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An Investigtaion into the Effect of Antenna Array Geometry on TDOA Accuracy and Coverage

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An Investigation into the Effect of Antenna Array Geometry on TDOA Accuracy and Coverage

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL MEMORANDUM
DREO TM 1999-066
June 1999

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ABSTRACT

In this technical note, we make an initial study of the effect of sensor geometry on the accuracy and coverage of Chan's Time Difference Of Arrival (TDOA) geolocation algorithm. Chan's algorithm is widely regarded as the most suitable method for hyperbolic location. A brief overview of the algorithm is presented followed by simulation results and discussion of its implementation with varied antenna geometries. We then look at the effect of a non-line-of-sight (NLOS) path on the accuracy of predictions with a possible solution to this problem. Finally we see the effect of increased TDOA error on position estimates.

RÉSUMÉ

Cette note technique contient une étude préliminaire des effets de la disposition des capteurs omnidirectionels sur la précision et la couverture de l'algorithme de géolocation de Chan fondé sur la Différence des Temps d'Arrivée. (DTA). L'algorithme de Chan est généralement reconnu comme le meilleur pour la localisation hyperbolique. Une brève revue de l'algorithme est suivie de résultats de simulations et d'une discussion de sa mise en oeuvre avec différentes dispositions des antennes réceptrices. L'effet de l'absence de trajets directs sur la précision des résultats est étudié et une solution possible à ce problème est présentée. Finalement les effets des erreurs de mesures de la DTA sur les estimations de position sont analysées.

EXECUTIVE SUMMARY

In this document, an investigation is made to illustrate the effect of sensor geometry and multipath on the accuracy of position estimates made using the TDOA algorithm developed and analysed by Chan and Ho in [1]. It is shown that the problem of position estimation is greatly improved when the mobile to be located is contained within the sensor array, as is the case in the E911 problem currently being solved to meet a mandate put forth by the FCC in the United States of America. When the mobile is located far away from the array of sensors, accuracy is decreased considerably.

We have illustrated that circular arrays give a more uniform coverage in all directions than linear arrays when the array size is confined to the same area.

The largest source of error in geolocation can be attributed to multipath effects. When no line of sight exists between the transmitter and some of the sensors in the array, we show that it is better to determine which sensors are receiving signals with LOS statistics and exclude all other sensors from the array when performing the calculations for position estimation.

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1.0 INTRODUCTION

In recent years, the FCC's mandate for provision of mobile position location within 125 meters in 67% of all cases of Emergency 911 (E911) calls has increased the interest in position location algorithms. This interest has naturally been focussed on methods of position location (PL) that could be implemented within the existing cellular infrastructure. Time Difference of Arrival (TDOA) methods of PL have emerged as a possible solution capable of achieving this challenging objective.

Since most research has been focussed on implementation within existing systems, very little energy has been devoted to the study of the effect of sensor geometry on system accuracy and coverage. In this technical note, we make an initial investigation in this area. We present an overview of Chan and Ho's method of hyperbolic location followed by simulation results and discussion of antenna geometries for PL techniques.

2.0 THE CHAN METHOD OF HYPERBOLIC LOCATION

The method of hyperbolic location developed by Chan and Ho in [1] is generally accepted to be an efficient estimator of position location. In this section, we give a summary of the algorithm. For a complete derivation and analysis, see [1]. In communications systems, it is often not possible to obtain an accurate reading of the amount of time taken for a signal to travel from an emitter to a sensor. For this reason, time difference of arrival algorithms have been used, since accurate methods exist for determining the *difference* in time for a signal arriving at a pair of sensors. This time difference of arrival at a pair of sensors defines a hyperbola with foci at the sensors. With an array of sensors, multiple hyperbolae are defined with the intersection point (or least-squares solution) estimating the position of the emitter.

Defining $r_{i,j}^2$ to be the squared difference in propagation time for a signal arriving at a pair of antennas *i* and *j* and K_i as the squared distance of sensor *i* from the origin, the following matrices are defined:

$$\mathbf{h} = \frac{1}{2}\begin{bmatrix} r_{2,1}^2 - K_2 + K_1 \\ r_{3,1}^2 - K_3 + K_1 \\ \vdots \\ r_{M,1}^2 - K_M + K_1 \end{bmatrix}, \qquad \mathbf{G}_a = -\begin{bmatrix} x_{2,1} & y_{2,1} & r_{2,1} \\ x_{3,1} & y_{3,1} & r_{3,1} \\ \vdots & \vdots & \vdots \\ x_{M,1} & y_{M,1} & r_{3,1} \end{bmatrix} \tag{1}$$

where $x_{i,1}$ and $y_{i,1}$ represent the coordinate differences between the location of sensor *i*, (x_i, y_i), and sensor 1, (x_1, y_1). An initial estimate of the position $\mathbf{z}_a$ can be made by:

$$\mathbf{z}_a \approx (\mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a)^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{h}$$

(2)

where **Q** is the covariance matrix of the time difference of arrival measurements. **Q** can be approximated by a square matrix consisting of ones on the main diagonal and 0.5 in all other entries [1]. Once an initial estimate of $\mathbf{z}_a$ is made, a more accurate estimate can be obtained by

$$\mathbf{z}_a = (\mathbf{G}_a^T \Psi^{-1} \mathbf{G}_a)^{-1} \mathbf{G}_a^T \Psi^{-1} \mathbf{h}$$

(3)

where $\Psi = \mathbf{BQB}$ and $\mathbf{B} = diag\{r_2, r_3, ..., r_M\}$ is a square matrix, obtained through (2), with a main diagonal containing the estimated distance from the source to sensors $2 \ldots M$.

Once $\mathbf{z}_a$ is calculated, it is further refined through the following process. Firstly, the following matrices are calculated.

$$\mathbf{h}' = \begin{bmatrix} (z_{a,1} - x_1)^2 \\ (z_{a,2} - y_1)^2 \\ z_{a,3}^{\ 2} \end{bmatrix}, \qquad \mathbf{G}'_a = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 1 \end{bmatrix}$$

(4)

Then, for detecting signals that are located either within the array of sensors, or close to the array of sensors, the following intermediate quantity is calculated

$$\mathbf{z}'_a = (\mathbf{G}'^T_a \Psi'^{-1} \mathbf{G}'_a)^{-1} \mathbf{G}'^T_a \Psi'^{-1} \mathbf{h}'$$

(5)

where $\Psi' = 4\mathbf{B}'(\mathbf{G}_a^T \Psi^{-1} \mathbf{G}_a)^{-1} \mathbf{B}'$ and $\mathbf{B}' = diag\{z_{a,1} - x_1, z_{a,2} - y_1, z_{a,3}\}$.

