Chapter 1. Introduction

Spiral antennas, a type of frequency independent antenna, have been studied for over 40 years. Frequency independent antennas provide uniform electrical characteristics over a wide frequency band. However, frequency independent antennas typically have broad radiation patterns and low gain, which is not suitable for many applications. One method to overcome this limitation is to use an array of frequency independent antenna elements. This approach allows for pattern control and higher gains, but the wideband characteristics of the frequency independent element are lost in the array environment. Inter-element spacing usually limits array bandwidth to a value much less than a frequency independent element can achieve outside an array.

A unique type of frequency independent antenna element, the star spiral, is presented in this dissertation. The star spiral is a type of slow-wave spiral that works very well in the wideband array with variable element sizes (WAVES) due to its unique shape. The WAVES array concept has been presented in the literature to a limited degree. This dissertation will further analyze the WAVES array concept and present designs using the star spiral in a WAVES array.

1.1 Motivation

Conventional antenna arrays are typically bandwidth limited by the individual antenna element at the lower frequency and by the formation of grating lobes due to inter-element spacing at the higher frequency. Techniques such as unequally spaced arrays, shared aperture arrays, and fractal arrays have been used to improve array bandwidth. Stutzman proposed another technique, called the wideband array with variable element sizes (WAVES) (Stutzman, 1985). It is a shared aperture technique that uses different element sizes to cover each octave of desired bandwidth. Frequency independent antenna elements, specifically the Archimedean spiral, were chosen because of their wide bandwidth. For each consecutively higher octave of bandwidth, the diameter of the Archimedean spiral is halved, allowing for tighter array spacing. Only the largest elements are active over the first octave of bandwidth. For the next octave, the two largest element sizes are active which maintains the array spacing less than one

wavelength. In theory the process can continue to higher octaves. Three octave designs have been proposed.

Much of the previous work on WAVES was theoretical with some measurements. However, for a simple linear WAVES array, simulations show that there is a performance gap between the low and high octaves. An investigation of slow-wave spiral antenna techniques was conducted to bridge the gap between the two octaves. The star spiral antenna is the result of that study. The unique shape of the star spiral allows for tighter element packing in a WAVES array and combined with its slow-wave nature the star spiral is able to eliminate the performance gap in a linear WAVES array. The shape of the star spiral is also advantageous in planar array packing and reducing blockage in overlapping arrays.

1.2 Literature Review

1.2.1 Wideband Arrays

The effect of inter-element spacing is an inherent problem in designing wideband arrays. It is desirable for inter-element spacing to be small, but the minimum spacing is limited by antenna element size and mutual coupling effects. As the frequency of operation is increased the inter-element spacing increases in terms of wavelength, and grating lobes appear for a spacing of one wavelength. Grating lobes are typically undesirable so the array bandwidth is limited by element size at the low frequency and the formation of grating lobes at the upper frequency. For a typical array this frequency range may correspond to an inter-element spacing between a half wavelength and one wavelength or a 2:1 bandwidth. Antenna elements, such as spirals, can have bandwidths of 9:1 or greater so techniques for increasing array bandwidth are very valuable.

Three of the main techniques for increasing array bandwidth are unequal array spacing, shared apertures, and non-rectangular array geometries. Much of the unequal array spacing work was done in the early 1960's. Unz (1960) studied a linear array with arbitrarily distributed elements. He found that the additional degree of freedom created by the random distribution of elements allowed him to achieve the same performance of an equally spaced array with fewer elements. The effects of various unequal spacing

schemes, such as logarithmic spacing, non-monotonically increasing spacing, and elimination of multiple spacing, were investigated by King, et al., (1960). King found that compared to an equally spaced array fewer elements were required for a desired bandwidth and grating lobes were replaced by sidelobes.

A method for quantifying the bandwidth of an unequally spaced array was presented by Bruce (1962). The sensitivity of the array pattern is found by taking the partial derivative of the pattern function with respect to the wavenumber. The most broadband arrays occur when the change in the partial derivative is stationary or the second partial derivative is zero. The second partial derivative reduces to the determinate of Bessel functions. The closer the determinant is to zero the more broadband the array pattern becomes.

