Investigation of a Curtain HF Antenna Array for TIGER - New Zealand

Q. Nguyen, J. Devlin
Department of Electronic Engineering
Latrobe University, Australia

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Abstract : A Log-periodic curtain antenna has been designed as an alternative to the Sabre 608 Log-periodic antenna. The new antenna should be more robust than the current antenna due to its well support design. An "actual-scaled" model of this new antenna structure was simulated using the Numerical Electromagnetic Code (NEC 2). A brief discussion on the linear array will also be presented to explain some of the discrepancies in the performance of the currently used antenna array, as observed over the years. The concept of frequency independent array manifests some significant advantages over that of the linear array. Its implementation is a possible solution in achieving better array design.

1 Introduction

The current version of Log-periodic antenna being used at various SuperDARN radar sites exhibits a number of structural instabilities, such as broken elements, twisted of horizontal boom, support tower bent, ...etc under severe weather conditions. These problems may seriously disrupt the operation of radar over a period of time and can be costly to repair. To overcome these structural problems, a new Log-periodic antenna is presented in this paper. This antenna consists of wired elements, light in weight, presents no wind resistance and demands low level of maintenance.

NEC is one of the best antenna modeling tools available and is widely used among the antenna designers around the world. It was developed in early 1980 and finally released to public in 1995 by US Department of Defense. Its core engine bases on the "Moment-Method" approach. All antennas presented in this paper were modeled using NEC 2.

2 Background Theory

The Log-periodic dipole array (LPDA) antenna was first introduced by Isbell [13], however, a complete analysis of this antenna was later done by Carrel in 1961 [3]. The LPDA consists of a number of dipole elements whose lengths are successively scaled to cover the desired frequency band. As frequency changes, the function of resonant element is smoothly transferred from one element to the next, provided there is no abruptly change in the physical dimensions of the neighbouring elements. Therefore, a scaling factor must appropriately be chosen to ensure enough resonant elements to provide a smooth transition covering the desired frequency range. Because the characteristics of the array elements are influenced by their surrounding, it is also necessary to scale the environment. As a result, the lengths of dipole elements and the spacing distance between elements are geometrically related by a common factor, τ ($\tau < 1$) defined by the following expression

$$\tau = \frac{l_{n+1}}{l_n} = \frac{s_{n+1}}{s_n} = \frac{R_{n+1}}{R_n} \tag{2.1}$$

Theoretically, for an LPDA antenna to display its broadband characteristics over a finite bandwidth, it is required that at any given frequency, only those dipole elements whose lengths approximately equal to half-wavelength (commonly called "resonant" elements) are excited. These resonant elements form an "active region". Inside this active region, there exists a "phase centre" which lies at a constant electrical distance along antenna boom behind the vertex. It was found that in the Log-periodic antenna family, the actual radiation emanates from this phase centre vicinity.

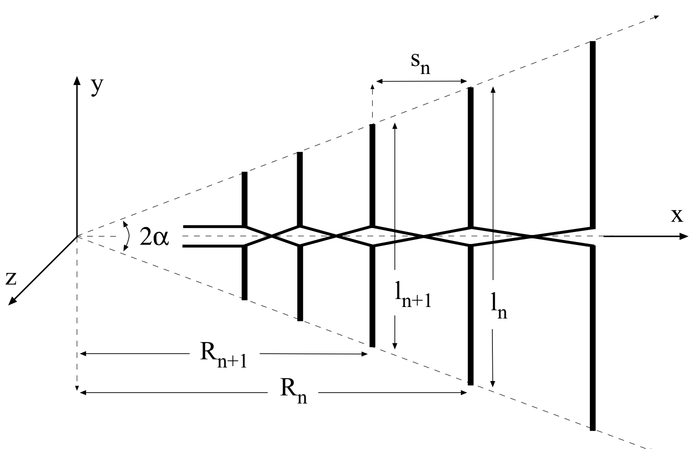

Figure 1: The Log-periodic dipole array

The upper and lower frequency limits of the LPDA are determined by the lengths of the shortest and longest elements, respectively. Since LPDA is fed at the small end, it must rapidly attenuate the incident wave along the antenna boom so that only a negligible (or possibly none) amount energy is reflected from the large end.