If, however, the source of the signal is located far away from the sensor array, the following equation can be used to determine the intermediate quantity $\mathbf{z}_a'$.

$$\mathbf{z}'_a \approx (\mathbf{G}'^T_a \mathbf{B}'^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a \mathbf{B}'^{-1} \mathbf{G}'_a)^{-1} \mathbf{G}'^T_a \mathbf{B}'^{-1} \mathbf{G}_a^T \mathbf{Q}^{-1} \mathbf{G}_a \mathbf{B}'^{-1} \mathbf{h}$$

(6)

Finally, the coordinates of the emitter can be found by adding the coordinates of sensor 1 to the square root of the intermediate quantity $\mathbf{z}_a'$. The solution is

$$\mathbf{z}_p = \sqrt{\mathbf{z}'_a} + \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}$$

or

$$\mathbf{z}_p = -\sqrt{\mathbf{z}'_a} + \begin{bmatrix} x_1 \\ y_1 \end{bmatrix}$$

(7)

With certain array geometries, this algorithm produces singular results. In particular, when using a linear array of sensors, the algorithm must be modified as follows. With an array of sensors defined by $y_i = ax_i + b$, $i = 1,2,\cdots,M$, where *a* and *b* are constants, the position estimates can be made similarly to those for an arbitrary array.

$$\mathbf{z}_l = (\mathbf{G}_l^T \Psi^{-1} \mathbf{G}_l)^{-1} \mathbf{G}_l^T \Psi^{-1} \mathbf{h}$$

(8)

where $\mathbf{z}_l$ in this case is an intermediate quantity used to calculate the emitter position *(x,y)*, and is of the form

$$\mathbf{z}_l = \begin{bmatrix} x + ay \\ r_1 \end{bmatrix}.$$

(9)

$$\mathbf{G}_a = -\begin{bmatrix} x_{2,1} & r_{2,1} \\ x_{3,1} & r_{3,1} \\ \vdots & \vdots \\ x_{M,1} & r_{M,1} \end{bmatrix}$$

(10)

and **h** and Ψ are as defined for an arbitrary array, the final solution *(x,y)* can be calculated using the quadratic equation

$$y = \frac{-E \pm \sqrt{E^2 - 4AC}}{2A},$$
$$x = w - ay$$

where

$$A = 1 + a^2, E = -2(aw + b), C = K_1 - 2x_1 w + w^2 - r_1^2$$

(11)

Note that if the array of sensors is on the x-axis, then $a = b = E = 0$, and the quadratic simplifies considerably. Also, the double solution to the quadratic equation illustrates that a linear array cannot determine from which side a signal is arriving.

3.0 SIMULATION METHODOLOGY

In this section, three distinct effects on position location accuracy are explored. First we explore the effect of sensor geometry and the number of sensors on the expected accuracy of PL estimations. Then we look at the effect of a NLOS path on the accuracy of predictions. We see one method of combating NLOS paths. Finally we investigate the effect of error variance of the TDOA measurements due to environmental effects and system limitations on the accuracy of PL measurements.

How to read the plots in this paper

Throughout the results section of this paper, plots are presented depicting the accuracy of the PL estimates as a function of position. In these plots, the colour of a certain location indicates the estimated accuracy of a measurement taken there. These measurements are a function of several variables, including position, antenna array geometry, and inaccuracy of TDOA measurements. Throughout the rest of this document, each figure consists of a pair of plots: a plot showing the accuracy of TDOA position estimates (on the left), and another showing the positions of the sensors used in the Monte Carlo simulation (on the right) Take, for example, figure 1:

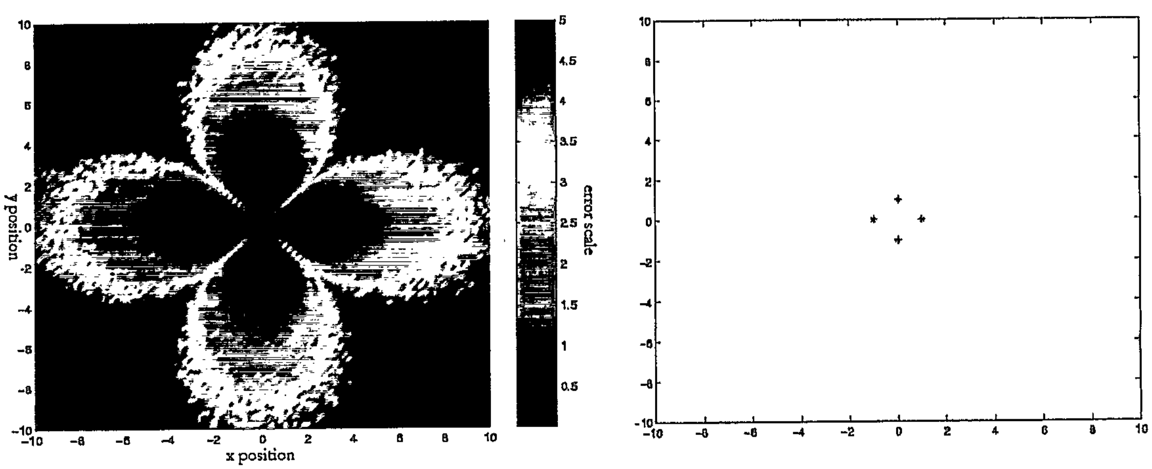

Figure 1 Coverage of a 4-element circular array with TDOA error $\sigma^2 = 0.001$ units

For this plot, the simulated sensors are located on a unit circle at the origin (i.e. (1,0), (0,1), (-1,0), and (0,-1)), as depicted in the plot on the right side of the figure, and the TDOA measurement error is assumed to be Gaussian distributed with a variance of 0.001 units. In generating this plot, the exact distances between an emitter at *(x,y)* and the sensors are calculated. The differences between these distances are then computed and are corrupted by a Gaussian distributed random variable with zero mean and variance of 0.001. This is designed to account for signals received with time errors at each of the receivers. The simulation is then repeated at each point, *(x,y);* 200 estimates are calculated for each point, and the mean error of these estimates is recorded. Figure 1 plots these mean error values as a function of colour. As can be seen in the plot and the associated colour bar, an emitter located at (0,-6) lies on the transition from light blue to dark blue, illustrating that the average position estimate error at this point is about 1.7 units.

4.0 EFFECTS OF ARRAY SENSOR GEOMETRY ON COVERAGE

4.1 Case 1 - Array Elements Widely Spaced

In the problem of TDOA position estimation within the context of E911 service, the neighboring base-stations act as sensors for determining time differences. In this situation, the mobile to be located is found within the sensor array. The following diagram shows the expected accuracy of PL estimates throughout a cell. As can be seen, the coverage is relatively uniform throughout the cell.