Theoretical models for designing and analyzing unequally or randomly spaced arrays were introduced by Ishimaru (1962) and Lo (1964). Ishimaru showed that by using Poisson's sum formula and a new function he called the source position function, unequally spaced arrays with a desired radiation pattern could be designed. Ishimaru's technique was also valid for designing arrays on curved surfaces. Lo used a probabilistic approach to analyze large randomly spaced arrays. He found that sidelobe level was closely linked to the number of elements in the array, but very weakly connected to aperture size. Lo also found that directivity was proportional to number of elements and beamwidth was related to aperture size. The implication of Lo's study was that beamwidth could be changed dramatically by lengthening the array with little effect on sidelobe level.

Skolnik (1964) used a computer technique known as dynamic programming to optimize a thinned, unequally spaced array. The array he designed consisted of 25 elements in a 50-wavelength aperture. Another method for designing a thinned and broadband array using unequal array spacing was shown by Ishimaru and Chen (1965) that used Anger functions to express the array pattern. They were able to design an array with the desired beamwidth and sidelobe level for an average element spacing of many wavelengths. Further work was done by Bratkovic (1973) on optimizing unequally spaced arrays with dynamic programming. He found that the optimum array had monotonic spacing.

The use of randomly spaced subarrays as elements in a uniform linear array has also been investigated (Goffer, et al., 1994). Probabilistic expressions for grating lobe location and level and gain loss are given. The use of random subarrays allows for better grating lobe performance compared to a standard uniform array. A paper by Yu (1997) presented a method for reducing the sidelobes of an unequally spaced array by spacing perturbation. Least square error approximation and point matching were used with the radiation pattern to determine the appropriate element locations. A small amount of beamwidth broadening was also found. Another paper shows that by using a density tapering method with a radial warping function and minimum spacing greater than a wavelength an array with no grating lobes can be achieved (Anderson, et al., 1998).

A recent paper by Tripp and Papanicolopoulos (2000) describes a wideband array geometry designed using frequency independent antenna techniques. The array is called the log-periodic phased array. The array grid is defined by angle with a log-periodic relationship along each radial line. The structure looks concentric rings of elements where element size and array spacing increases with the radius of the array. Another type of frequency independent antenna array is the fractal array. A fractal array is recursively generated using fractional dimensions of the previous iteration. Currently fractal antennas and arrays are very popular in the literature. A review of fractal arrays is given by Werner, et al. (1999).

The previous papers dealt mainly with increasing array bandwidth using unequally spaced antenna elements of uniform size. Other techniques, such as shared aperture and non-rectangular grids, also can improve array bandwidth. A shared aperture array containing elements in L, S, and C frequency bands has been built and measured (Boyns and Provencher, 1972). Mutual coupling arrays of this type can be a problem, but this problem can be lessened by using elements with different polarizations. A 96-element phased array has been designed to operate over a one-octave bandwidth (Laughlin, et al., 1972). Each row of elements is staggered from the previous row creating a triangular grid of elements. A similar array was designed by Robinson, et al. (1989). The array consisted of two offset linear arrays of quadridged waveguide horns. A bandwidth of approximately 2.5:1 was achieved.

1.2.2 Spiral Antennas

Spiral antennas belong to a class of antennas known as frequency independent antennas. An antenna that can be completely specified by angles is frequency independent (Rumsey, 1957). The impedance and pattern performance of a frequency independent antenna are constant with frequency. In practice, an antenna must have a finite size so it only exhibits frequency independent behavior over a certain frequency range. A practical spiral antenna exhibits frequency independent behavior over a frequency range determined by its inner and outer radius.

Much of the early work on spiral antennas was published in the late 1950's and early 1960's. The planar equiangular spiral antenna and the unidirectional equiangular spiral or conical log spiral antenna were presented by Dyson (1959a, 1959b). Bandwidths of greater than 20:1 were observed with nearly constant impedance and pattern performance. Bawer and Wolfe (1960) collected much of the previous work on spiral antennas and summarized the performance of the spiral antenna for variations in different parameters. They looked at the equiangular, Archimedean, and square spiral antennas.

Much of the early work on spiral antennas was based on experiment and the band theory. The band theory essentially means that the spiral operates in the region where the circumference of the spiral is equal to a wavelength. In the early 1960's more rigorous mathematical explanations were pursued. Curtis (1960) derived the radiation patterns for an Archimedean spiral by approximating the spiral as a series of semicircles. Wheeler (1961) looked at the radiation from various regions of an equiangular spiral using a similar technique to Curtis, but without the semicircle approximation. A more general explanation of the spiral antenna was given by Cheo, et al., (1961). They solved Maxwell's equations for an equiangular spiral consisting of an infinite number of coplanar arms. It was found that the frequency independent behavior of the spiral is dependent on the curvature of each arm of the spiral.

