied to this signal model to determine the direction of interference signals. The GPS signal is assumed to be negligibly small relative to the additive noise. It is therefore irrelevant in the context of estimating the AOA of the interference signal.

III. SYNTHETIC ARRAY CONCEPT

In parameter estimation with a synthetic array, instead of using multiple channel receivers with multiple antennas, a phase array is synthesized by moving a single antenna in an arbitrary direction. During the data collection, the receiver collects impinging signals with different phases at different times. If the communication channel during each period of data collection is quasi-stationary, the parameters of the channel (e.g. AOA) can be estimated. AOA estimation with a synthetic array has some benefits, e.g. it is not affected by inter-channel phases, gains and mutual coupling between antenna elements. Therefore, it does not require calibration, which is a serious problem in multi-antenna array processing. Figure 2 shows the concept of a synthetic array. Let assume there are \( M \) real sensors located uniformly on a circle. These sensors collect signals for a predetermined time about \( t_{synthetic} \) seconds. One can divide the collected data of each sensor to \( M \) equal parts. Without any hardware limitation, if the channel situation does not change during this period, each section of these \( M \) parts of individual sensors can be used for DOA estimation. A synthetic array uses this property to create an antenna array. Figure 2 visually shows this concept. Instead of collecting \( M \times t_{synthetic} \) seconds signals, a single rotating antenna collects signals represented by shaded cells in Figure 2. It should be noted that in \( N \times (t-1)^{th} \) seconds the single antenna is in the position of the \( n \)th real antenna. Subspace-based AOA estimation algorithms employ some parts of \( t \) seconds of shaded blocks for correlation matrix estimation.

A question may be posed – It takes a second or so to move the antenna around the circle. Is it reasonable to assume that the channel is stationary during this time? In addition, this can be stated as a tradeoff between single and multiple antenna arrays. Multi antenna arrays collect data simultaneously and therefore, channel stationarity is less of an issue. In addition, an \( N \) element array collects \( N \) times the data than a single antenna does. Therefore, the tradeoff is ultimately between array performance and hardware complexity.
IV. ANGLE OF ARRIVAL ESTIMATION ALGORITHM

The MUltiple SIgnal Classification (MUSIC) algorithm is a sub-space based high-resolution AOA algorithm (Schmidt 1986). MUSIC finds the AOA of the incoming signal with properties of the covariance matrix of the vector of received signals. In this section, the theory underlying the AOA estimation with a uniform circular array is presented below. The geometry of uniform circular array is shown in Figure 3. Azimuth and zenith angles in this topology are estimated from the x and z axes, respectively. The UCA-MUSIC algorithm uses the beam-former $F$ to make the transformation from element space to beam space. Phase mode excitation-based beam-forming synthesizes a beam space manifold. The elements of the vector $a(\theta)$ are periodic with a period of $2\pi$ and it can be represented as a Fourier series (Jong & Herben 1999).

$$a(\xi, \phi) = \sum_{h=-\infty}^{\infty} j^{2\pi h} a_h(\xi, \phi) e^{-j2\pi r}$$

(7)

$$a_h(\xi, \phi) = \frac{1}{2\pi} \int_0^{2\pi} a(\gamma, \xi, \phi) e^{j2\pi r\gamma} d\gamma = J_{2\pi}(\xi) e^{j2\pi r}$$

The spectral width of $a(\xi, \phi)$ is infinite in theory but the magnitude is negligible $J_{2\pi}(\xi)$. One has $|h > 2.72\pi r / \lambda|$. $r$ is the radius of the circular array and $\lambda$ is wavelength of signal. Choosing the proper array element number can mitigate aliasing. In other words the only non-negligible coefficients are

$$a_h(\theta), \quad -H \leq h \leq H$$

(8)

where $\lfloor x \rfloor$ is the largest integer smaller than the argument. The transformer $F$ is defined by

$$F^H = WCV^H$$

(9)

$$b(\theta) = F^H a(\theta)$$

$W$ is a centro-hermitian matrix that satisfies

$$JW = W^*$$

(10)

where $J$ is the reverse permutation matrix with ones on the anti-diagonal and zeros elsewhere. The feature of a centro-

Figure 3: Geometry of a circular array

hermitian matrix is that it can be easily transformed to real matrices. $V$ excites the UCA with phase mode $m$

$$V = \frac{1}{\sqrt{M}} [v_0, v_1, \ldots, v_{M-1}]$$

$$v_m = [\exp(-j2\pi m / M), \ldots, 1, \ldots, \exp(j2\pi m / M)]^T$$

(11)

