AFRL-SN-RS-TR-1999-36
Final Technical Report
March 1999

ADAPTIVE NULLING WITH A CYLINDRICAL ARRAY

University of Nevada Reno

Randy L. Haupt

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
ROME RESEARCH SITE
ROME, NEW YORK

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-SN-RS-TR-1999-36 has been reviewed and is approved for publication.

APPROVED: Hugh L. Southall

HUGH L. SOUTHALL
Project Engineer

FOR THE DIRECTOR: Robert V. McGahan

ROBERT V. McGAHAN, Technical Advisor
Electromagnetics Technology Division
Sensors Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1999	Final Mar 98 - Aug 98

4. TITLE AND SUBTITLE

ADAPTIVE NULLING WITH A CYLINDRICAL ARRAY

5. FUNDING NUMBERS

C - F30602-98-C-0033
PE - 62702F
PR - 4600
TA - 15
WU - P2

6. AUTHOR(S)

Randy L. Haupt

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Nevada Reno
Electrical Engineering Department/260
Reno NV 89557-0153

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory/SNHA
31 Grenier Street
Hanscom AFB MA 01731-3010

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFRL-SN-RS-TR-1999-36

11. SUPPLEMENTARY NOTES

Air Force Research Laboratory Project Engineer: Hugh L. Southall/SNHA/(617) 377-4284.

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A genetic algorithm is used to adaptively place a sidelobe null using a cylindrical array antenna. Results show that a null can be placed down to the noise floor of the measurement system within 20 to 50 power measurements. This approach to adaptive nulling is a viable means of quickly placing a null in the sidelobes of a phased array antenna.

14. SUBJECT TERMS

Phased Array Antennas, Genetic Algorithm, Adaptive Nulling, Adaptive Array Processing

15. NUMBER OF PAGES

36

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

Abstract

A genetic algorithm is used to adaptively place a null in the sidelobes of a cylindrical array antenna. The experiment took place at the Air Force Research Laboratory (AFRL)/Sensors Directorate, Hanscom AFB, MA. Results show that a null can be placed down to the noise floor of the measurment system within 20 to 50 power measurements. Thus, the approach to adaptive nulling is a viable means of quickly placing a null in the sidelobes of a phased array antenna.

Contents

Chapter 1

Background

Low sidelobes don't guarantee adequate reception of a desired signal in the presence of interfering sources. Adaptive nulling complements low sidelobe antennas by placing nulls in some of the low sidelobes to reject the strongest interfering sources. An ideal adaptive algorithm for a phased array antenna has the following desirable characteristics [1]:

- Places multiple deep nulls in the directions of interference,
- Rejects interference over the bandwidth of the antenna,
- Places the nulls very quickly,
- Complements existing phased array technology, and
- Minimizes pattern perturbations.

No adaptive algorithm meets all the characteristics. Selecting the adaptive algorithm, hence the desirable characteristics, depends upon the antenna, the cost, the performance requirements, and the interference environment.

Most adaptive antenna algorithms calculate the adapted weights by multiplying the quiescent amplitude and phase weights by the inverse of the sample covariance matrix to calculate the adapted weights. The resulting complex weights produce nulls in the far field pattern in the directions of interference. A sample covariance matrix is formed from the complex signals received at each element in the array. Although mathematically elegant and fast, these methods impose two impractical hardware requirements on the antenna array. First, the array must have an expensive receiver or correlator at each element. Most arrays have a single receiver at the output of the summer, so the antenna must be designed especially for the algorithm. Not only are multiple receivers expensive, but the receivers require a sophisticated method for calibration [2]. Second, the array must have variable analog amplitude and phase weights at each element. Usually, a phased array has only digital beam steering phase shifters at the elements. The feed network determines amplitude weights There are two problems from an algorithmic standpoint as well. First, digital phase shifters only approximate the phase calculated by the adaptive algorithms. The weight quantization error limits null placement. Second, these algorithms get stuck in local minima [3]. As a result, they do not find the optimum weights to reject the interference. Some common adaptive algorithms include the Least Mean Square Algorithm and the Howells-Applebaum Adaptive Processor. Examples can be found in references [3] and [4]. These methods are reasonably fast but the difficulties mentioned prohibit their wide-spread use, particularly for arrays with more than a handful of elements.

Another class of algorithms adjusts the phase shifter settings in order to reduce the total output power from the array [5], [6], [7]. These algorithms are cheap to implement because they use the existing array architecture without expensive additions, such as adjustable amplitude weights or correlators. Their drawbacks include slow convergence and possibly high pattern distortions.

This class has four approaches. The first approach is the random search algorithm [3]. Random search algorithms randomly sample a small fraction of all possible phase settings in search of the minimum output power. The search space for the current algorithm iteration can be narrowed around the regions of the best weights of the previous iteration. This approach is usually too slow for beam steering and radar applications. It is less likely to get stuck in a local minimum and does not require an expensive receiver at each element. A second approach forms an approximate numerical gradient and uses a steepest descent algorithm to find the minimum output power [8]. This approach has been experimentally implemented but is slow and gets stuck in local minima. As a result, the best phase settings to achieve appropriate nulls are usually not found. The third approach is a beam space algorithm that assumes the location of the interference is known. This algorithm forms a cancellation beam in the direction of the interference. The height of the cancellation beam is adjusted to cancel the sidelobes and place a null in the

Adaptive Algorithm	Advantages	Disadvantages
Random Search	hops out of local minima	very slow
Gradient	small pattern distortion	slow gets stuck in local minima
Beam Space	fast hops out of local minima small pattern distortions	must know locations of interference

Table 1.1: Advantages and disadvantages of three phase-only adaptive nulling algorithms.

interference direction. This approach is fast but requires knowledge of the interference locations and a reasonably accurate estimate of the amplitude and phase weights at each element. Table 1.1 summarizes the advantages and disadvantages of the three phase-only algorithms.

Serous drawbacks to current adaptive algorithms include: The adaptive algorithms

1. Require an expensive receiver at each element - makes array impractical to build.
2. Get stuck in local minima - doesn't use full potential of the antenna to reject interference.
3. Slowly converge - often not useful for radar or scanning applications.
4. Can't be implemented on existing antennas–they require adjustable amplitude weights and receivers at every element in addition to beam steering phase shifters.
5. Cause the main beam to move from its desired pointing direction.
6. Significantly raise the sidelobe levels of a low sidelobe array.

This report describes a simple technique suitable for implementation on phased arrays with attenuators and phase shifters. The approach combines a genetic algorithm with the hardware limitations of the array to place nulls in the directions of interference with small perturbations to the far field pattern. Excellent nulling results were obtained experimentally for a single

CW jammer. Nulls were placed down to the noise floor of the measurement system with as few as 24 power measurements.

Chapter 2

Experimental Antenna

The experimental phased array antenna was developed by the Air Force Research Laboratory (AFRL) at Hanscom AFB, MA for experiments with artificial intelligence techniques, such as neural networks and genetic algorithms. This antenna consists of 128 vertical columns of 16 dipoles equally spaced around a cylinder that is 41 inches in diameter (see Figure 2.1 and 2.2). The center frequency of the antenna is 5 GHz. Only eight of the elements are active at one time. Each element has an associated eight-bit phase shifter and eight-bit attenuator. A unique feature of the antenna is that all the elements can be connected to the power combiner at once as in a standard corporate feed for a phased array or one element at a time can be connected to the receiver, while the others are terminated in a matched loads. The latter mode simulates a digital beamforming antenna. In this application, we had all eight elements simultaneously connected to the power combiner. The eight element sector is 22.5° in arc (1/16 of the cylinder). The cylindrical array is 41 inches in diameter, making the element spacing about one inch or 0.42λ.