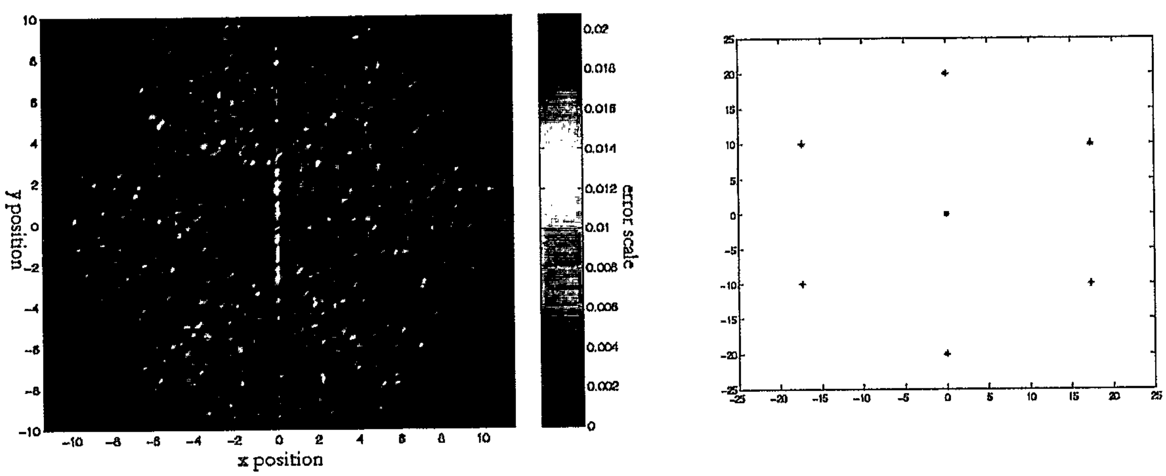

Figure 2. Position location accuracy with 5 nearest base-stations

This simulation was run with a TDOA measurement error variance of 0.001 units. In this simulation, for each position *(x,y)*, the 5 nearest base-stations to the emitter were used as sensors. 200 position estimates were made for an emitter at each point, and the mean error value is plotted for each point as a function of colour. Mobiles located outside of the cell region are not considered.

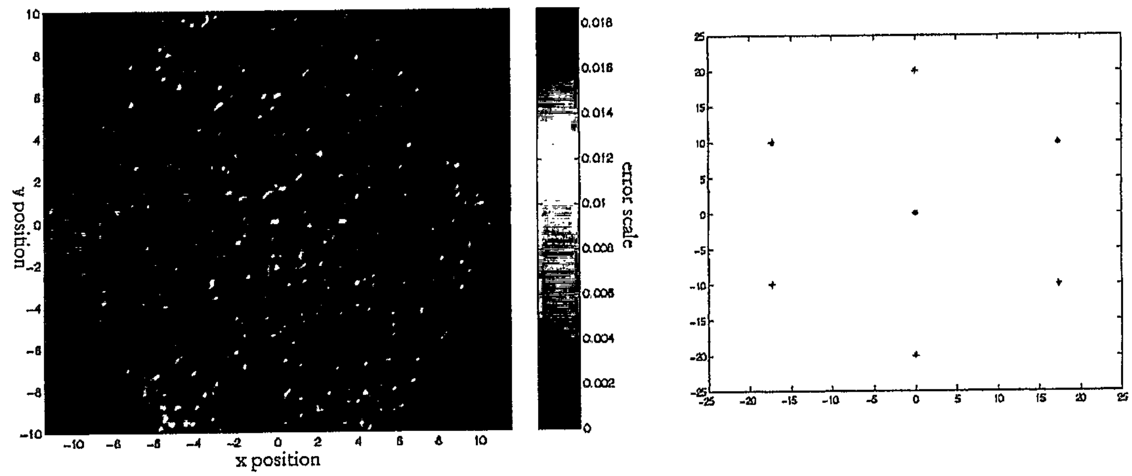

Figure 3. Position location accuracy with 6 nearest base-stations

As illustrated above, the expected PL readings taken within a cell using the surrounding base stations as TDOA sensors yield a very consistent level of accuracy throughout the cell. This simplifies considerably the analysis of system performance as it can be assumed to be independent of the mobile's location.

In the following sections, we illustrate some of the disadvantages of attempting PL when the mobile to be located is not contained within the array of sensors, or is located at some distance from the sensor array.

4.2 Case 2 – Linear Array Geometry

In this section, we compare the coverage of linear arrays of sensors and circular arrays of sensors. Traditionally, a linear array of sensors has been used in PL problems, as the general direction of the target mobile was typically known. Linear arrays suffer from the problem that two signals arriving from locations that are mirror images of one another in the plane of the array cannot be distinguished from one another. Using the TDOA algorithm for linear arrays outlined earlier in this document, the coverage was measured. For a four-sensor array with sensors located at (±1,0), and (±1/3,0), the coverage looks like this:

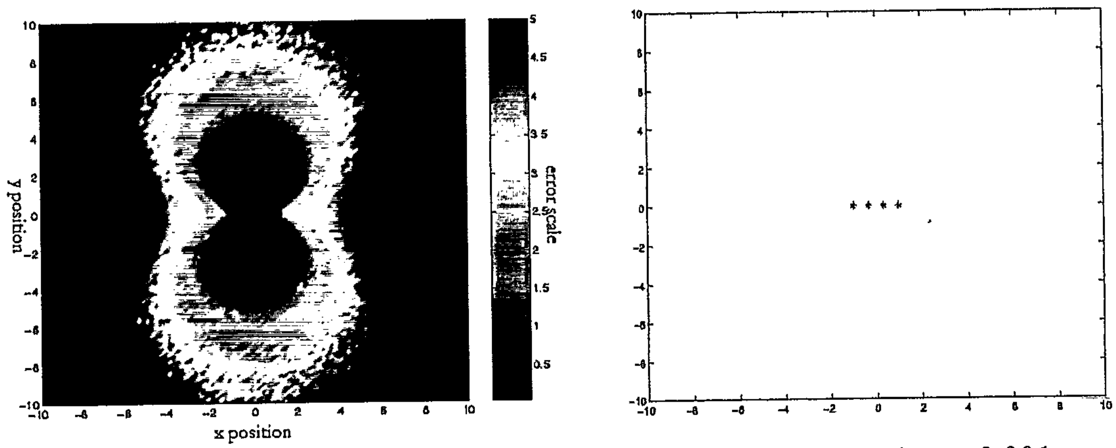

Figure 4. Four element linear array TDOA error variance 0.001

If the number of sensors is increased dramatically to a nine-sensor array with the same total length (i.e. sensors located at (±1,0), (±3/4,0), (±1/2,0), (±1/4,0) and (0,0)), the coverage pattern looks like:

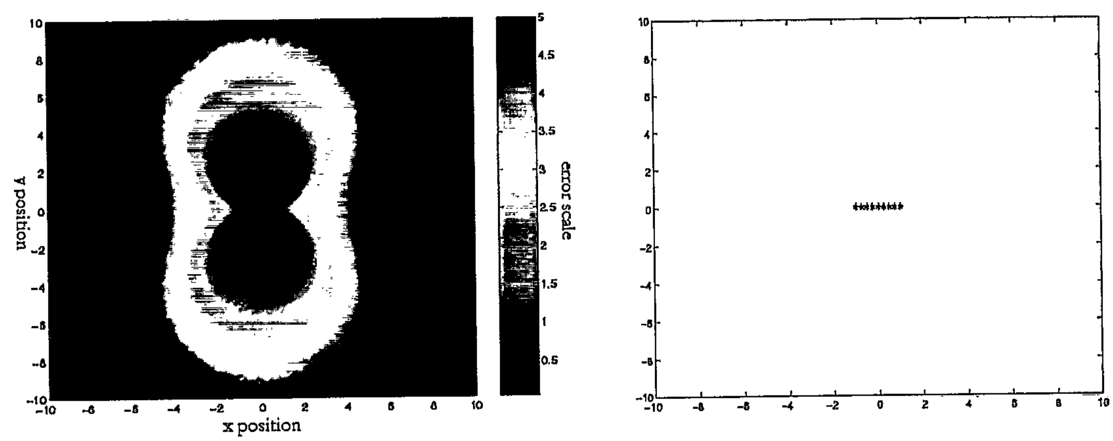

Figure 5. Nine element linear array TDOA error variance 0.001

These plots illustrate some of the difficulty that can be expected in trying to locate mobiles that are situated away from the array of sensors. Although the same level of error was assumed in both cases, the average error of a mobile located 6 units away from the centre of the linear array is at best 100 times the error expected using the standard hexagonal base station geometry earlier in this document.

4.3 Case 3 – Circular Array Geometry

When the same simulations are run using a circular array instead of a linear array, the following results are found: First, the problem with the linear array of estimating the position only on one side of the array is avoided. Secondly, as will be illustrated, above a certain number of antenna elements, approximately equal coverage is available in all directions from the antenna array. Thirdly, the linear array appears to provide no increase in coverage in any direction over the circular array.