Designing of LPDA involves three key parameters: the scale factor, τ, the spacing factor, σ and the subtented angle, α. The relationship between these three parameters is found to be

$$tan(\alpha) = \frac{1-\tau}{4\sigma} \tag{2.2}$$

Based on the chosen values for these parameters, the number of dipole elements (n), dipole length (l_n), spacing between elements (s_n) and boom length (L)

can be determined [3], [2]. Since any set of values for τ, σ and α that are possible, hence, no unique design of a LPDA structure exists for a given set of specifications. To achieve an optimal LPDA design (constant gain/impedance over entire band, short boom length, minimum number of elements), repeating this design process for different values of τ and σ is necessary to establish the trend. Therefore, this design method is a tedious and time-consumed approach.

3 A Different Approach to LPDA Design

Supposed a LPDA is designed to operate in a given frequency range between f_{min} and f_{max}, so the design bandwidth, B is given by

$$B = \frac{f_{max}}{f_{min}} \tag{3.1}$$

At any frequency within the design bandwidth, the active region should only involve the resonant elements. As a result, there exists an active bandwidth, B_a. To account for this active bandwidth, the actual antenna structure bandwidth, B_s should be broaden beyond the design bandwidth.

$$B_s = B_a B = \frac{l_1}{l_n} = \tau^{1-n} \tag{3.2}$$

Using the similar triangle theorem, the transcendental equation below can easily be derived from the geometry of LPDA

$$\frac{s_1}{L} = \frac{1-\tau}{1-\tau^{(n-1)}} \tag{3.3}$$

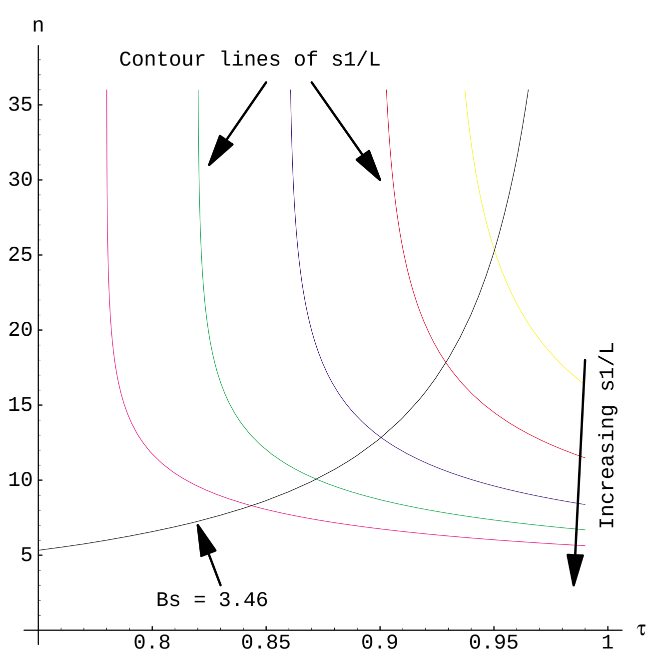

Figure 2: The design curve of LPDA for chosen values of B_s, L and n

The contour plots of equation (3.3) and (3.2) in figure 2 show that for a given structure bandwidth B_s, only two design parameters, namely L and n are required to completely determine the dimensions of our LPDA. Selecting an appropriate value for s_1/L is a little bit difficult here. This ratio is the key in calculating the element spacing distances along the boom length. From modeling result, s_1/L is normally chosen such that it gives rise to $0.05\lambda_{max} \lesssim s_1 \lesssim 0.08\lambda_{max}$. As a result, this method allows the designer to choose a practical boom length, as well as having control over number of dipole elements on array.

Using this new design approach, a LPDA antenna was designed for frequency band between 13 and 30 MHz. It consists of 18 elements, its boom length is 14.6 meters long and mounted at 16.8 meters high above real ground (dielectric constant = 13, ground conductivity = 0.005 mhos/m).

