CIRCULAR DUAL-POLARISED WIDEBAND ARRAYS FOR DIRECTION FINDING

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Abstract

This paper outlines the development of a new circular array of dual-polarised Fractalled Exponential Flare antennas for use as a wideband Direction-Finding (DF) array. The prototype array had a number of limitations which lead to the development of some novel array concepts to overcome these problems. These concepts include a high frequency inward-facing array and a dual-polarised array that uses half the number of elements of the original prototype to achieve the same or better performance.

1 Introduction

Electronic Support Measures (ESM) tasks are increasingly being carried out on lightweight expendable platforms such as Unmanned Air Vehicles (UAVs). Developing an ESM system to work on such platforms presents new challenges.

The work described here covers the antenna aspect of the development of a Radar ESM (RESM) system where the aim was to produce an array and beamformer with maximum possible flexibility but which was small and lightweight enough to be mounted in a typical UAV.

2 Requirements and Initial Concept

The requirements for the RESM system called for an array and beamformer that are wideband (2-20GHz or greater), dual-polarised and supports beamforming for DF with an omni-directional mode for listening.

2.1 The Array

The optimal layout for a directional array to support an omni-directional mode is circular. A series of linear arrays covering different angular sectors cannot form an equivalently uniform omni-mode with the same number of elements.

A standard way to perform direction finding using a circular array is through the use of phase-modes. However to support phase-modes, the phase centres of adjacent array elements must be less than half a wavelength apart at all frequencies. Furthermore, if the phase-centres of the elements are very close together then mutual coupling between elements will become a problem and DF accuracy will suffer.

If the elements of the circular array have fixed phase centres that are half a wavelength apart at the highest frequency then at the bottom of a 10 octave band the phase centres would be 0.05 wavelengths apart which is far too close for accurate DF. The ideal behaviour would be for the phase centre to move linearly with wavelength from the centre to the edge of the circular array as shown in Figure 1

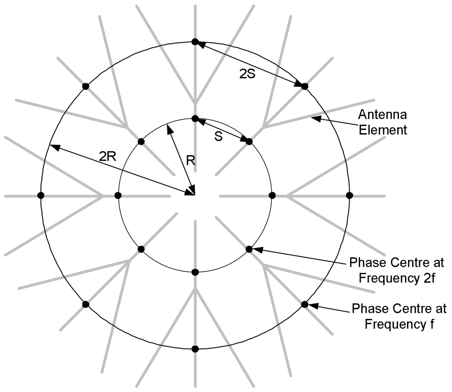

Figure 1: Ideal element phase centre behaviour in a circular array.

One antenna that shows this behaviour is the tapered slot antenna. This antenna is shown in Figure 2.

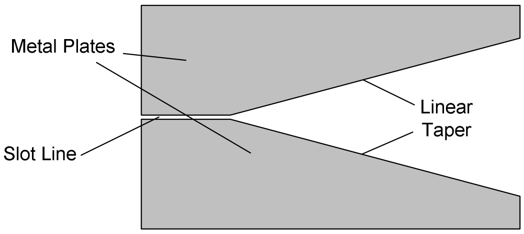

Figure 2: The Linear Tapered Slot Antenna.

The phase centre for a slot antenna lies along the axis of symmetry of the antenna at the point where the width of the slot is half a wavelength. With a linear slot the phase centre should move linearly with wavelength as required. However this antenna does not have a uniform beamwidth over its operational frequency band. A variant of this antenna, known as the Vivaldi antenna [3], has an exponentially flared tapered slot which does produce a uniform beam width with frequency. An example of this antenna is shown in Figure 3

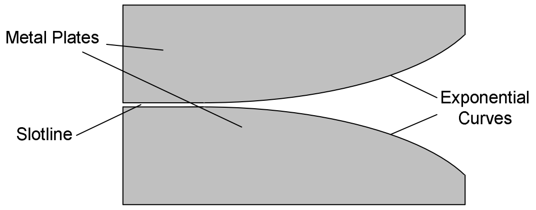

Figure 3: The Vivaldi Antenna.

Due to the shape of the flare the Vivaldi antenna is also shorter and so more compact than a linear tapered slot antenna with the same bandwidth. The phase centre no longer moves linearly, but it was felt that this was an acceptable compromise for the beamwidth stability and the compact size. The Fractalled Exponential Flare antenna [2] is even shorter than a standard Vivaldi as it blends two exponential flares together and it was this antenna that was chosen for this array.

The tapered slot antenna produces linear polarisation. For dual polarisation two antennas need to be combined in such a way that the antennas are perpendicular to each other. For the greatest flexibility the phase centres of both antennas should be coincident at all frequencies. With appropriate phasing between the two elements this will allow the element pair to receive any polarisation, i.e. any linear, elliptical or circular polarised signal.