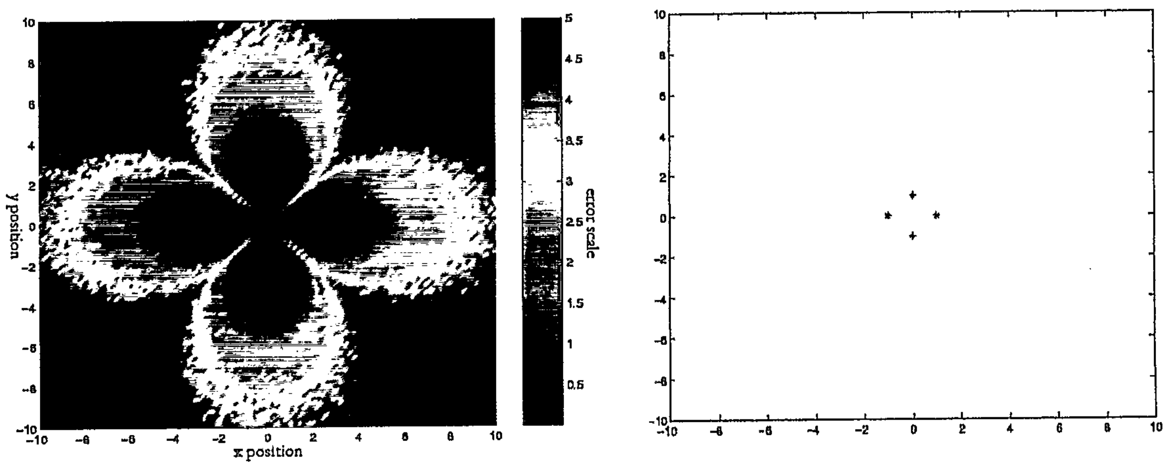

Figure 6. Four element circular array TDOA error variance 0.001

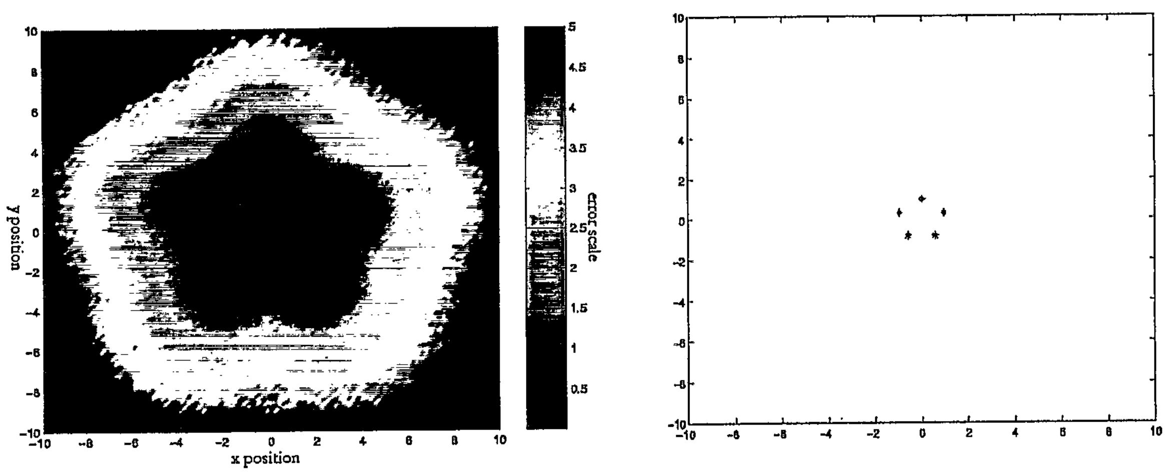

Figure 7. Five element circular array, TDOA error variance 0.001

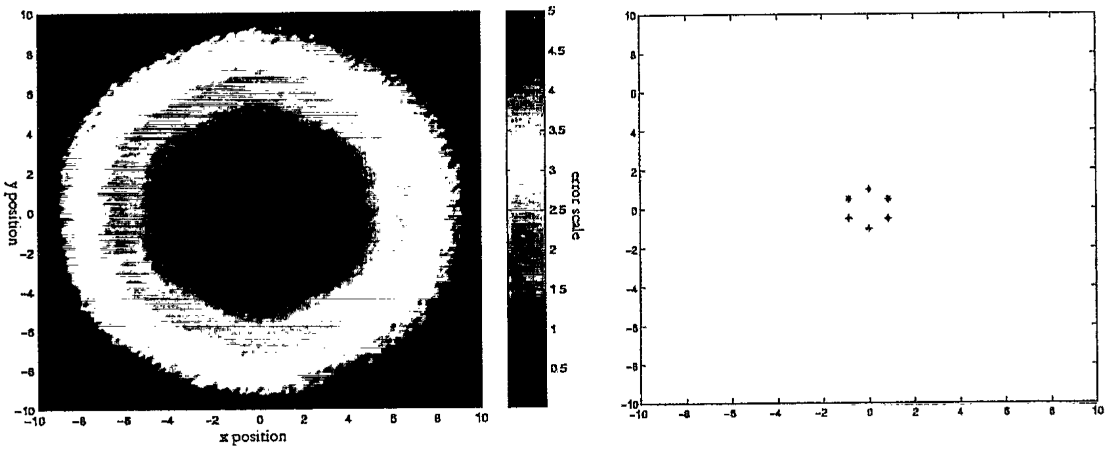

Figure 8. Six element circular array, TDOA error variance 0.001

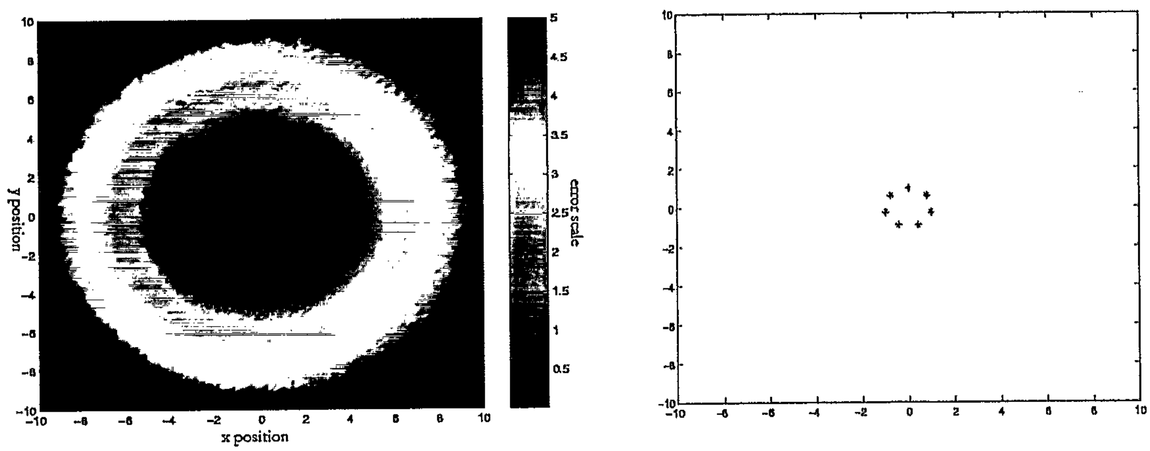

Figure 9. Seven element circular array, TDOA error variance 0.001

5.0 EFFECTS OF MULTIPATH

It is well known that one of the biggest sources of error in TDOA position estimation is due to multipath effects. In this section we first see the effect of TDOA estimation when one sensor in an array does not have a direct line of sight path from the emitter. We then investigate one means to combat NLOS (no line of sight) paths in TDOA.

5.1 Effect of NLOS Paths on Estimate Accuracy

To illustrate the effect of including a sensor receiving NLOS information in TDOA estimation, a six-element array was simulated with the sensor at 30° designated to receive the NLOS signal. The following series of plots shows the effect on coverage when the path from the emitter to the receiver is increased by factors of 1.001, 1.005, 1.01, and 1.05

respectively. Please note in these simulations that no other error was added to the TDOA measurements in order to isolate the effects of the NLOS path.