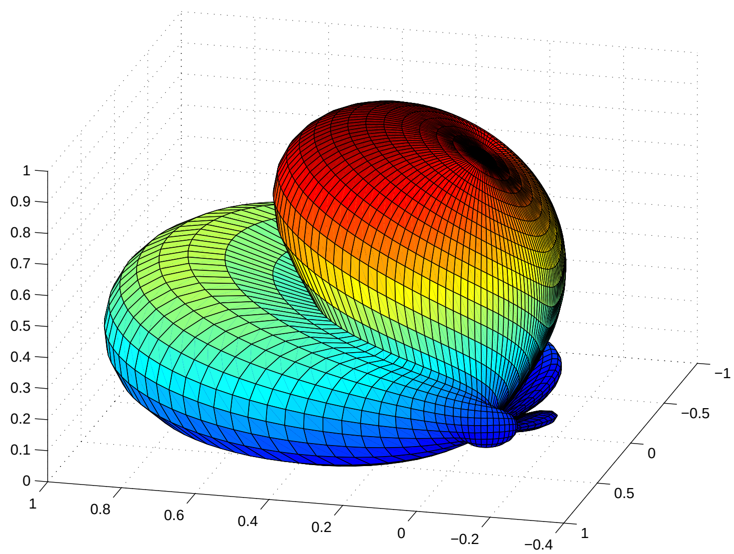

Figure 3: 3D antenna pattern of LPDA at 14 MHz (chejbf14p.dat)

The resultant radiation pattern in figure 3 indicates a well develop main front lobe and very little power leaking at rear (F/B ratio > 20 dB). It produces a flat gain over the designated band. Its VSWR falls below the 2 : 1 mark.

The radiation pattern breaks up rapidly as frequency changed, especially at 28 MHz where four different lobes appear, including one in vertical direction. Even though, this antenna behaves very good in free-space, however, once it is placed over real ground, the ground reflection introduces some distortions, especially in radiation pattern and its impedance. On the other hands, some extra dB gain was added to due to ground reflection.

Breaking up of radiation patterns is caused by a non-constant electrical height of antenna with respect to ground. To assure a constant radiation pattern over the interested band, LPDA antenna must be inclined at a suitable angle against the horizontal ground plane (whose value is determined from the desired take-off angle), hence, maintained a constant electrical height above ground.

As the inclined angle gets larger, the lower the take-off angle will result, whereas, higher take-off is obtained if smaller inclined angle is used. This inclined arrangement is quite expensive because it requires extra towers. However, it allows one to choose an optimum take-off angle to penetrate ionospheric layer at different heights [6], [24].

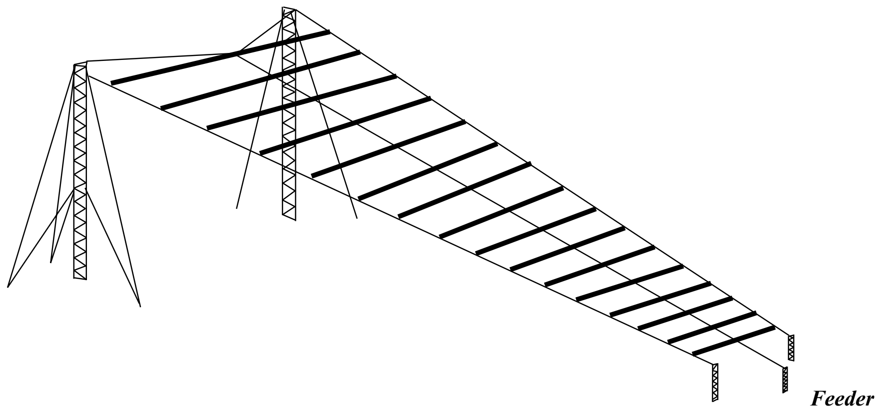

Figure 4: Horizontally polarised Slopping-LPDA to maintain constant electrical height above ground

4 Inverted-V LPDA Antenna

It has been observed that the electrical characteristics of an inverted-V dipole is very much similar to its equivalent half-wavelength dipole radiator. Inverted-V dipole produces lower gain in comparison to dipole, however, it has a broader bandwidth and physically shorter in term of horizontal spacing. The gain of inverted-V dipole can be improved by making the element fatter such as using thicker tubing or wire-loop.

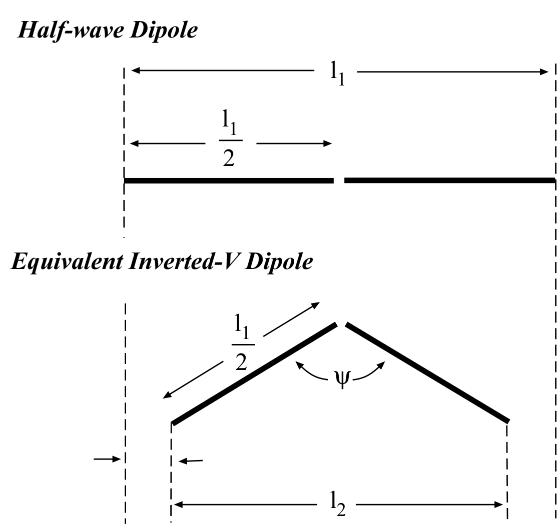

Figure 5: Dipole and its equivalent Inverted-V version

Implementing inverted-V dipole in LPDA design provides some advantages over that of the conventional LPDA (or the Slopping-LPDA). It requires only one tower to raise the inverted-V LPDA; is cheaply made out of wire; simplifies installation process; presents no wind resistance; maintains constant electrical height above ground; allows longer boom length without any construction limitations, ...etc are some of the advantages of using inverted-V LPDA. From the modeling results, the inverted-V LPDA antenna behaves very well over the design frequency band.