The antenna must be calibrated in order to form a main beam. In this case, the calibration or quiescent pattern is a 25 dB, $\bar{n} = 3$ Taylor taper. Phase shifters are adjusted to compensate for the curvature of the array.

Figure 2.3 is a picture of one of the two phase shifter/attenuator banks. The phase shifters have eight bits ranging from 1.4° to 180°. The attenuators are linear over an 80 dB range with the least significant bit having an attenuation of .3125 dB.

Figure 2.4 shows the antenna mounted in the anechoic chamber at AFRL. The chamber is 72 ft. × 36 ft. × 36 ft. A horn antenna serves as the feed and is located a distance of 47 ft. from the antenna. The source is CW and the receiver is an SA 1780. Measurements have a dynamic range of 50 dB. The antenna is controlled with a HT Basic program running on a PC. Figure 5 is a picture of the antenna measurement control room.

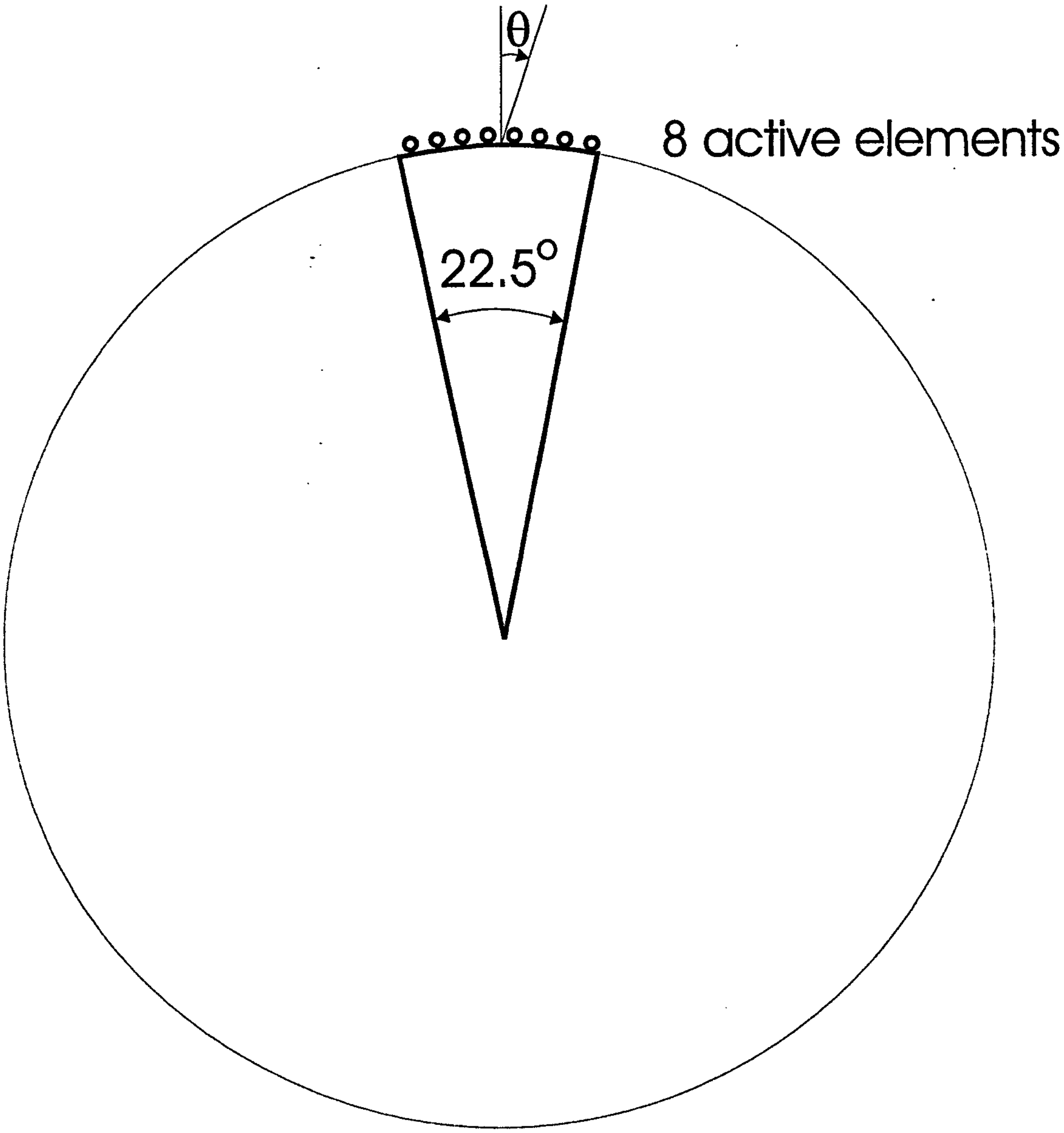

Figure 2.1: Diagram of the experimental antenna.

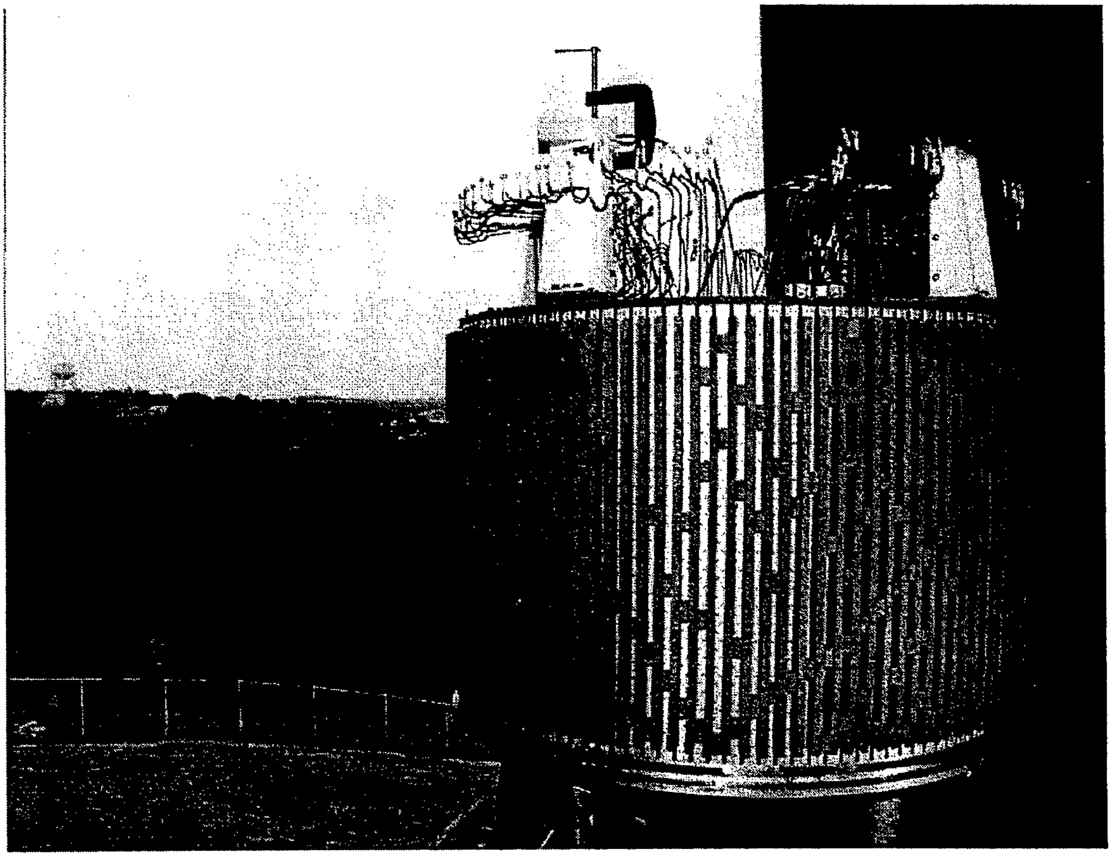

Figure 2.2: Close up picture of the cylindrical antenna array.