One method of combining tapered slot elements such that the phase centres of each element are coincident is shown in Figure 4 using Vivaldi antennas.

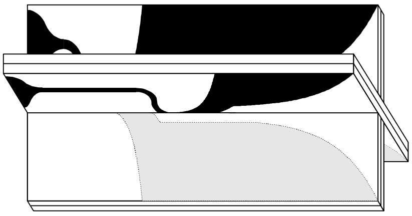

Figure 4: Crossed Vivaldi Elements with coincident phase centres [4].

The crossed design in Figure 4 comprises two antipodal Vivaldi flare antennas [5] constructed as shown in Figure 5.

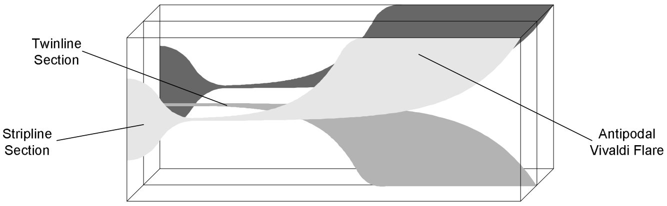

Figure 5: The Antipodal Vivaldi Antenna.

An antipodal design was used because it has good polarisation purity across its operating frequency range. It is formed from two bonded PCBs and so is easy to manufacture.

One problem with slot antennas is that the gap in the flare at the phase centre is half a wavelength, but to form a phased array the adjacent phase centres need to be a half wavelength apart. Therefore it was proposed that the crossed elements were angled at 45 degrees and arranged as shown in Figure 6 which minimises the spacing between the phase centres of adjacent elements.

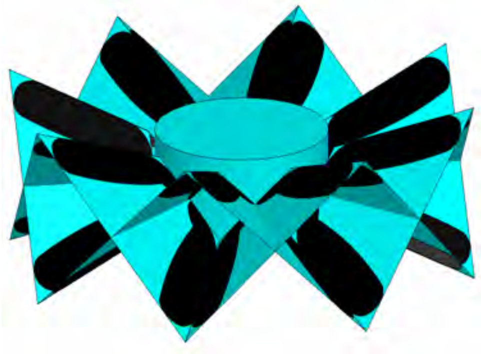

Figure 6: Circular array concept.

2.1 The Beamformer

The original beamformer planned for this array was an analogue device such as an R-KR lens [1] with several input ports and where each input port produces a separate beam. This beamformer was then connected to the receiver using a switching network. The beamformer would also have the capability of being used in an omni-directional mode as well as being able to form beams.

An alternative to this kind of beamformer would be to feed the outputs of each of the antennas directly into receivers where the inputs to the receivers are digitised. Once the antenna outputs have been digitised then they can be combined in whatever way is required. Using this approach with crossed linear elements it is possible to receive both hands of circular polarisation and any form of elliptical or linear polarisation simultaneously simply by combining the digitised data in as many ways as required. Similarly, for an array it is possible to create multiple simultaneous independent beams in exactly the same way with no loss of gain. The other advantage is that as the outputs from the array elements are fed directly into the receivers there are no losses associated with an analogue beamformer and switching network. For wideband systems, it is often some of the more narrowband components that are the source of the greatest losses in the system.

Given the benefits of digital beamforming in terms of flexibility and lower losses it was decided to use this rather than the analogue approach. However as the weight and complexity of a digital beamformer is directly proportional to the number of channels it has, then this meant that limiting the elements in the array became an important requirement.

3 From Concept to Prototype

The next step was to devise a method of feeding the array elements. This was closely linked with the number of elements used in the array because the requirement to keep the phase centres of the elements half a wavelength apart at the highest frequency of operation governs the distance of the phase centre from the centre of the array. This distance then governs the maximum space available for the feed network. Table 1 shows values for this distance for various numbers of elements and frequencies.

Elements	2 GHz	6 GHz	12 GHz	18 GHz
8	98 mm	33 mm	16 mm	11 mm
12	145 mm	48 mm	24 mm	16 mm
16	192 mm	64 mm	32 mm	21 mm

Table 1: Distance of phase centre from array centre with varying frequency and number of elements

The solution used to feed the array given the space restrictions is shown in Figures 7 and 8.

Figure 7: Crossed Fractalled Exponential Flare array element showing feed structure.

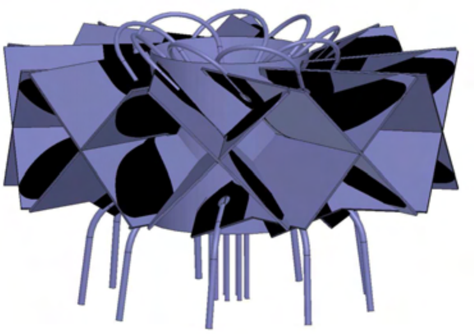

Figure 8: Feed arrangement for circular dual-polarised array.