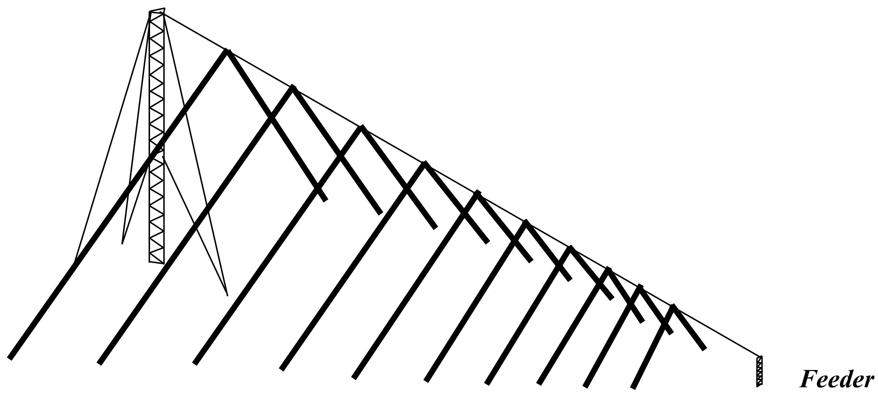

Figure 6: An Inverted-V LPDA

Let consider the design of an inverted-V LPDA antenna for the frequency band from 8 to 20 MHz using the parameters specified in the previous section, but in this case, the boom length was lengthen to 20 meters.

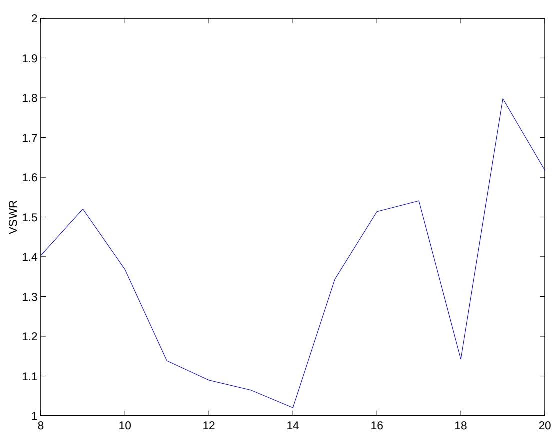

Figure 7: VSWR of Inverted-V LPDA from 8 to 20 MHz

The input impedance of inverted-V LPDA fluctuates a little bit at the two extremes of the frequency band. The resultant VSWR remains well below the 2 : 1 limit.

Its gain is approximately constant across this broadband. However, the gain tends to fall off at the higher end of the frequency band (1 dB variation). Re-

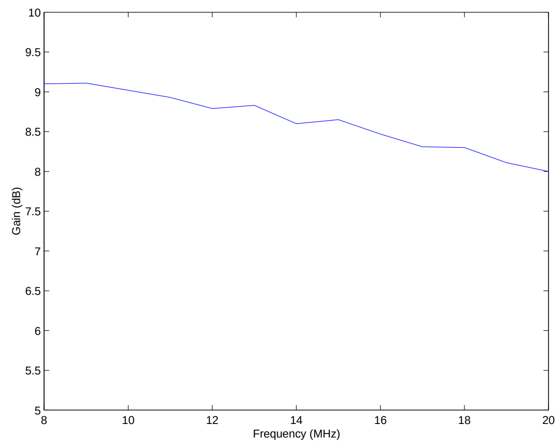

Figure 8: Gain of Inverted-V LPDA over 8 to 20 MHz

duction in gain can easily be explained by looking at the current distribution in the high frequency region. There are not enough resonant elements contributing to the active region to provide the constant gain, whereas at the low frequency end, almost all elements were excited, thus, produced better gain.