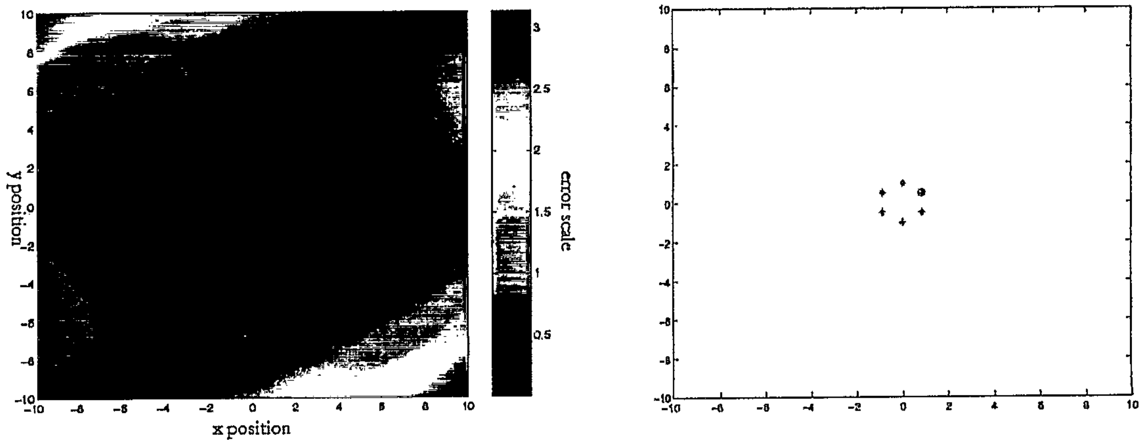

Figure 10. Six element circular array, one sensor with 0.1% NLOS error

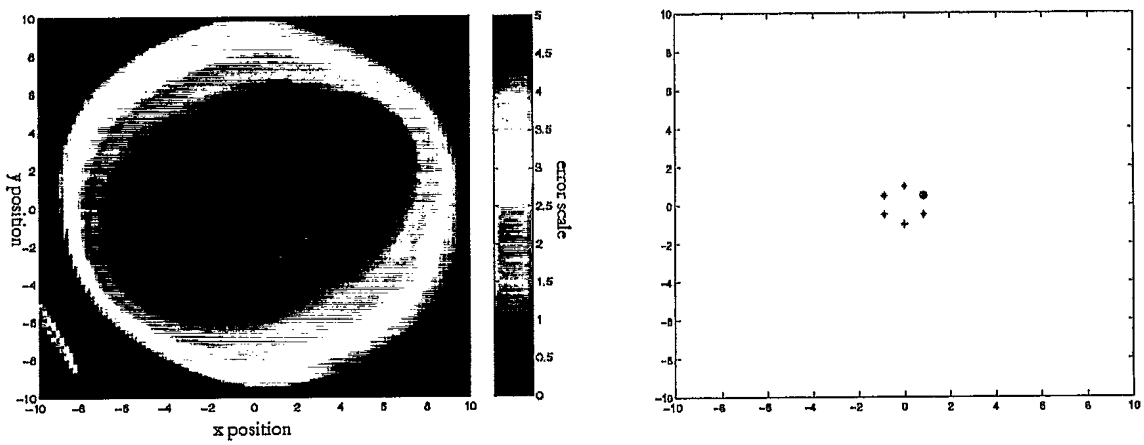

Figure 11. Six element circular array, one sensor with 0.5% NLOS error

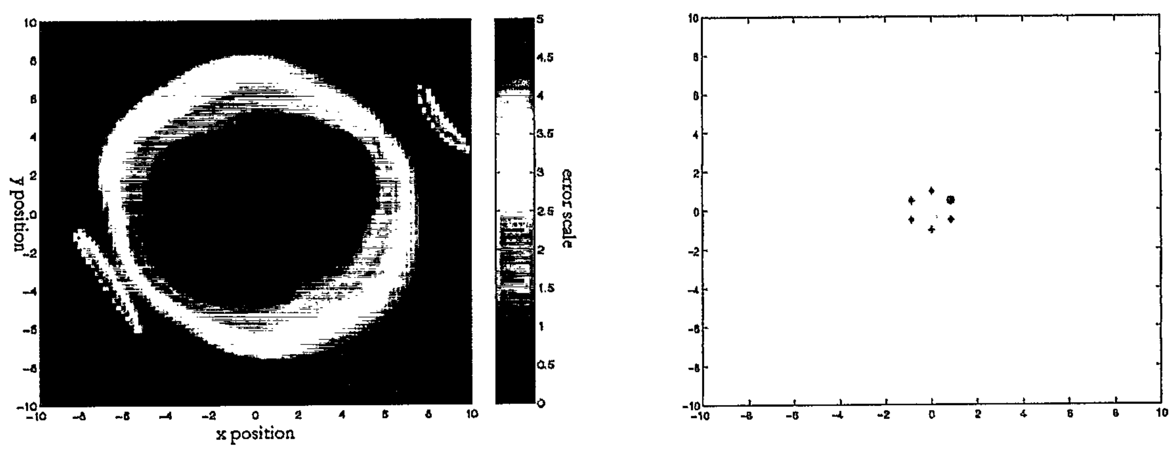

Figure 12. Six element array, one sensor with 1% NLOS error

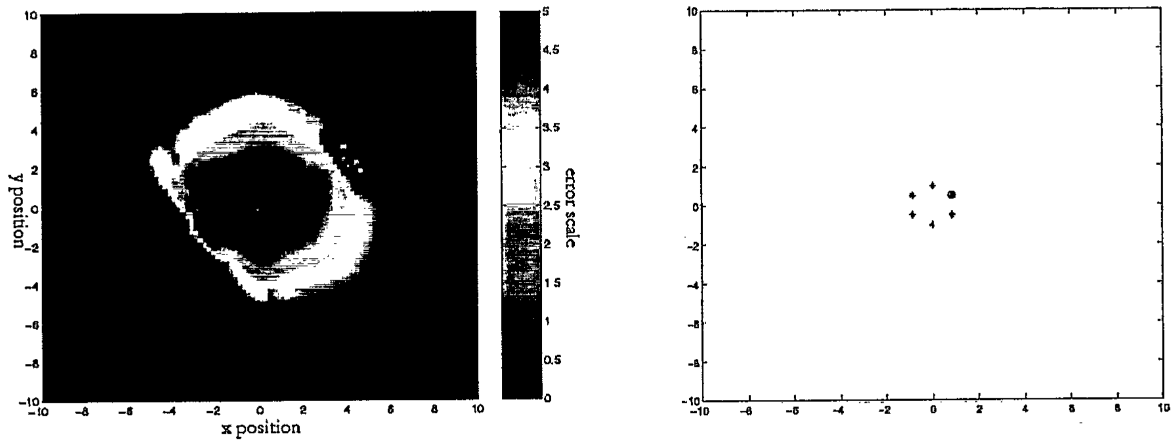

Figure 13. Six element array, one sensor with 5% NLOS error

5.2 Avoiding NLOS problems

As can be seen from the previous plots, a small error in measurement time due to NLOS between the transmitter and one of the sensors can contribute a very large error to TDOA estimates. One possible solution to this problem is not to include sensors receiving NLOS signals within the antenna array. This is possible due to the nature of NLOS signals. Signals that have a direct line of sight between a transmitter and receiver are received with different statistics than signals with a line of sight. If a signal received at a sensor within an array has a power envelope that is Rayleigh distributed (NLOS), then that sensor is not included in the TDOA estimates. We now show the effect of removing sensors from a six element circular array.

5.3 Effect of Isolating and Ignoring NLOS Signals

Through the use of goodness-of-fit testing it is possible to determine the existence and relative strength of a LOS path amidst NLOS paths. As shown in the previous section, even a very small percentage increase in path length due to an indirect route from the transmitter to the receiver can cause large errors in the location estimate. By determining if the signal received at each of the sensors has a LOS component, it is possible to include signals that have been received with a LOS component. This essentially removes a sensor from the array. The following series of figures illustrates the effect of removing sensors from a six element array.