The matrix $C$ is defined as

$$C = diag\{j^{-H}, \ldots, j^0, \ldots, j^{-H}\}$$

(12)

$B$ is the real valued beam-space direction of arrival matrix. With these definition the output vector is defined by (Jong & Herben 1999)

$$y(\tau) = CVx(\tau) = Bs(\tau) + n(\tau)$$

$$B = \sqrt{M} \begin{bmatrix} b(\theta_1), b(\theta_2), \ldots, b(\theta_N) \end{bmatrix}$$

(13)

$$n(\tau) = CV\eta(\tau)$$

The beam-space covariance matrix is

$$R = \text{Re}\{\mathbf{R}_s\} = BP_BP^T + \sigma^2 I$$

(14)

where $P_R$ is the real part of signal covariance matrix. With this definition the UCA-MUSIC algorithm can be described as

$$P_{\text{MUSIC}}(\theta) = \frac{1}{b^T(\theta)GG^Tb(\theta)}$$

(15)

where $G$ is an orthonormal matrix that spans the noise subspace and $b$ is the transformed version of steering vector.

In practice, due to multipath, which arises quite often in wireless communication, the covariance matrix of incoming
signals will be singular. In this case, MUSIC cannot estimate the noise subspace correctly. The jammer and interference signals typically come from terrestrial sources that are subject to multipath. Therefore, it is more probable that the interference signals present themselves at the receiver from different multipath angles. Forward/Backward technique makes it possible to use MUSIC with highly correlated or coherent signals. Eigen structure super-resolution UCA-MUSIC algorithms fail when the signal covariance matrix is singular. In order to improve the UCA-MUSIC performance in a correlated signal environment, forward/backward is averaged prior to the calculation of the Eigen decomposition. Forward/backward averaging can be applied in beam-space with UCA_MUSIC as

$$\tilde{R} = \frac{1}{2} \left( R + JR^* J \right)$$

where $R^*$ is a complex conjugate covariance matrix and $J$ is a reverse permutation matrix (Mathews & Zoltowski 1994).

V. TRAJECTORY ESTIMATION

The ability to estimate the trajectory of a moving antenna gives one the opportunity to use MUSIC with any arbitrary geometry array. In this experiment, a Crista Inertial Measurement Unit (IMU) (Cloud Cap Technology 2007) is used. This IMU consists of three accelerometers and three gyroscopes on the x, y, and z axes and is sufficiently small to be attached to the receiver. This IMU can measure rates of 300°/s and 10 g accelerations. The digital output is controlled by an interface that manages update rates and over-sampling. For each output data updates, over-sampling averages the number of A/D measurements. The digital output is stored on PC, post processing based on the outputs of the six sensors can be performed to determine the trajectory. The characteristics of the IMU are shown in Table 1. The question is whether these performance specifications are sufficient to enable MUSIC to determine the AOA of the interference accurately? This will be examined in the next section.

<table>
<thead>
<tr>
<th>Size</th>
<th>5.2 x 3.9 x 2.5 (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>37 (grams)</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of Crista IMU

<table>
<thead>
<tr>
<th>Accelerometers</th>
<th>Range</th>
<th>±10 g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyros</td>
<td>Range</td>
<td>±300°/s</td>
</tr>
<tr>
<td>Scale Factor Error</td>
<td>Fixed temperature</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>In-Run Bias Error</td>
<td>Fixed temperature</td>
<td>&lt;2.5 mg</td>
</tr>
<tr>
<td>Turn-on to turn-on Bias</td>
<td>30 mg</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>0.3 mg</td>
<td></td>
</tr>
</tbody>
</table>

VI. PRACTICAL CONSIDERATION AND EXPERIMENTAL RESULTS

In this section, practical considerations in terms of designing issues of synthetic array are described. Some simulations have been done to reveal the effect of improper design parameters in DOA estimation. Finally, the field test results are described.

a. Practical considerations in the implementation of a synthetic array

An important UCA parameter is its radius $r$ where the angular estimation accuracy and resolution capability depend on array aperture. Therefore, it is important to choose the UCA radius sufficiently large. However, some limitations should be considered in choosing the radius of circular array. Narrow-band signal are assumed herein. Therefore, the source bandwidth is smaller than the reciprocal of the time delay along the array aperture (with GPS signals, the total array aperture should be less than a few metres). Increasing the aperture diameter is an issue because the sensitivity to near field effects distorts MUSIC. In AOA estimation with MUSIC, plane waves have been assumed. The multipath of specular points is spherical. If the antenna array is too large, it will suffer near-field effects. On the other hand, practical requirements with respect to size and weight should be considered.