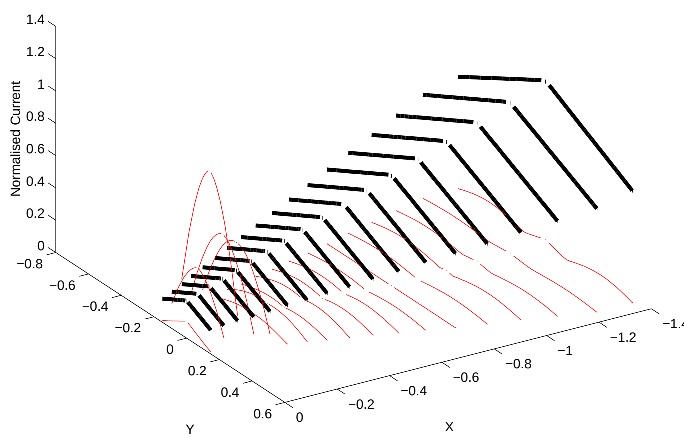

Figure 9: Current distribution on an Inverted-V LPDA at 20 MHz

To increase the gain at high frequency end, it is necessary to add extra high frequency elements. It was found that if three or more extra elements are added, a constant gain is maintained throughout this frequency band. Notice that, at 20 MHz the second harmonic current mode strongly develops on those larger elements, and is clearly visible on the longest element as shown in figure 9. This harmonic problem causes the rear lobe to strongly develop on both sides at rear and a small " kink " toward the back. The radiation pattern of inverted-V LPDA at 8 and 20 MHz are very much the same. There is no sig-

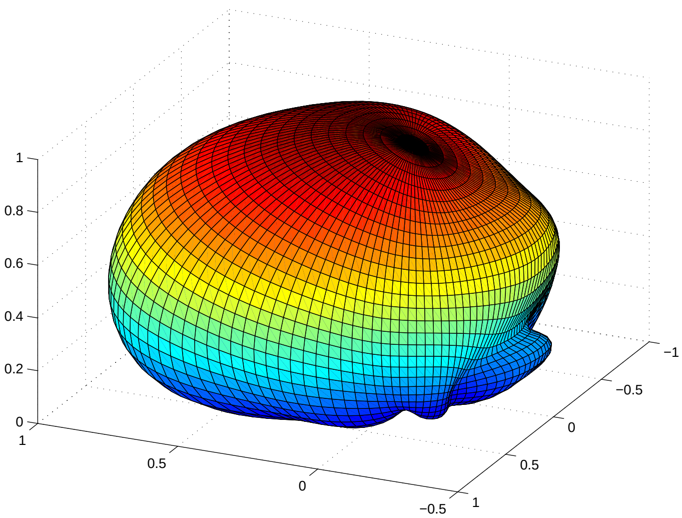

Figure 10: 3D antenna pattern of Inverted-V LPDA at 20 MHz (lp8m1f20p.dat)

nificant variation in main front lobe, except for the development of rear lobe as frequency increased. Consequently, this has successfully demonstrated that a constant radiation pattern over broadband is possible, provided the LPDA antenna structure is mounted such that all dipole elements are at a constant electrical height with respect to ground. Depending on the inclined angle, different take-off angles can be achieved. Since the virtual height of ionospheric layers varies with respect to time, vertically stacking of two or more LPDA allows one to closely monitor the variation in ionosphere condition. This method has been used to sustain reliable links in long distance HF communication [8].

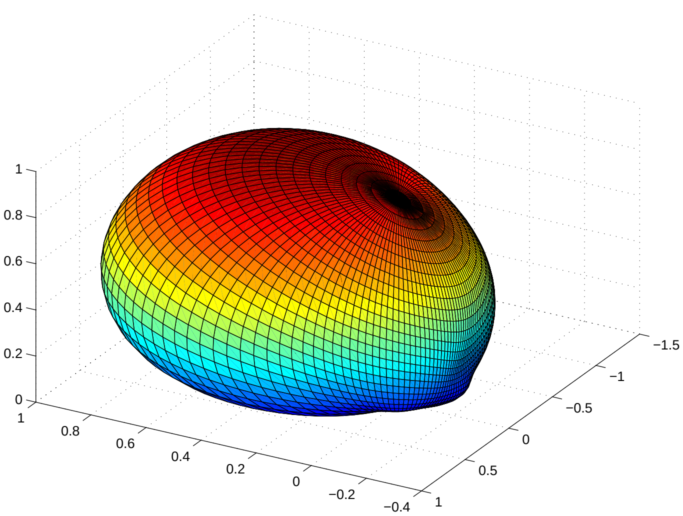

Figure 11: 3D antenna pattern of Inverted-V LPDA at 8 MHz (lp8m1f8p.dat)

5 High Frequency Antenna Arrays

Over the years, many antenna designers have found that, in general, the conventional method of designing antenna array does not accurately predict the radiation pattern of array [12]. Disagreement between theoretical and practical results, sometimes, is quite significant.