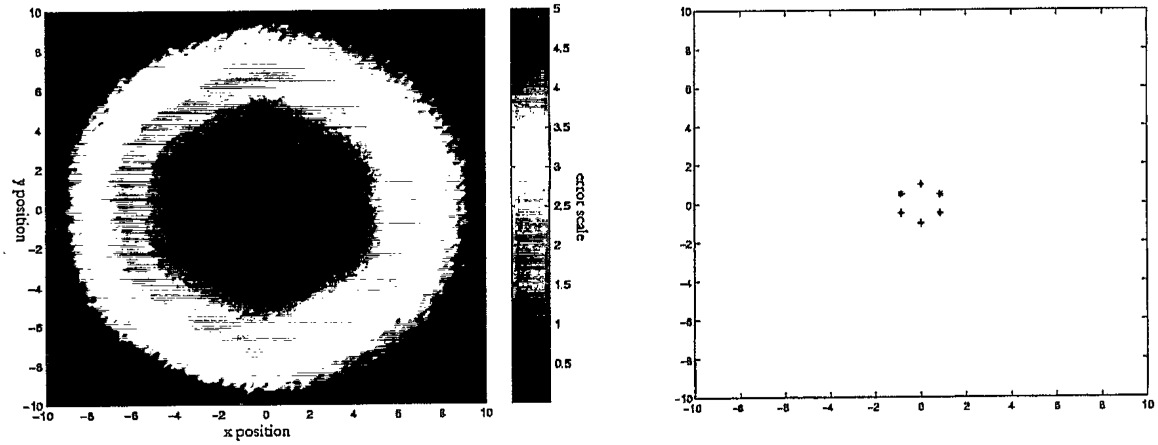

Figure 14. Six element circular, TDOA error variance 0.001, all LOS

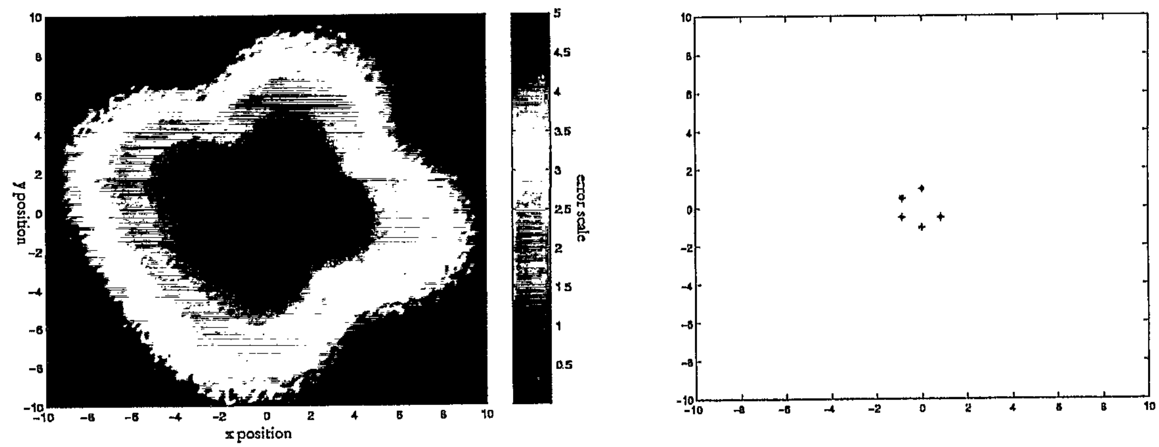

Figure 15. Six element circular, TDOA Variance 0.001, NLOS sensor at 30°

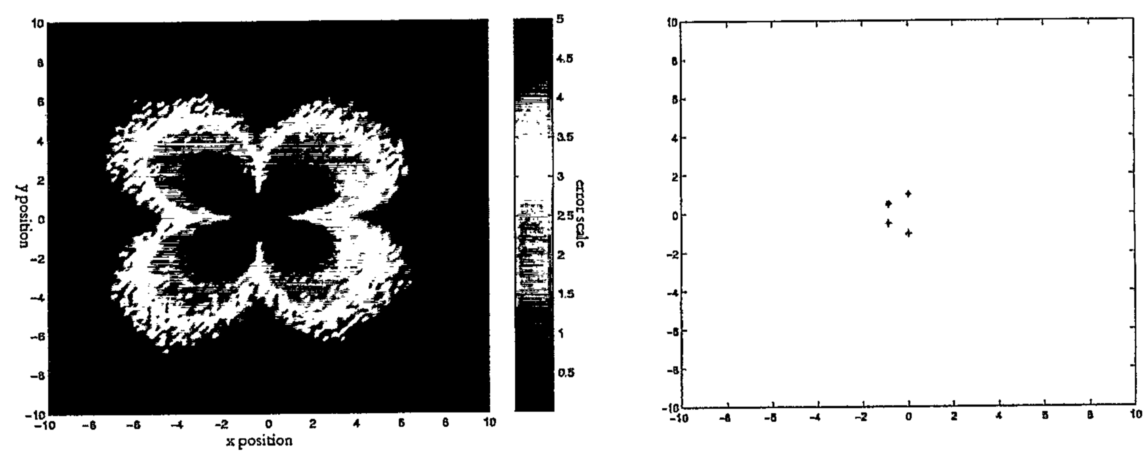

Figure 16. Six element circular, TDOA variance 0.001, NLOS elements ±30°

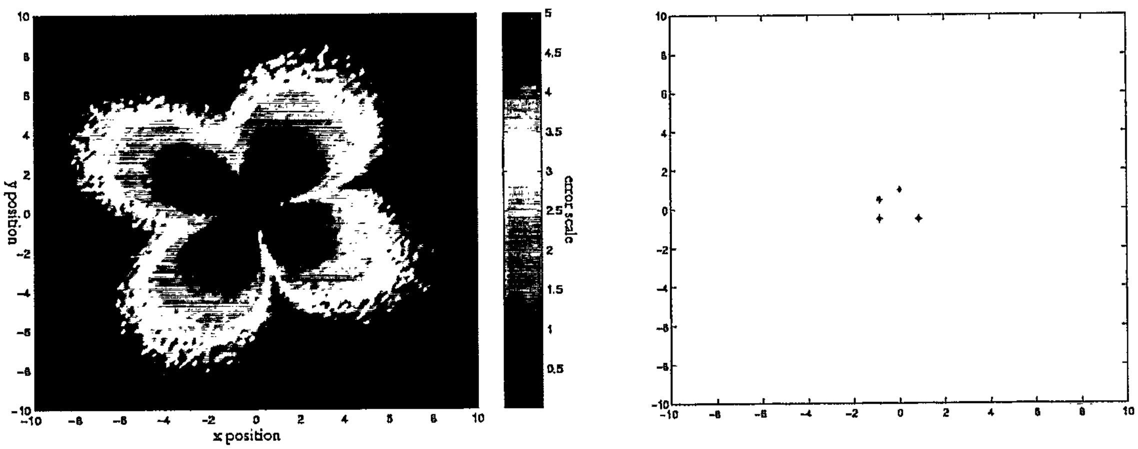

Figure 17. Six element circular, TDOA variance 0.001, NLOS elements +30°, -90°

As can be seen in this series of figures, removing sensors from the array degrades the accuracy of position estimates; however, this degradation in performance is preferable to the errors encountered due to NLOS paths.

6.0 EFFECT OF TDOA ERROR ON PL ACCURACY

Throughout most of the simulations run in this report, the error on the TDOA measurements had a variance of 0.001 units. In this section we explore the effect of changing this variance on the average accuracy of the TDOA estimates. It is assumed that the time errors on the signal received at the individual sensors are uncorrelated and have an unknown distribution. The correlation matrix of the TDOA values is assumed to consist of ones on the main diagonal with all other matrix values equal to 0.5.