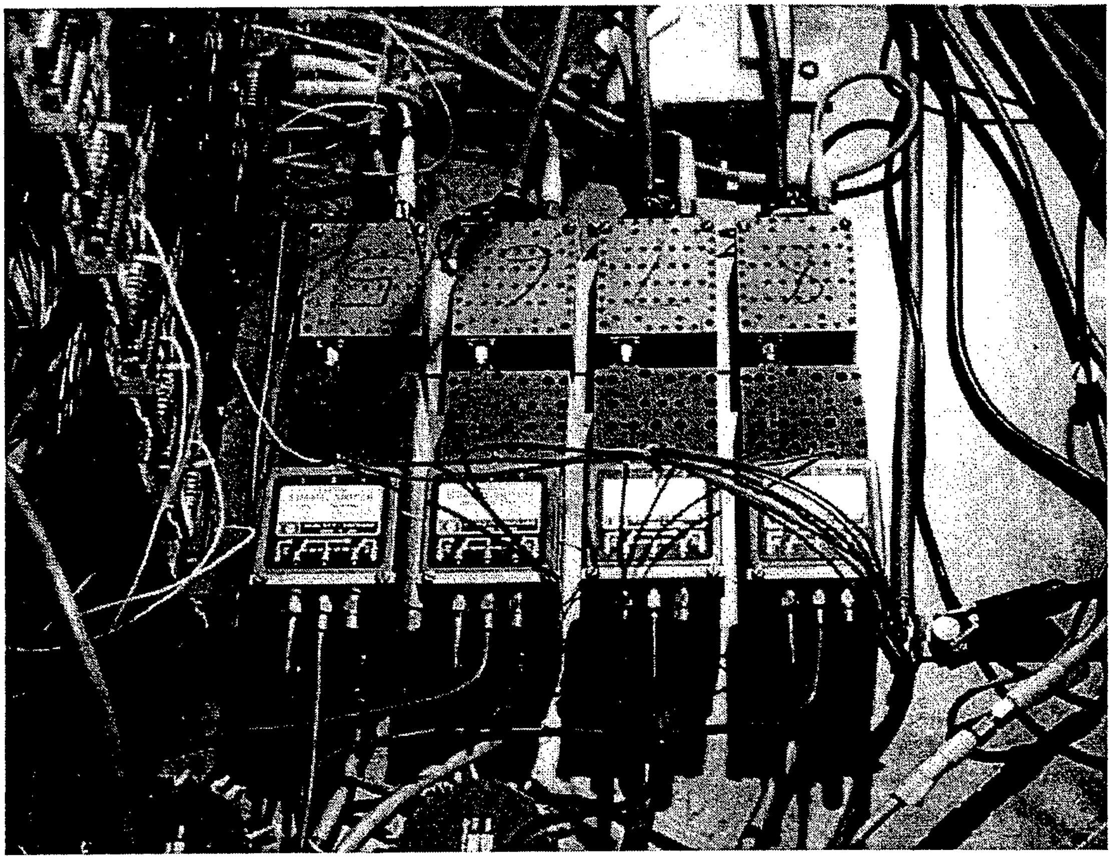

Figure 2.3: View of one bank of four phase shifters and attenuators inside the antenna. The phase shifters are the darker colored squares next to the attenuators that are lighter colored and numbered 5 through 8.

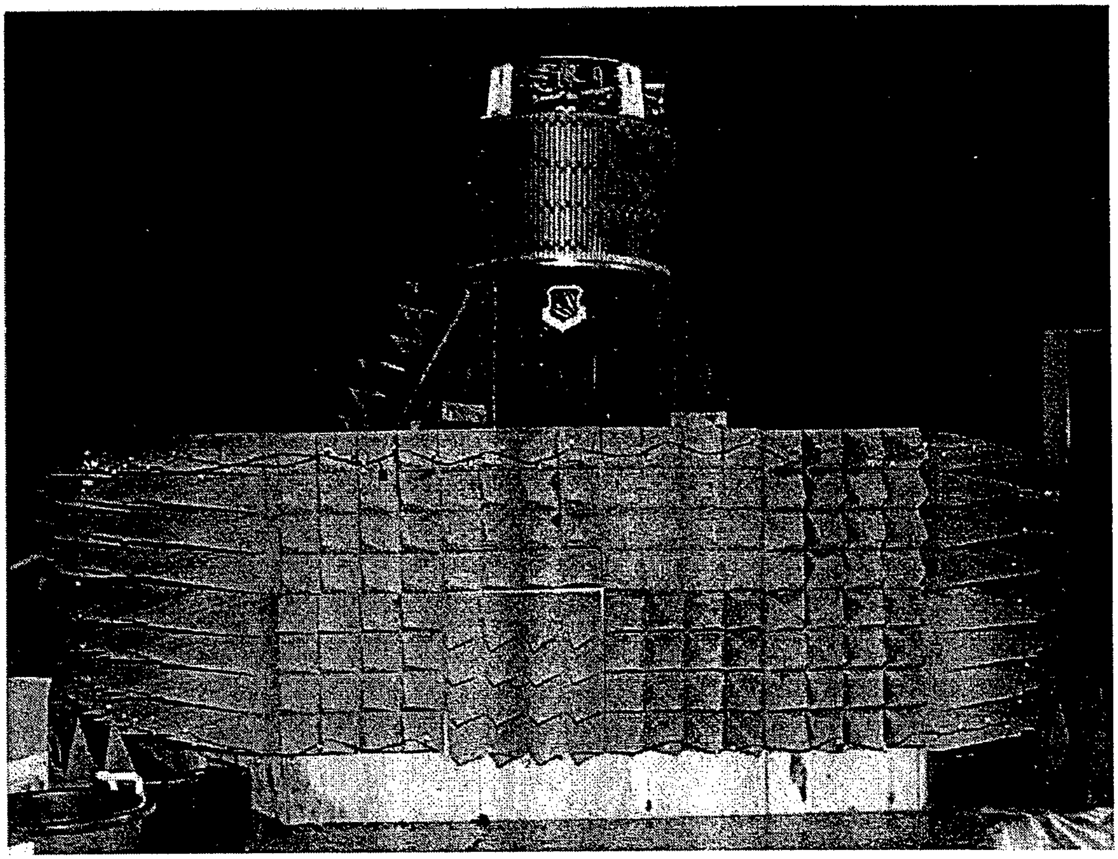

Figure 2.4: Picture of the antenna in the anechoic chamber where the measurements were made.