In Figure 8 it can be seen that one half of the crossed elements are fed from the bottom of the array while the other half are fed from the top with all of the feed lines routed through the middle of the array to the bottom.

When prototype elements of this design were measured it was found that the phase centres of the elements did not move along the axis of symmetry of the antenna as predicted but instead remained at the end of the flare across the whole frequency band. It is believed that this is because the metal forming the flare was reduced to fit it within the envelope of the array. Simulations show that outside edges of the metal surfaces forming the flare support significant surface currents and contribute significantly to the behaviour of the antenna.

The final prototype array is shown in Figure 9 and comprises nine crossed elements with an overall diameter of 92mm.

Figure 9: Photograph of final prototype array.

The final prototype that was constructed was limited to forming phase modes from 3-6GHz, beamforming up to about 11GHz and direction finding up to around 18GHz.

Beamforming with a circular array can be achieved with an element phase centre spacing close to a wavelength. This is different from a linear array where the phase centres need to be closer to half a wavelength apart. This requirement for linear arrays comes from the need to “scan” the array to produce beams off of boresight. This scan angle can be up to 90-degrees requiring less than a half wavelength spacing. With a circular array the maximum scan angle for the array is half the angular spacing between adjacent elements. If a greater scan angle is required then a different sector of the array is utilised.

4 Alternative Circular Array Concepts

The limitations of the prototype array led to the proposal of a number of new array concepts to overcome some of the challenges set by the requirements.

2.1 High Frequency Array

One of the problems encountered at the high end of the proposed frequency band (20GHz+) with a circular array is that the phase centres for the elements need to be very closely spaced. This leaves very little space for the feed network. The proposed solution is shown in Figure 10.

Figure 10: High frequency array of inward facing elements.

In the array shown in Figure 10 the antenna elements face inwards towards the centre of the array. To limit blockage and cross-coupling between opposing elements, each element is rotated by 45-degrees about its axis of symmetry in the same rotation sense around the whole array. This means that opposing elements are at right-angles to each other, and being linearly polarised this means that they are effectively invisible to each other. This can be seen more clearly in Figure 11 where the Fractalled Exponential Flare elements have been replaced by dipoles for clarity.

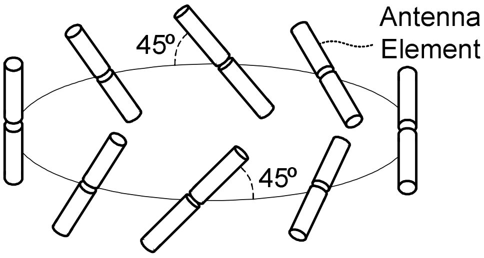

Figure 11: Side view of array showing element polarisations.

As the elements are inward facing in this array then the phase centres of the elements, which were found to lie at the front of each element, are much closer together. This means that the array can use phase modes and be used for beamforming at much higher frequencies than the outward facing array.

In addition there is no space limitation for the feed network meaning that it can be designed without sharp bends which can radiate and produce losses in the array.

Finally, although the array is not dual polarised, because the elements are rotated through 45 degrees relative to the plane of the array then the array can detect horizontal, vertical and both hands of circular polarisation albeit with a 3dB loss. Note also that as the elements are not crossed then the array can be much more tightly packed allowing the frequency range of the array to be increased further, albeit at the expense of reduced gain.

2.1 Inward/Outward facing Dual-Polarised Array

This array is a variation of the inward facing array that has a number of unusual and useful properties. The arrangement of the array is identical to the inward facing array except that the elements are bi-directional, i.e. they have a beam pattern with two main lobes facing in opposite directions. The elements are arranged such that one lobe faces inwards towards the centre of the array and so the other lobe will face outwards. An example of this arrangement using planar elliptical dipoles as elements is shown in Figure 12.

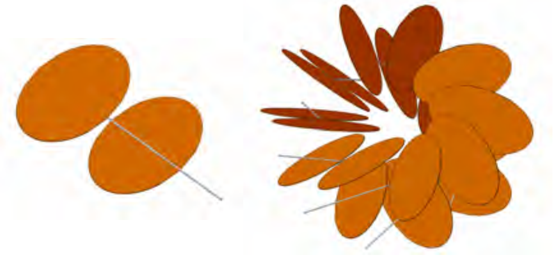

Figure 12: Inward/Outward facing array of planar elliptical dipoles.