In the linear array theory, it ignores the mutual coupling between array elements and does not encounter the scattering or diffraction of radiation by the neighbouring array elements. The reason for this may be due to the conventional assumption in array theory that the radiation pattern of each element in the presence of other elements is the same as the radiation pattern of an isolated element (in absence of all other elements). This is not true in practice, however, this assumption should be implemented to establish the first order approximation of the performance of linear array under certain circumstances [12].

Therefore, if an antenna has a "good" radiation pattern, it does not automatically mean that an array made up by these identical antennas will give rise to a "desired" radiation pattern, but, the coupling effects would distort the individual element pattern in the presence of other array elements. Theoretically, an ideal array is one that has no mutual coupling.

In SuperDARN radar system, a linear array of 16 LPDA antennas is used for both transmission and reception. The antennas are equally spaced along the array. The entire array is approximately 225 meters in length ie a spacing of 15 meters between the array elements. The Log-periodic antennas are phased array to produce the broadside radiation to cover a sector of approximately 60°, over a frequency band between 8 MHz to 20 MHz [9], [10]. There are number of concerns regarding to the linear array configuration that would influence the overall performance of the array.

5.1 Electrical spacing between array elements

Recall that the radiated field of a LPDA is determined from its "phase centre". As the operating frequency varied, the phase centre associated to the active region moves along the antenna. However, the excursion of active region along the boom length of a LPDA causes the electrical spacing between the phase centres to change accordingly. From the earlier works in linear array, the optimum electrical spacing distant between the array elements was experimentally found to be approximately equal to half-wavelength at resonant [19]. Therefore, if the array is operating at 20 MHz, the expected element spacing is about 7.5 meters ($d_{20MHz} = 7.5$ m); whereas at 8 MHz, the optimum spacing is about 18.75 meters ($d_{8MHz} = 18.75$ m). Clearly, different element spacings are required as array operates at different frequencies. However, in our HF radar system, the element spacing is fixed at 15 meters ie only suit best to operate at 10 MHz.

The fixed spacing distance between array's element is defined as

$$d_{fix} = 15m = \frac{\lambda_{fix}}{2}$$

Recall from antenna array theory, the visible range of an array is a function of the electrical spacing distance (βd, where β is the free-space phase shift constant and d is the separation distance between array elements). At the low frequency end, the ratio between fixed spacing distance to that of the expected spacing distance was found to be

$$\frac{d_{fix}}{d_{8MHz}} = \frac{15}{18.75} = 0.8$$

Hence, if d_{fix} is used, the visible range is narrowed down to

$$\beta d_{fix} = 0.8\beta(\frac{\lambda_{8MHz}}{2})$$

This would eliminates some sidelobes. However, if the first null of the system is greater than this visible range, the main lobe would be effected. On the other hands, at the high end of frequency band

$$\frac{d_{fix}}{d_{20MHz}} = \frac{15}{7.5} = 2$$

Therefore, the visible range is broaden by a factor of 2

$$\beta d_{fix} = 2\beta(\frac{\lambda_{20MHz}}{2})$$

This means that at 20 MHz, more sidelobes would be included in the visible range, hence, may degrade the system performance. This problem was actually observed by Greenwald et al [10] in which a significant development of sidelobes occurs above 18 MHz.

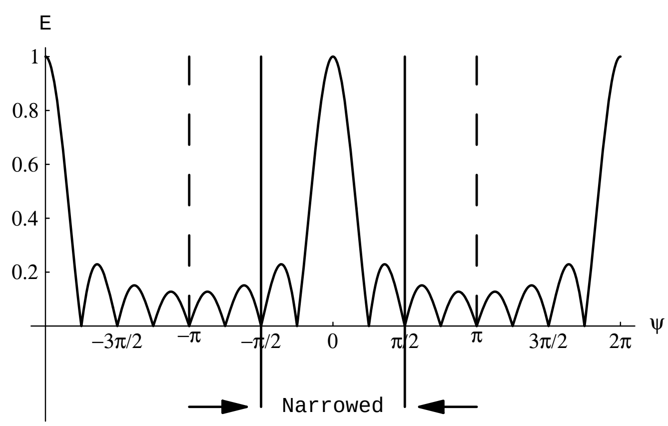

Figure 12: Narrowing in visible range

Therefore, as the electrical spacing between the phase centres varies in according to the operating frequency, this consequently changes the radiation pattern of the array.