Spiral antennas are typically backed by a lossy cavity. The lossy cavity improves the low frequency impedance behavior and axial ratio of the spiral by reducing reflections from the end of the each arm of the spiral. The lossy cavity also absorbs the back radiation from the spiral providing for a larger pattern bandwidth by reducing the

reflection from the ground plane that causes pattern nulls. Spirals with bandwidths of 9:1 or greater are common. The bulk of the lossy cavity and the gain reduction due to the loss are the two major drawbacks of using a cavity-backed spiral. As a result, conductor backed spirals have gained some popularity for certain applications. Experiments have shown a 1.2:1 circular polarization bandwidth for conductor backed spiral antennas (Nakano, et al., 1986 and Wu, 1994). For very low profile designs a slot spiral can be used to further reduce the height of the antenna. Slot spirals with bandwidths of 25:1 and depths of one hundredth the wavelength of the lowest frequency have been demonstrated (Nurnberger and Volakis, 1999).

Size reduction of spiral antennas has been studied for many years. Material loading is one way to reduce the size but material loss and weight can be a problem in some applications. Slow-wave spiral techniques were developed to overcome the problems inherent in material loading. Adding some type of high frequency profile, such as a zigzag or sine wave, to the spiral and increasing the circumference of the spiral, such as the square spiral, are ways of producing a slow-wave spiral. The radiation zone for a specific wavelength is moved closer to the center of the spiral when slow-wave techniques are employed. This effectively reduces the velocity of propagation along the length of the spiral, which reduces the low frequency cutoff of the spiral providing for size reduction (Roland and Patterson, 1967). The low frequency cutoff may also be reduced by resistively terminating the end of each arm of the spiral to reduce reflections from the end of the spiral, but this reduces efficiency, and, thus, gain.

1.2.3 Wideband Array With Variable Element Sizes

Stutzman (1985) first introduced the wideband array with variable element sizes (WAVES) concept. He presented the theory and performed a feasibility study by measuring the patterns of an Archimedean spiral with copper disks layered above the spiral representing higher octave antennas. A two-octave, eight element, planar array of Archimedean spirals was built and tested by Shively and Stutzman (1988, 1990). The planar array was measured along the diagonal where a triangular lattice and amplitude taper improved the radiation pattern performance of the array. The smaller spiral elements were switched on when the grating lobe due to the larger elements became too

large. Other theoretical work has been done by Chatzipetros (1993). He used array theory to predict the performance of some three-octave WAVES array designs. All of the previous work on WAVES has consisted of array theory predictions and measurements of the Shively eight element, planar array.

1.3 Dissertation Overview

This dissertation is organized into three main parts. The first part is contained in the first three chapters and is primarily a review of previous work and other background materials. Chapter 1 is a review of the relevant literature. The basic theory and some simple simulations of an Archimedean spiral are presented in Chapter 2. A verification of the NEC4 code for simulation of Archimedean spirals is also performed (Burke, 1992). NEC4 is used as the primary simulation tool due to its relatively fast run times and versatility in regards to geometry input. A circular Archimedean spiral will be built and measured to validate the simulation tools and to be used as a comparison with the star spiral in later chapters. Past work on the wideband array with variable element sizes is summarized in Chapter 3. Linear and planar WAVES arrays of Archimedean spirals are simulated and the need for a slow-wave spiral is detailed.

The next section consists of a detailed analysis of the star spiral antenna element in Chapter 4. The star spiral was developed to overcome the performance gap in the linear WAVES array of Archimedean spirals presented in Chapter 3. The star spiral also yields itself to some interesting array geometries and can improve array packing. Simulations of the star spiral in an array environment are shown Chapter 5. The input impedance and scan performance of the star spiral will be investigated using Analysis Software for Infinite Arrays (ASIA) (LaPean, 1996). The last part of the thesis details the use of the star spiral in WAVES arrays. Improvements in performance, a 3-octave array, scan performance, and various array architectures will all be presented in Chapter 5. Finally, conclusions and future work will be given in Chapter 6.