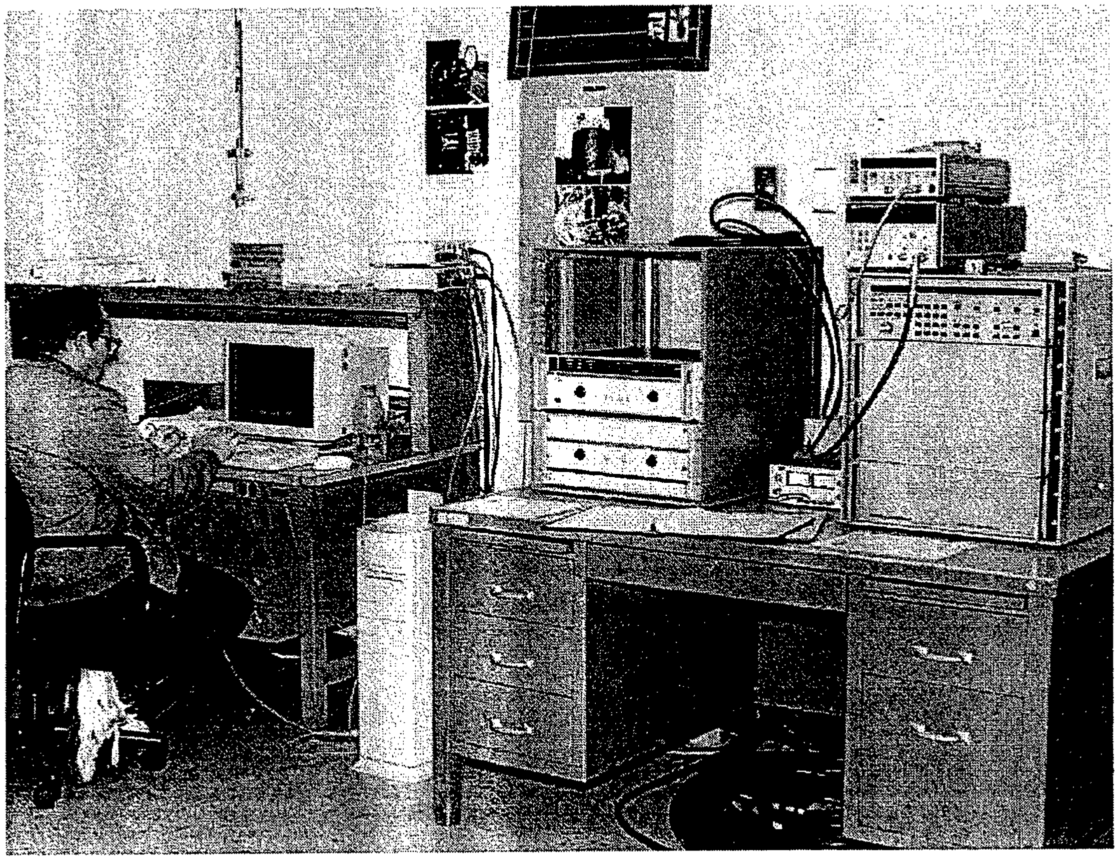

Figure 2.5: Picture of the antenna measurement equipment and a highly trained expert in antenna measurements.

Chapter 3

Adaptive Genetic Algorithm

An adaptive algorithm modifies the quantized phase and amplitude weights based on the total output power of the array. If no interference is present, then the algorithm tries to minimize the desired signal. The adaptive algorithm is based on a genetic algorithm and uses a limited number of bits of the digital phase shifters. A genetic algorithm is a computer program that finds an optimum solution by simulating evolution in nature. In this application the phase shifter settings evolve until the antenna pattern has nulls in the directions of jammers. A genetic algorithm was chosen for this application, because it is an efficient method to perform a search of a very large, discrete space of phase and amplitude settings for the minimum output power of the array. An adaptive phase-only array has 2^{NP} possible phase settings ($N =$ number of elements and $P =$ number of attenuator and phase shifter bits used for nulling), many corresponding to local minima in the total power output. Such a large number of phase settings and local minima make random search and gradient based algorithms impractical to use. Figure 3.1 shows a model of the adaptive antenna array.

Figure 3.2 shows a flowchart of the adaptive genetic algorithm ??. It begins with an initial population consisting of a matrix filled with random ones and zeros. Each row of the matrix (chromosome) consists of the nulling bits for each element placed side-by-side. There are NP columns and M rows. The output power corresponding to each chromosome in the matrix is measured and placed in a vector (Figure 3.3). M must be large enough to adequately search the solution space and help the genetic algorithm arrive at an excellent solution. On the other hand, M needs to be small, so the algorithm is fast. The speed of the algorithm is also a function of N and

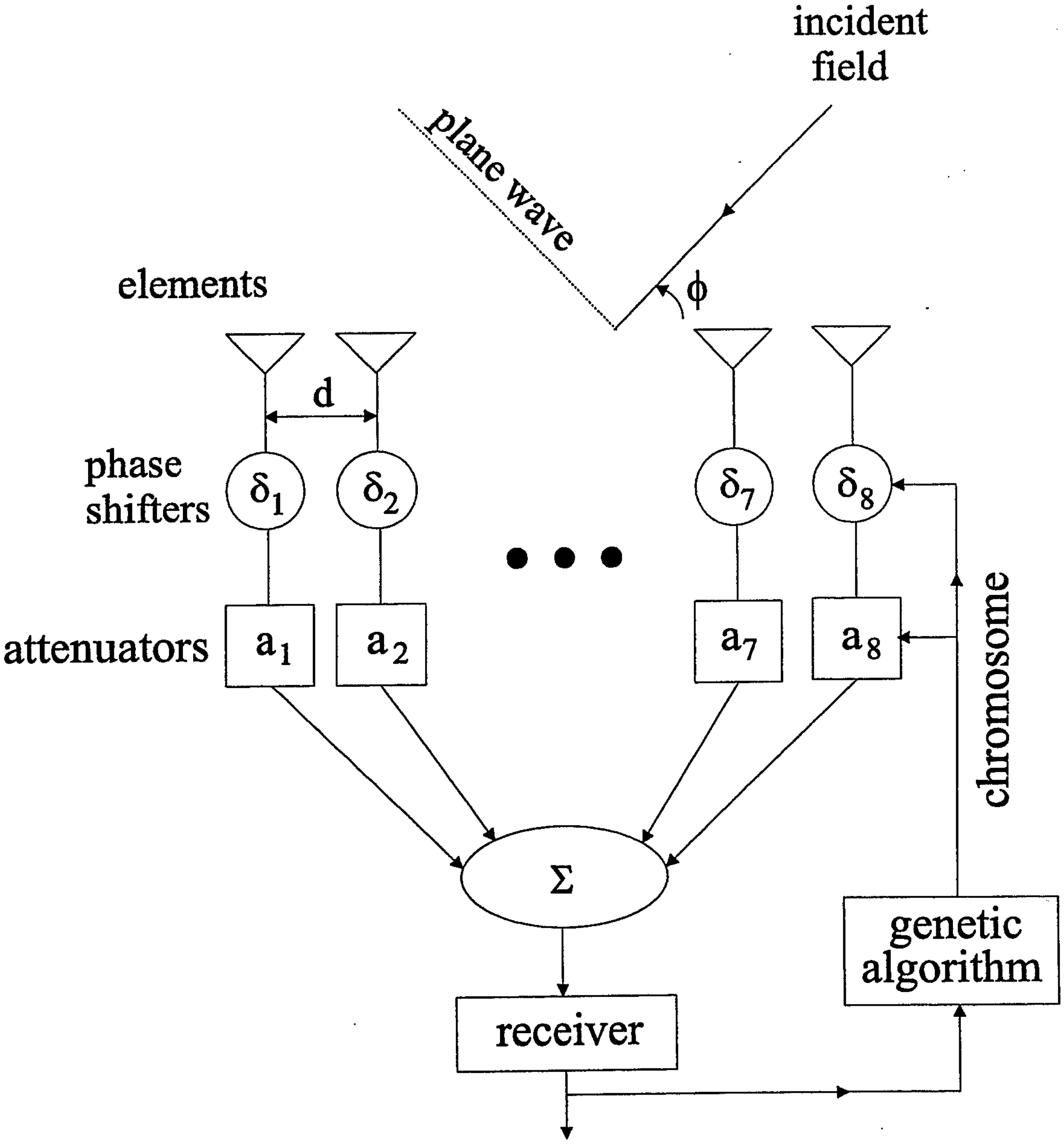

Figure 3.1: Model of the adaptive array.