5.2 Variation of gain in linear array

Figure 13 shows the main beam steered at an angle, θ to the boresight of array. In order to direct the main beam to the specified target, the progressive phase shift of adjacent elements was given by

$$\alpha = \beta d \cos(\phi)$$

As the array is “virtually rotated” so that it is perpendicular to the target (to new position BD, where ($BD = AB$)), the target's view of the physical aperture of the linear array is BC , ($BC < AB$), where AB is the actual physical aperture of the array. BC is found to be

$$BC = AB\cos(\theta)$$

Since the gain of the linear array is directly related to the physical aperture of the array (length of the array in this case, $L = AB$). It was theoretically proven that the directive gain of a linear array is approximately equal to (for a large array) [21]

$$D = \frac{4L}{\lambda} \tag{5.1}$$

Hence, for target at an angle, θ to the boresight of array,

$$D = \frac{4L\cos(\theta)}{\lambda}$$

so, the gain of antenna array is reduced by a factor $\cos(\theta)$. In practice, the gain is also reduced because of changes in the mutual coupling between array elements as the main beam scanning off the boresight [22], [17].

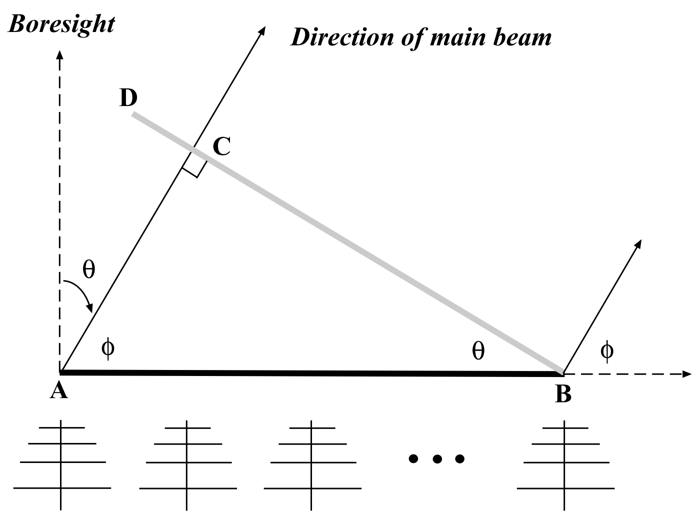

Figure 13: Reduction of physical aperture of scanning array

5.3 Impedance effects in scanning array

As the main beam scanning through an angle from its boresight, the driving impedance of each element in array also varies accordingly by some amount depending on its interaction with the neighbouring elements ie a function of mutual coupling between the array elements [4]. Thus, it is expected that the impedance of elements at the two ends of linear array to vary considerably large in comparison to the center elements (“end effects”).

As the frequency changes from one resonant frequency to another, the mutual impedance is also heavily influenced due to the fixed spacing in this linear array. However, if the spacing between array elements is made larger with respect to the lowest operating frequency, the effect of mutual coupling decreases rapidly [17].

Variations in self- and mutual impedances causes an impedance mismatch with the feeder, consequently, raises VSWR and allows less power to be transferred to antenna, hence, reduces system gain [1]. This effect was found in many practical situations, especially in linear and planar dipole array.

5.4 Beamwidth variation in scanning array

It is well known from the antenna array theory that as the physical aperture of the antenna array reduces, the resultant beamwidth (BW) is broaden [7]. Thereby, the ratio of beamwidth when the target is at an angle θ_0 to when target located perpendicular to array is

$$\frac{BW_{\theta=0}}{BW_{\theta=\theta_0}} = \frac{1}{\cos(\theta_0)} \tag{5.2}$$

Since the physical aperture of the array changes as the main beam scanning through an angle in the broadside direction, therefore, causes the beamwidth to vary accordingly. Equation (5.2) has shown that the beamwidth is approximately inversely proportional to $\cos(\theta_0)$, where θ_0 is the angle measured from the boresight to direction of main beam. An interesting technique for graphically portraying the variation of the beamwidth with scan angle has been described by Von Aulock [23].