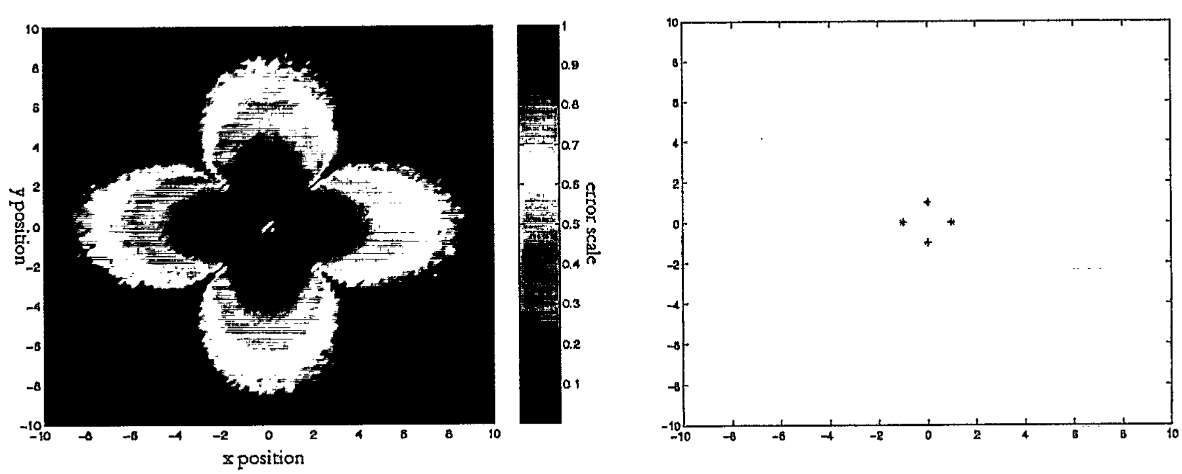

Figure 18. Four element circular array, TDOA error variance = 0.0001

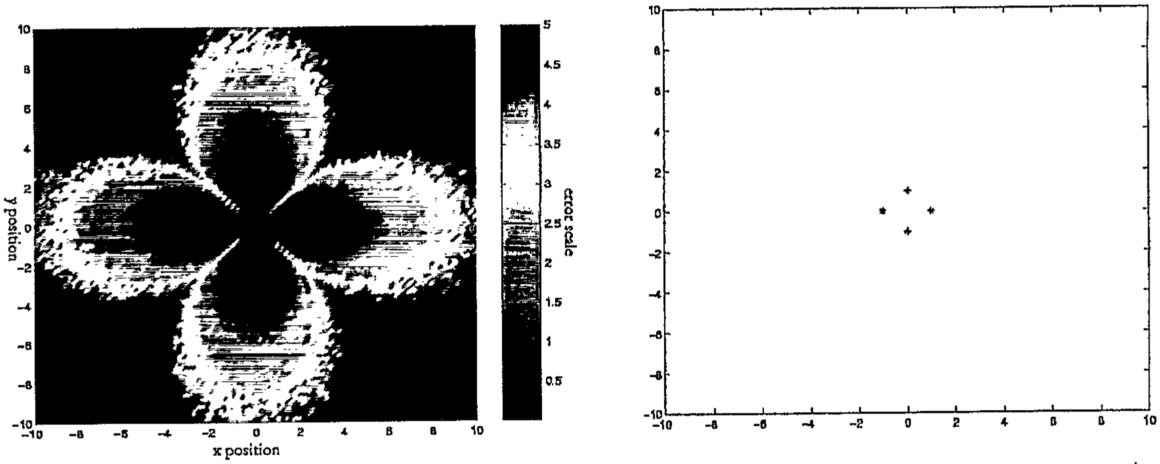

Figure 19. Four element circular array, TDOA variance = 0.001

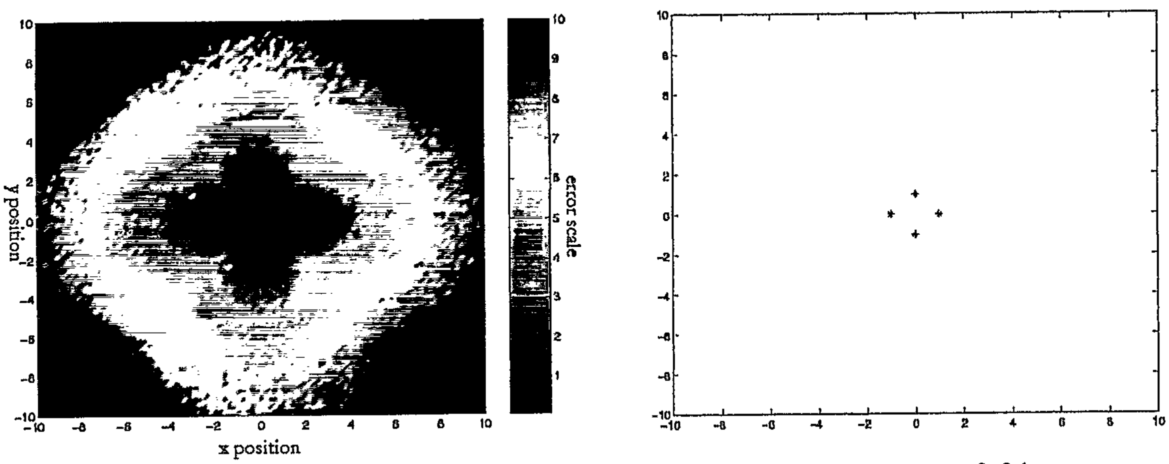

Figure 20. Four element circular array, TDOA variance = 0.01

Figures 18-20 illustrate that the greater the uncertainty of the time difference measurements, the larger the error on the location estimates. Given typical time difference error values for a specific platform in a given environment, a more complete prediction of position estimation errors can be derived.

7.0 CONCLUSION

In this document, an investigation was made to illustrate the effect of sensor geometry and multipath on the accuracy of position estimates made using the TDOA algorithm developed and analysed in [1]. It was shown that the problem of position estimation is greatly improved when the mobile to be located is contained within the sensor array, as is the case in the E911 problem currently being solved to meet a mandate put forth by the FCC in the United States of America. When the mobile is located far away from the array of sensors, accuracy is decreased considerably.

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[1] Y.T. Chan and K.C. Ho. "A Simple and Efficient Estimator for Hyperbolic Location". *IEEE Transactions on Signal Processing*, 42(8)1905-1915, 1994.

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(U) In this technical note, we make an initial study of the effect of sensor geometry on the accuracy and coverage of Chan's Time Difference Of Arrival (TDOA) geolocation algorithm. Chan's algorithm is widely regarded as the most suitable method for hyperbolic location. A brief overview of the algorithm is presented followed by simulation results and discussion of its implementation with varied antenna geometries. We then look at the effect of a non-line-of-sight (NLOS) path on the accuracy of predictions with a possible solution to this problem. Finally we see the effect of increased TDOA error on position estimates.

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