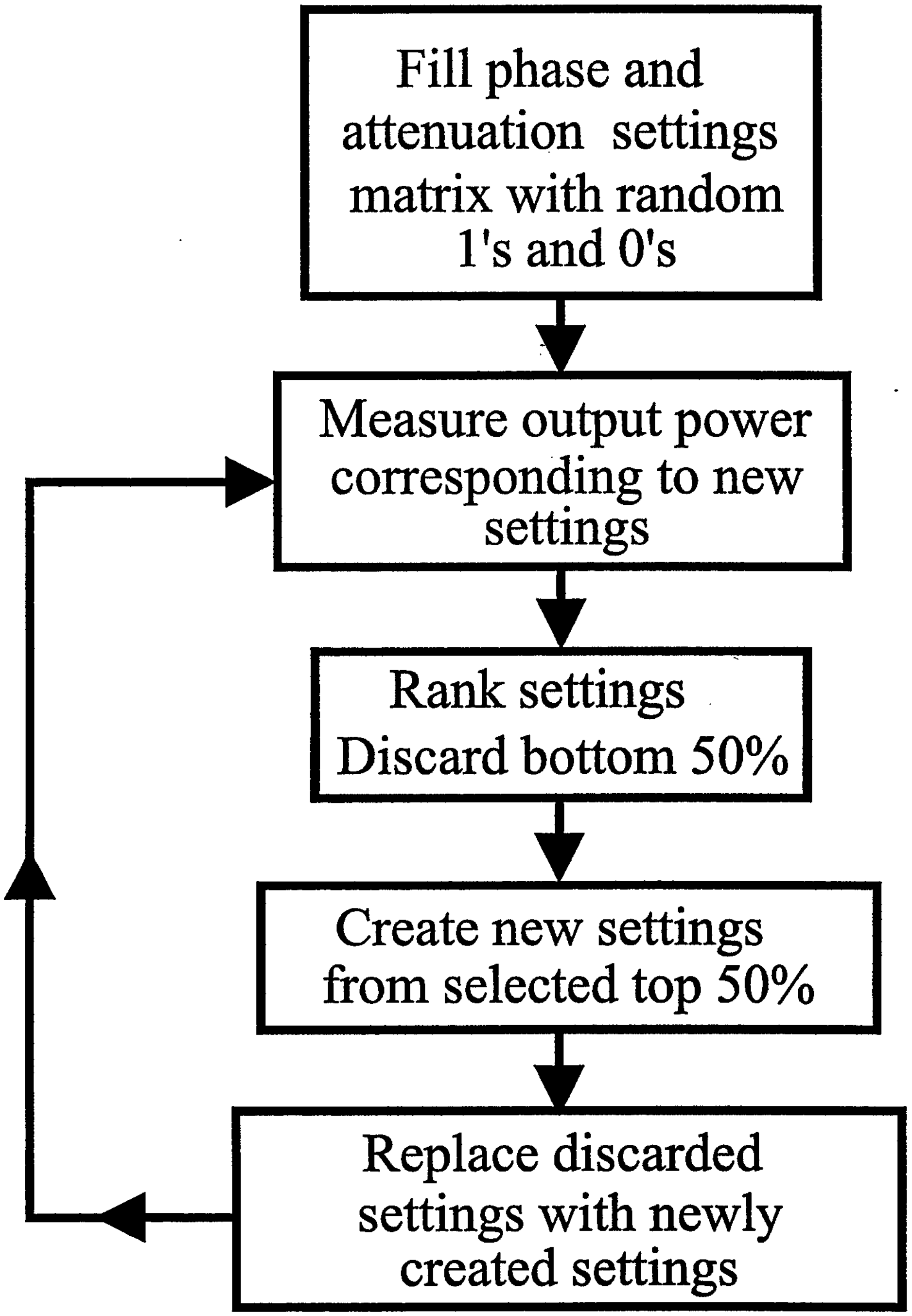

Figure 3.2: Flow chart of an adaptive genetic algorithm for the cylindrical array.

P. As N and P increase in size, M needs to be larger to keep the algorithm out of local minima, and the number of iterations required for convergence increases. In this application, we chose $M = 16$. The output power vector and associated chromosomes are ranked with the lowest output power on top and the highest output power on the bottom. The next step discards the bottom 50% of the chromosomes, because they have the greatest output power. New nulling chromosomes to replace those discarded are created from the chromosomes that were kept (Figure 3.4). Two chromosomes are selected at random. Chromosomes are paired as follows: chromosome 1 with 2, chromosome 3 with 4, etc. Next, a random point is selected and bits to the right of the random point are swapped to form two new chromosomes. These new chromosomes are placed in the matrix to replace two settings that were discarded, and their output powers are measured. When enough new chromosomes are created to replace those discarded, the chromosomes are ranked and the process repeated. A small number of the nulling bits in the matrix can be randomly switched from a one to a zero or vise versa. We mutated one bit in the population each generation. These randomly induced errors allow the algorithm to try new areas of the search space, while it converges on a solution. Usually, the best amplitude and phase setting is not randomly altered (called elitism). More general descriptions of genetic algorithms can be found in [9] and [10]. The next section shows results for determining the best values for P and M.