The revolution period of the synthetic circular array is another factor affecting AOA estimation accuracy. A higher revolution period results in more data and a better estimation of signal statistics. In addition, there are some practical problems that limit the increase of the revolution period. During the data collection, a quasi-stationary communication channel is assumed. This assumption is not valid for long revolution times. Alternatively, practical limitations of the receiver such as clock stability restrict the synthetic circular array revolution period.

The number of synthetic array sensors is another important situation that requires more attention. In array signal processing, if the number of antenna elements is higher, the estimation accuracy is better. In addition, based on the Cramer-Rao lower bound criteria of AOA estimation (Lu 2007), if the distance among sensors is long, the estimation accuracy is better. The aliasing problem limits the sensors spacing to half of the wavelength and the narrow-band assumption restricts the diameter of circular array. In the following, simulations are conducted to evaluate some design parameters.

b. Sensitivity of the MUSIC Algorithm to model error

Various authors (Friedlander 1990, Friedlander & Weiss 1994) have investigated the sensitivity of the MUSIC to antenna location perturbations. In this paper, the angle of
arrival estimation error caused by trajectory estimation is investigated. In the circular motion case, the error in the AOA estimation is due to errors in radius estimation and angular velocity. For this purpose, a simulation with the same parameters as used in the field is performed. A uniform circular array with a 46 cm radius is assumed. The wavelength is 19 cm and the number of circular array elements is 50 antennas. Two sources with arrival angles of \((\theta_1, \phi_1) = (40^\circ, 60^\circ)\) and \((\theta_2, \phi_2) = (80^\circ, 40^\circ)\) are considered, where \((\theta, \phi)\) are azimuth and elevation angles, respectively. The sources are correlated with the correlation coefficient of \(0.6 \exp(j \pi / 4)\). The number of snapshots is 50.

The AOA estimation results without any radius error is shown in Figure 4. Figure 4 shows that, without element position errors, MUSIC can correctly estimates direction of arrivals (the AOA estimation resolution depends on searching steps). To evaluate how sensitive is UCA-MUSIC to sensor position errors, a simulation with different errors in radius estimation was performed. The AOA estimation error under various radius estimation errors, for the first source is shown in Figure 5. The results show that errors in the radius estimation of a few cm can cause errors of a few degrees in the AOA estimation. Therefore, a precise trajectory estimation algorithm is required in the AOA estimation with the MUSIC algorithm.

As mentioned in a previous section, in array signal processing, element spacing plays an important role. For evaluating the effect of element spacing in a synthetic array, simulations were performed with the same parameters. In this case, the AOA estimation of a circular array with five elements with a radius of 10 and 50 cm are compared. The results are shown in Figure 6 and 7. These figures demonstrate that the proper selection of radius and antenna element is important for AOA estimation with a circular array. Experimental results show that an antenna spacing less than half of the wavelength is preferred. Almost all subspace techniques for the AOA estimation assume that the number of incoming signals (LOS and multipath) is known. This assumption is not valid in practical cases. Therefore, the number of signals impinging on the array should be estimated. There are some approaches based on theoretical criteria to estimate the source numbers (Wax & Kailath 1985). In this paper, the Akaike information theoretical criteria (AIC) algorithm is used to this end (Liberti & Rappaport 1999). To evaluate the effect of the incorrect estimation of the number of sources, a simulation with the same parameters is performed. In the first simulation, it is assumed that the estimated source number is one instead of two. In the second simulation, the source number estimation algorithm incorrectly estimated three signals. The AOA estimation results for under estimation, correct estimation and over estimation are depicted in Figure 8. The results show that in the under estimation case the resolvable angles have errors from their nominal values. On the other hand, in the over estimation case (Figure 8) two incoming signals are estimated correctly. Therefore, over estimating is preferred to under estimating the source numbers.

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**Figure 4:** AOA estimation with UCA-MUSIC without antenna position errors.