6 Frequency Independent Array

Development of the frequency independent array which produces an optimum gain; narrow beamwidth and importantly; its electrical properties remain constant throughout the desired bandwidth, is another area of interest. This is possible by re-arranging the LPDA antennas together in a suitable configuration such that it still exhibits the same broadband characteristics as that of its individual elements.

To obtain frequency independent operation in an array of LPDA antennas, once again, the frequency independent principles must be implemented here. The array elements must be arranged such that their locations can be defined by angles rather than distances [20]. One of the most obvious choice of such an arrangement is a semi-circular (or circular) array configuration where all of the array elements have their vertices (feed-points) meet at a common origin [7], [15].

Semi-circular array is proposed because it would solve some of the linear array's problems. The radial disposition of the elements will maintain a constant electrical spacing between array elements ie spacing distance between phase centers remain constant as the active region travels back and fro along the antenna's boom. The directional radiation pattern formed can be phase-steered in the plane of the circle without any significant change of beam shape. Importantly, the beamwidth was proven to remain constant in this frequency independent array [5]. In some of the earlier studies, the effects of mutual coupling has been

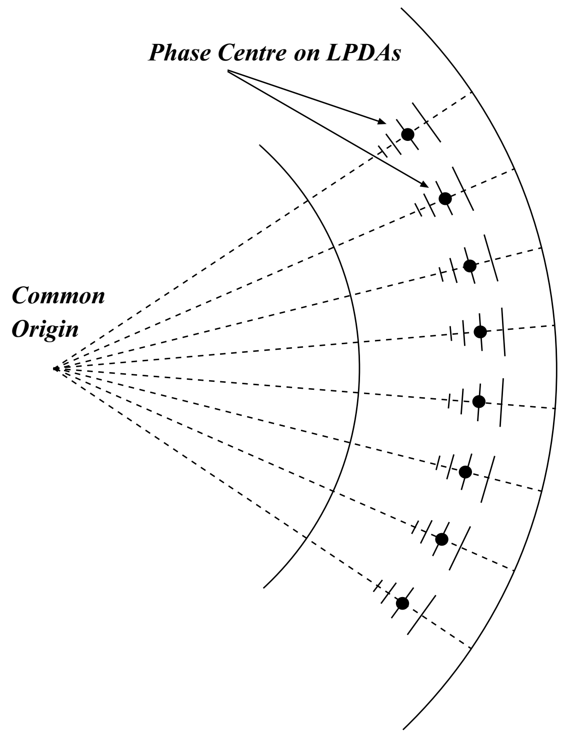

Figure 14: The E-plane frequency independent array

taken into account in calculating directional patterns. It was found that due to the symmetry of circular array, the effects of mutual coupling is at minimal as beam scanned off boresight [18], [16].

This concept of semi-circular (and circular) array has been implemented in many HF antenna applications. It is widely used in HF communication radar sites but instead of using the horizontally polarised monopoles LPDA, the vertically polarised LPDA were implemented. Excellent performance over greater bandwidth were obtained. However, this is quite expensive because it requires a massive ground mesh to maximise the performance of vertically polarised monopoles LPDA [6]. Also, in direction-finding (DF system) and target detection applications, this circular array configuration can scan through 360° while maintains an outstanding performance [14].

7 Conclusion

A different approach in designing LPDA has simplified the conventional designing procedure. The Inverted-V LPDA displays very good performance over the desired bandwidth. Wire structure is much more reliable and requires minimal maintenance. So far, no modification or any optimise on this type of LPDA. Currently, investigation on using "variable design parameters" is under consideration. This new structure shall be fully discussed in near future.

The linear array has some drawbacks in the HF radar because it does not ensure the broadband characteristic. The gain of array is reduced by some amount due to the mutual coupling effect as the main beam scanning through an angle in broadside direction.

The presence of mutual coupling is basically due to an interchange of energy among the array elements. The amount of energy passing between elements depends either on : radiation characteristics of each individual element, relative spacing between them or the orientation of direction of fire. In practice, mutual coupling is difficult to predict analytically but it must be taken into account because of its significant contribution to the performance of the array.

The proposed semi-circular array eliminates some of the above problems. Theoretically, it is a frequency independent array. The influence of mutual coupling onto array's performance is at minimum level due to its symmetrical configuration. The semi-circular array also has an advantage in term of space occupied by array.

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