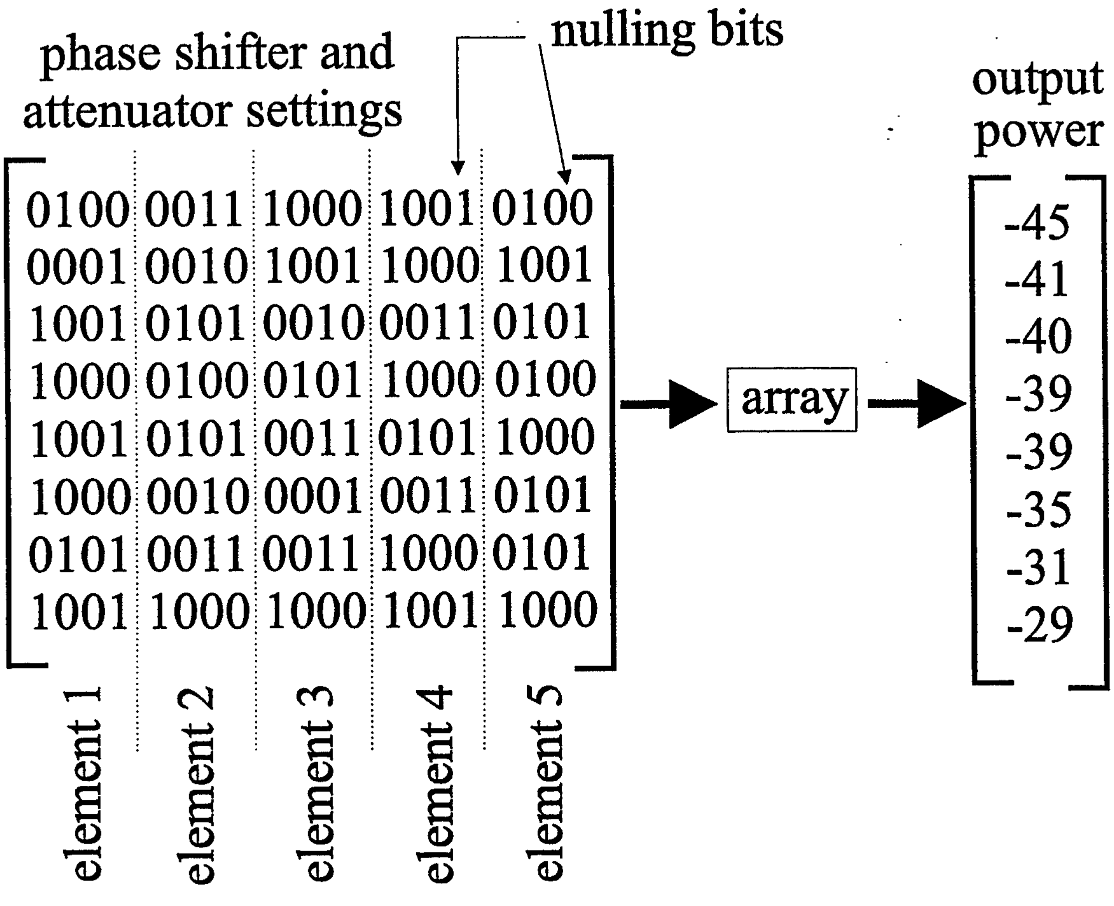

Figure 3.3: The nulling bits are sent to the array and an output power is measured for each chromosome.

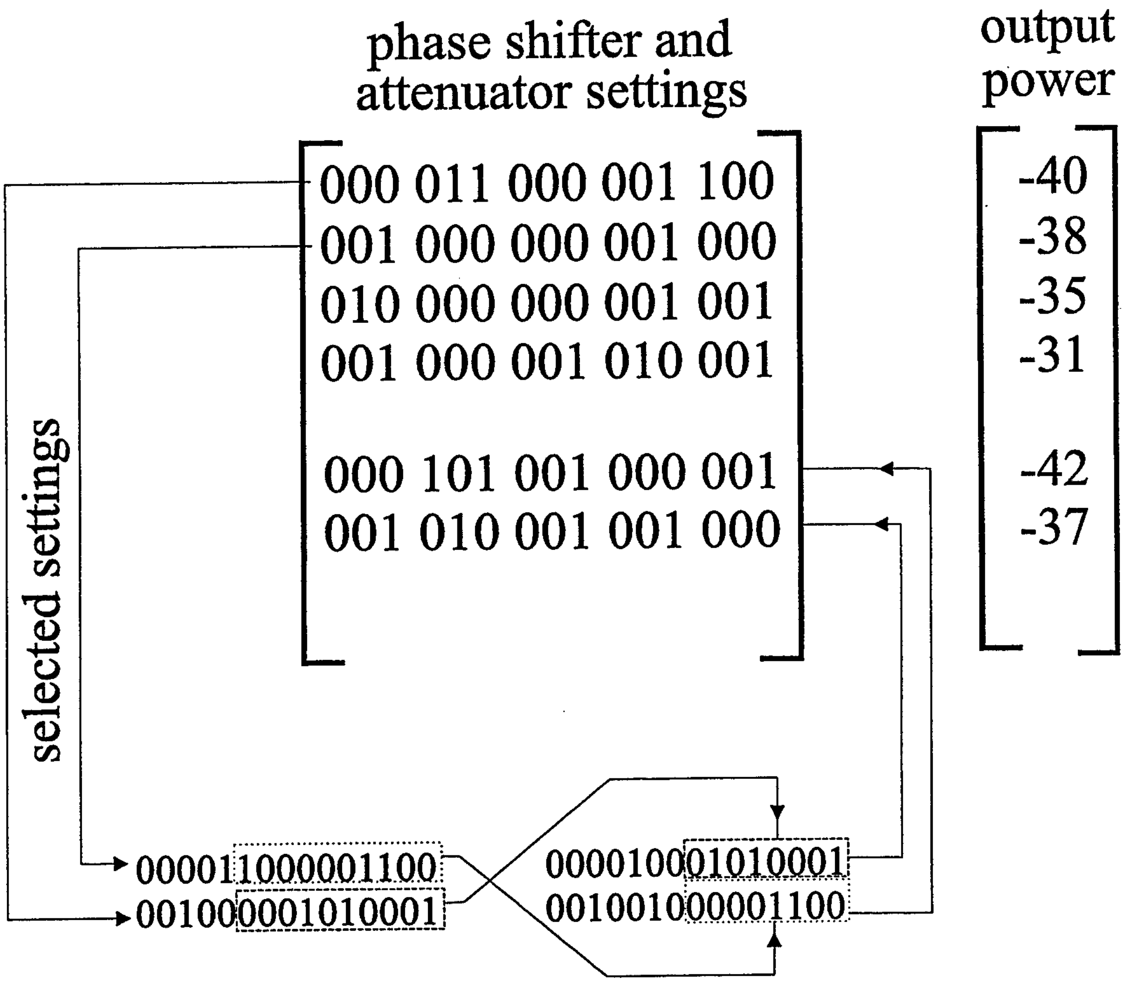

Figure 3.4: Two chromosomes are selected to create two new offspring.

Chapter 4

Experimental Results

The jammer was a CW source at 5 GHz. Only the four least significant bits of both the phase shifters and attenuators were used in this run. Figure 4.1 shows the adapted pattern superimposed on the quiescent pattern. The null at 45° is −56 dB and about 31 dB below the quiescent pattern. Since this null is below the noise floor of the measurement system, the algorithm cannot improve any further. Figure 4.2 shows the convergence of the genetic algorithm for a population size of 16 chromosomes. Note that the algorithm converged in only two iterations or less than 24 power measurements. The solid line is the null depth of the best chromosome and the dashed line is the average null depth for the entire population (16 chromosomes). In this case, the average plot is important, because the antenna still receives a signal while measuring the output power from the chromosomes. Only one chromosome each generation is mutated (mutation rate of 0.1%). This mutation rate is extremely low, so the primary search mechanism of the genetic algorithm is crossover.

The adapted pattern has a large sidelobe at −45°in addition to putting a null at 45°. This phenomenon is characteristic of phase-only nulling [11]. We used amplitude weighting in this experiment, but the effects of the amplitude weights were so small that they can be ignored. Theory predicts that the increase in the symmetric sidelobe should be about 3 dB. Figure 4.1 shows an increase of approximately 14 dB. The sidelobes on either side of the adaptive null also increased. A small shift of several degrees away from the adaptive null is also noticeable.

Figure 4.3 shows the adapted pattern superimposed on the quiescent pattern. The null at 28.5° is at −49.4 dB or 22 dB below the quiescent pattern.