**Figure 5:** MUSIC estimation error versus radius estimation error.

**Figure 6:** AOA estimation with \(r=50\) cm and \(M=5\)
c. **Field Results of AOA Estimation**

To evaluate the performance of DOA estimation, a jammer test was conducted. The test was performed by propagating jammer signals centered on L1. To avoid creating problems for other users, a narrow beam directional antenna with controlled power was used, as shown in Figure 9. A NovAtel GPS 702™ antenna received the incoming signal. The GPS L1 signal raw samples were collected using an appropriate frontend. The frontend was interfaced with a stable external OCXO oscillator. To implement a synthetic array, a precise circular table with controllable angular velocity was used. The GPS antenna was mounted on a metal bar connected to the circular table. Rotation of the table was precisely controllable by a PC. Figure 10 shows the configuration of the antenna, metal bar and circular table. The antenna was mounted on the metal bar, 46 cm away from the center of the table (that is the radius of synthetic circular array is 46 cm). Fifty synthetic antenna elements were synthesized during 2.5 seconds revolution period of the circular table. The IMU was attached to the radius of the circular array. Figure 11 shows the synthetic circular array configuration and IMU coordinates. The x axis of the IMU is placed on the radius direction of the circle. The outputs of the IMU were fed to the trajectory estimation part to derive the antenna elements position that is critical for AOA estimation. In this case (circular motion), the radius of the circular array and the angular velocity were required.

The outputs of the z gyro directly give the angular velocity. The radius of the circular array can be estimated as:

\[ r = -\frac{a}{\omega^2} \]  

where \( r \) is the radius, \( a \) is the acceleration in the x direction and \( \omega \) is the angular velocity. Figures 12 and 13 show the outputs of the z gyro and x accelerometers, respectively (in this particular application the outputs of other accelerometer and gyro were just noise). Because of the rapid angular velocity (144 degrees/s) and smooth antenna motion, the IMU can precisely estimate the revolution time, which is 2.5 second. The precision of the circular table is such that the exact trajectory is initially precisely known and can therefore be used to assess performance. The IMU output is then used independently to obtain an approximation of the actual trajectory from which the AOA performance degradation can be derived. Experimental results based on Figures 12 and 13 give about 1 cm radius estimation errors. Experimental results with the IMU in the circular motion case show acceptable accuracy. In the arbitrary motion case, the accuracy of the trajectory estimation depends on the changing rate of the trajectory and the estimation algorithms, which make it difficult in general.
Figures 14 and 15 show the field data collection equipment, transmitter and receiver geometry. Figure 15 also gives the actual AOA between the transmitter and receiver to compare the results. AOA estimation by MUSIC requires knowing the number of incoming signal (signal sub-space dimension). In this paper, the AIC algorithm was used for source number estimation (Liberti & Rappaport 1999). Based on Figures 11 and 15, the jammer signals come from the east and the synthetic array measures the azimuth angle from the x axis which is laid in a south direction. With this configuration, the true azimuth angle is about 90 degrees.
To evaluate the performance of the synthetic array precisely, a total station was used to measure the coordinates of the array. The configuration of the coordinate estimation of the synthetic array is shown in Figure 16. The laser transmitter was placed at the transmitter antenna location and two reflectors were mounted on the center of the array and the place of the single antenna. Based on this configuration, we can precisely estimate the azimuth and elevation angle between the antenna array and the transmitter. The measured azimuth and elevation angles were 88 and 16 degrees, respectively. The AOA estimated by MUSIC are shown in Figure 17. Experimental results show that there is one resolvable signal with azimuth and elevation angles of 92 and 19 degrees, respectively. Estimated errors are at the level of 4 degrees in each component. The sources of these errors are caused by limitations such as the synchronization of the circular table with the receiver in terms of time of data collection, stationarity of the channel, coherency among impinging signals, the number of sensors and signal model assumptions. To validate the results, a second experiment was performed with the same coordinates of the synthetic array. The estimated azimuth and elevation angles were 82 and 20 degrees in this case. The estimated errors were therefore 6 degrees in azimuth and 4 degrees in elevation. In this second experiment, the covariance matrix was nearly singular, which affected the AOA estimation accuracy.
VII. CONCLUSIONS

In this paper, an approach for the DOA estimation of GNSS jammer signals based on the synthetic array concept was presented. Different simulations examined design parameters and practical considerations. In order to estimate the trajectory of a moving antenna, a low cost IMU was employed. A precise circular table was used as a benchmark to compare the results of the trajectory estimation. Experimental results showed that the IMU could estimate the trajectory of the circular array with negligible errors. A synthetic antenna array was developed and tested to determine the AOA of incident signals with the MUSIC algorithm. Hardware complexity was reduced to one single channel receiver and one antenna element. To determine the applicability and accuracy of the proposed method, a test was successfully performed with known direction of jammer signals to independently verify the effectiveness of the method.

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