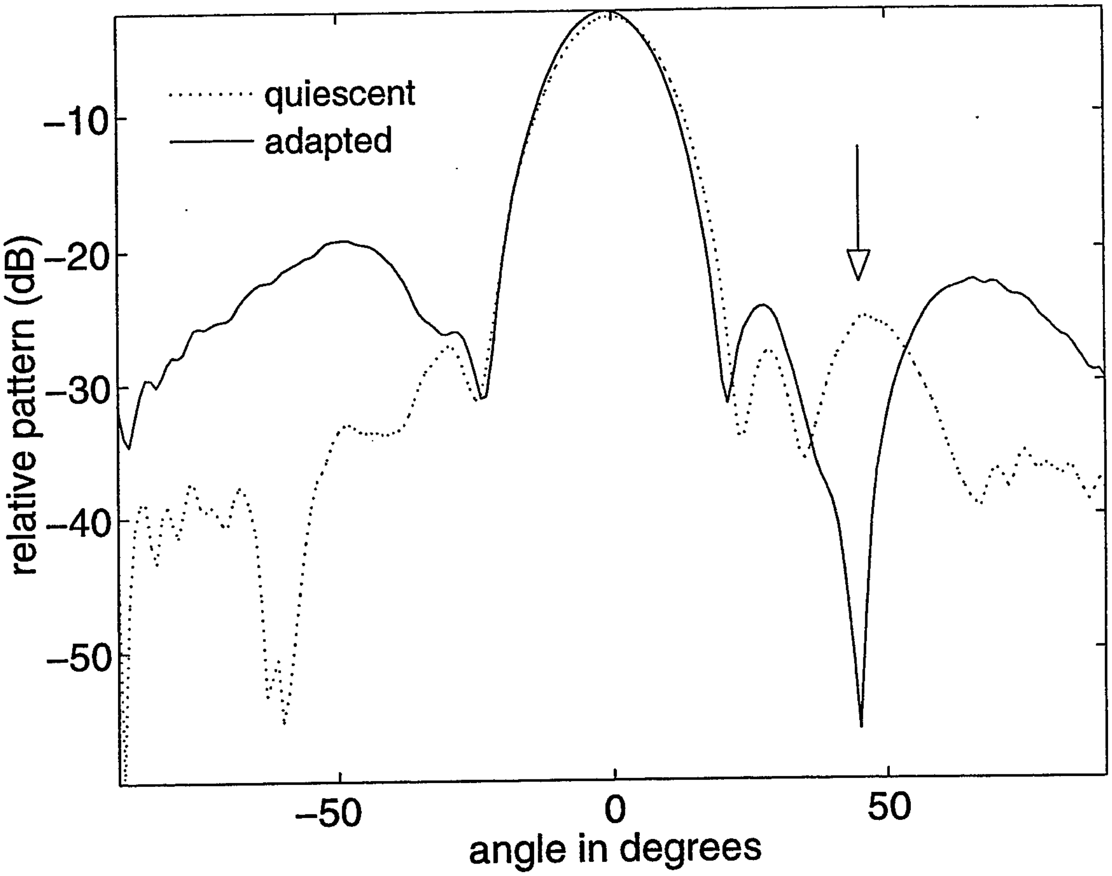

Figure 4.1: A null was placed in the antenna pattern at 45°.

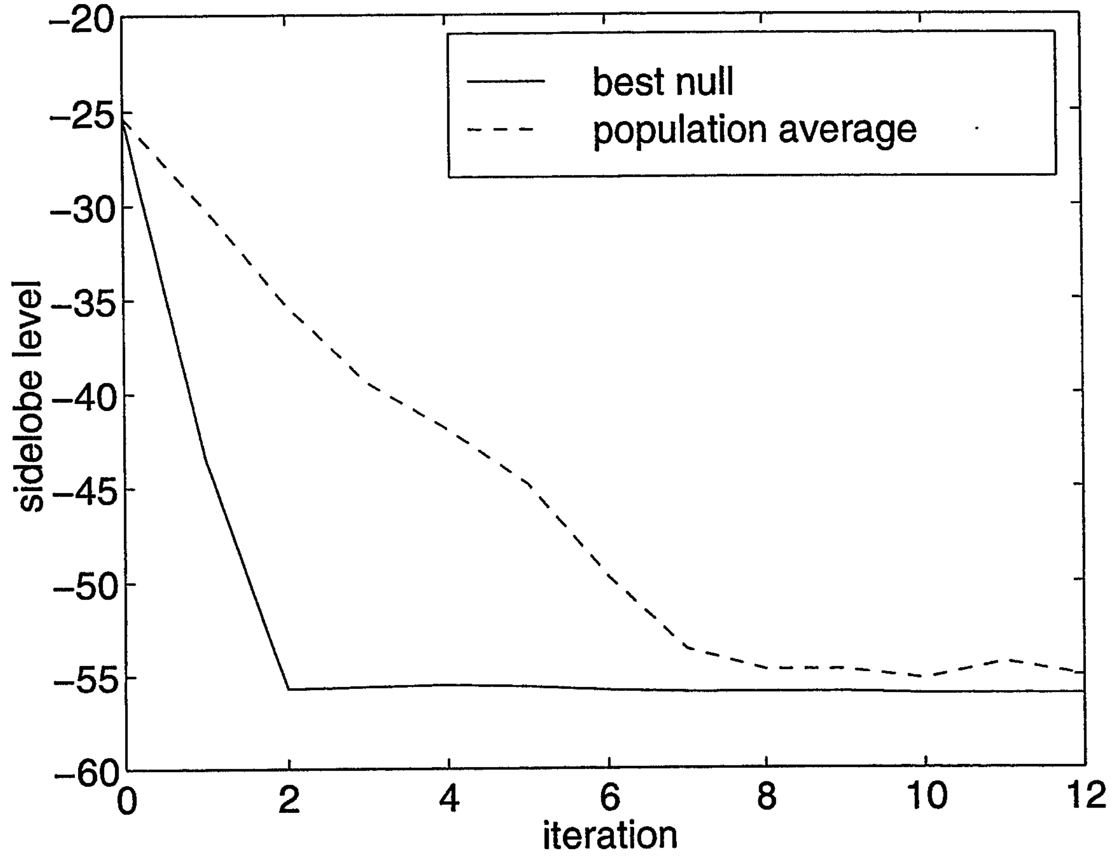

Figure 4.2: Graph shows the convergence of the genetic algorithm when the interference was at 45°.

Figure 4.4 shows the convergence of the genetic algorithm for a population size of 16 chromosomes. The null was formed in four iterations or 40 power measurements. The solid line is the null depth of the best chromosome and the dashed line is the average null depth for the entire population (16 chromosomes). Only one chromosome in each generation is mutated (0.1% mutation rate). The average sidelobe level for the 16 chromosomes of the final population is −34.8 dB.

The adapted pattern raised the sidelobe at −28.5°by approximately 10 dB. The sidelobe at 75° increased about 18 dB. A small shift of several degrees away from the adaptive null is also noticeable..

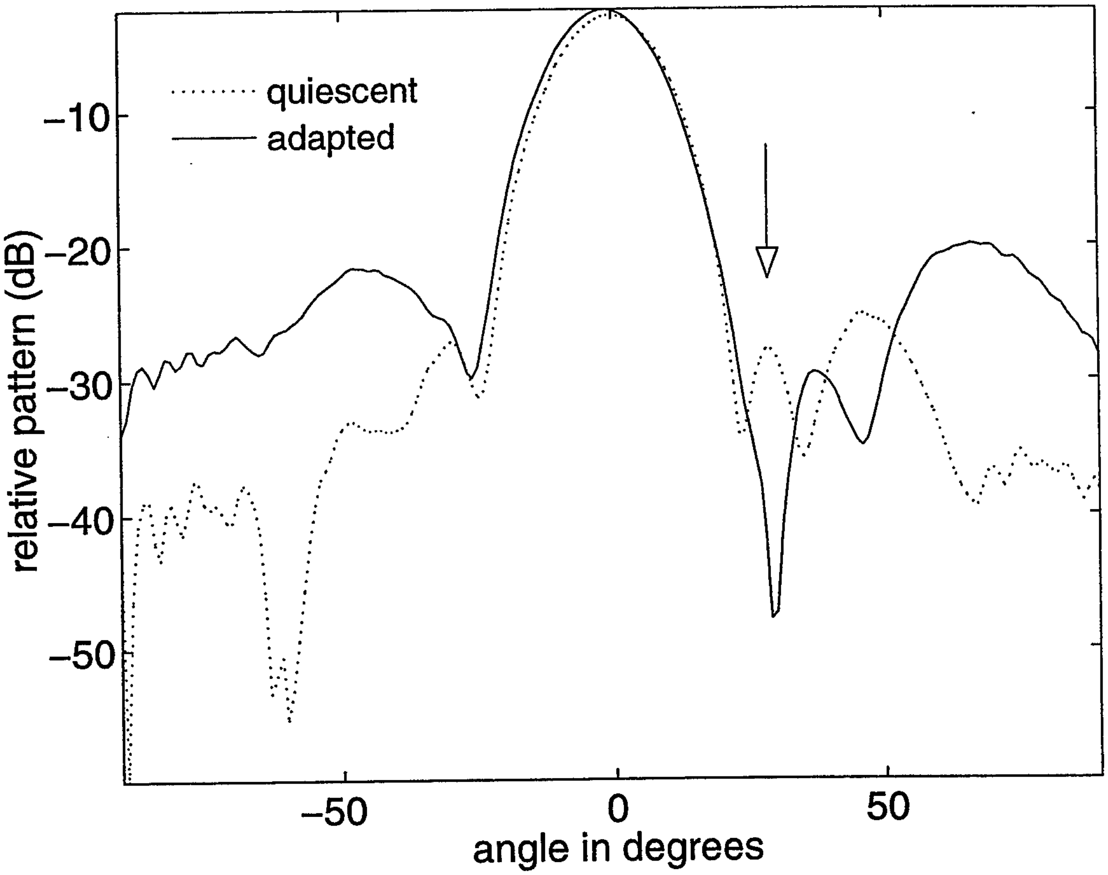

Figure 4.3: A null was placed in the antenna pattern at 28.5°.

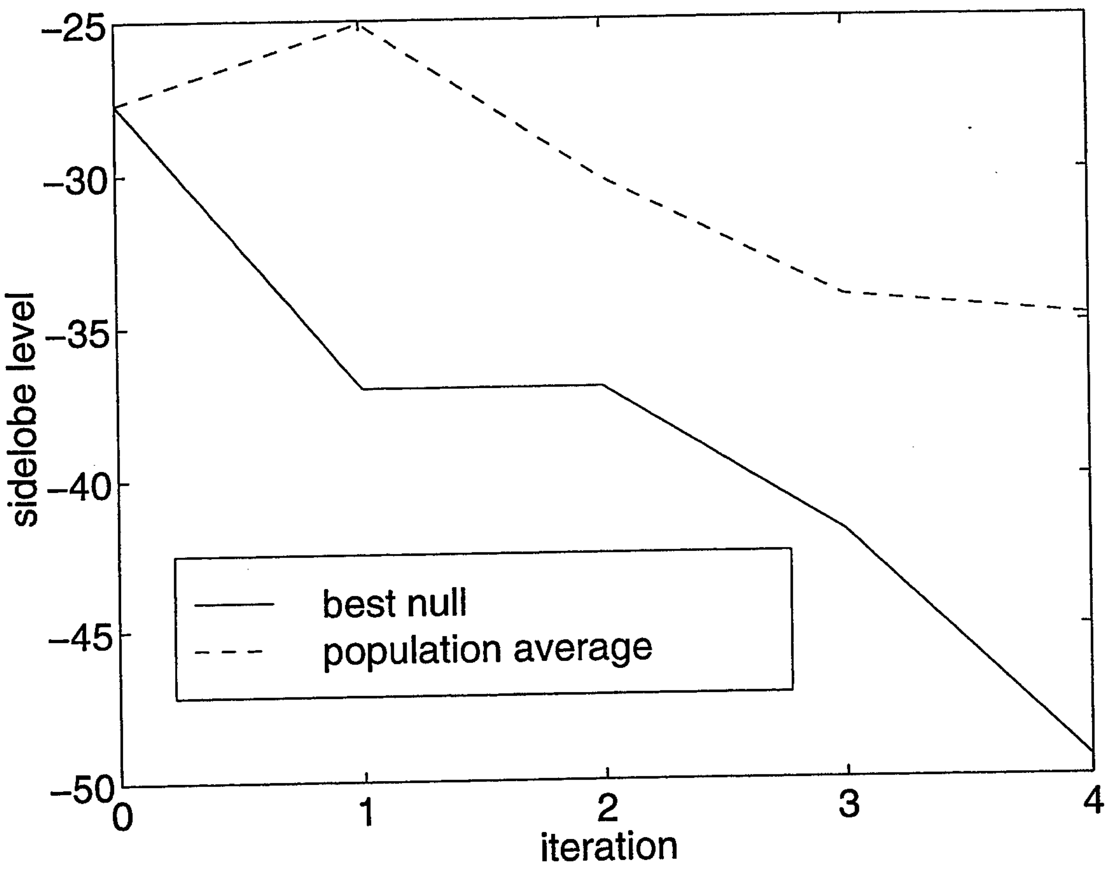

Figure 4.4: Graph shows the convergence of the genetic algorithm when the interference was at 45°.

Chapter 5

Conclusions and Suggestions

The experiment was quite successful. The genetic algorithm quickly placed deep nulls in the antenna pattern in two different sidelobes.

Several possibilities for future exploration include:

- Place two sources to use as jammers. The algorithm can be tested for sources entering two sidelobes or the mainbeam and one sidelobe.
- Modify the genetic algorithm so several of the parameters can be readily changed: mutation rate, size of population, number of bits used for nulling, and different types of nulling (phase-only, amplitude-only, and phase and amplitude).
- Improve the crude genetic algorithm implemented in this experiment
- Have MATLAB running on a computer next to the controlling computer or simultaneously on the controlling computer. The genetic algorithm can run in MATLAB and the weights can be loaded from MATLAB to the basic program for controlling the antenna.
- Use more attenuator bits for this application. Since the attenuators are calibrated in dB, the use of only four bits in effective made the adaptive algorithm phase-only.

Bibliography

[1] R.L. Haupt, "Phase-only adaptive nulling with genetic algorithms," IEEE AP-S Trans., vol. 45, May 97.

[2] R. Kinsey, "Array antenna self-calibration techniques," AMTA Workshop: Testing Phased Arrays and Diagnostics, San Jose, CA, Jun 89.

[3] R. A. Monzingo and T. W. Miller, *Introduction to Adaptive Antennas*, New York: Wiley, 1980.

[4] R. T. Compton, *Adaptive Antennas Concepts and Performance*, Englewood Cliffs, NJ: Prentice Hall, 1988.

[5] C. A. Baird and G. G. Rassweiler, "Adaptive sidelobe nulling using digitally controlled phase-shifters," IEEE AP Trans., Vol 24, No. 5, pp. 638-649, Sep 76.

[6] M. K. Leavitt, "A phase adaptation algorithm," IEEE AP-S Trans., Vol. 24, No. 5, pp. 754-756, Sep 76.

[7] H. Steyskal, "Simple method for pattern nulling by phase perturbation," IEEE AP-S Trans., Vol. 31, No. 1, pp. 163-166, Jan 83.

[8] R.L. Haupt, "Adaptive nulling in monopulse antennas," IEEE AP-S Transactions, Vol. AP-36, No. 1, Jan 88.

[9] J. H. Holland, "Genetic algorithms," Sci. Amer., pp 66-72, July 1992.

[10] R. L. Haupt, "An introduction to genetic algorithms for electromagnetics," IEEE Antennas and Propagation Magazine, Vol. 37, No. 2, pp. 7-15, Apr 95.

[11] R. A. Shore, "Nulling at symmetric pattern location with phase-only weight control," IEEE AP-S Trans., Vol. 32, No. 5, pp. 530-533, May 84.