When electromagnetic (EM) radiation is incident on the array then the component of the field with the same polarisation as the elements on the outside edge will be intercepted by these elements. The remaining component of the field will then travel through the array and be intercepted by the elements on the opposite side of the array because they have the orthogonal polarisation. This is shown in Figure 13 with dipole elements for clarity.

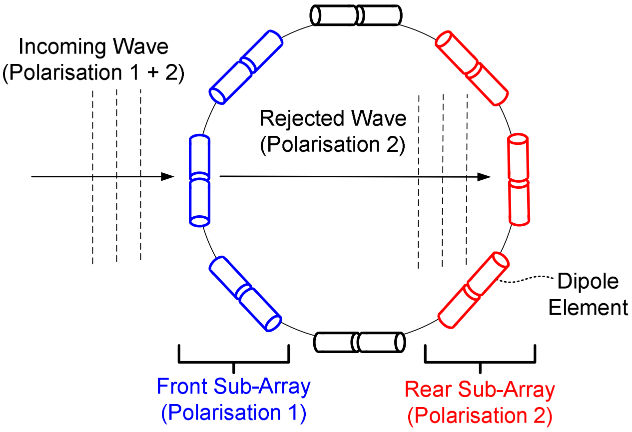

Figure 13: Interception of an EM wave by the inward/outward facing circular array.

This means that the inward/outward facing array is dual polarised and yet uses only half the number of elements required by the current prototype array for the same aperture and beamwidth.

At first glance it might appear that there is an ambiguity in determining which direction the incident wave came from. However as the array is curved there will be a phase gradient across the front and back halves of the array that eliminate this ambiguity and even provides elevation information for the direction of the incoming wave. This is illustrated more clearly in Figure 14.

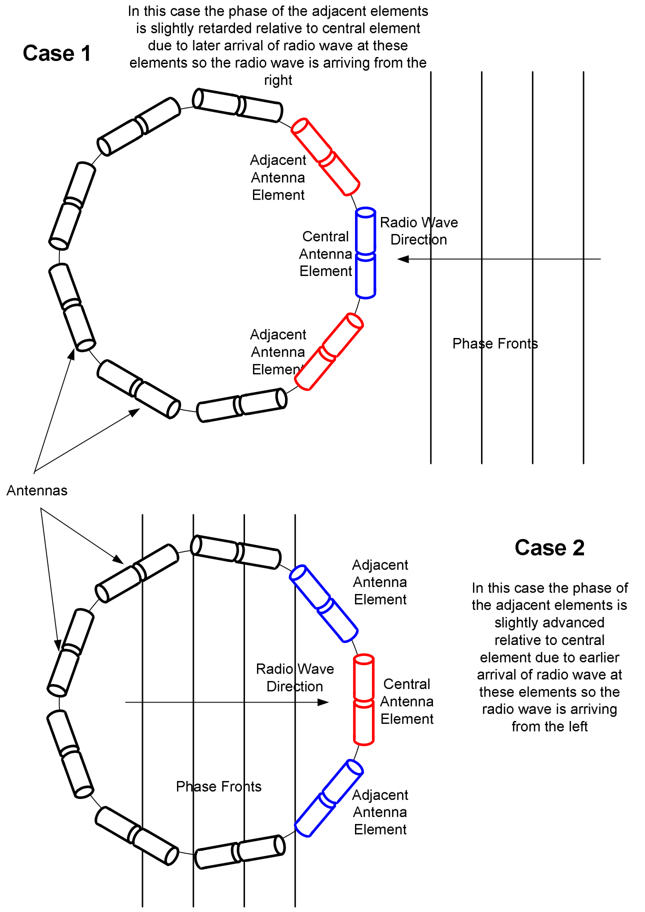

Figure 14: Determining the direction of arrival.

If the incident field is split equally between the front half and back half of the array as would be the case with most common polarisations (i.e. horizontal, vertical, right-hand circular and left-hand circular) then both the front half and back half of the array can be used separately for DF. This effectively doubles the DF bandwidth of the array compared to the current dual-polarised prototype array.

It could be argued that the prototype array (Figure 9) has two arrays of elements with orthogonal polarisations to perform direction-finding, and so should have the same bandwidth. However, in the case of the prototype array the element phase centres for each array are coincident and so no extra information is provided. With the inward/outward facing array the two parts of the array are spatially separated and so providing extra information. This is further enhanced if the array is comprised of an odd number of elements and thus making the two arrays asymmetric.

As the phase centres of elements of opposite polarisation are not coincident then at first it would appear impossible to distinguish between the most common polarisations. However, once the direction of incidence has been determined then it will be possible to establish the polarisation by knowing the relative locations of the two parts of the array.

All of this is only possible through the use of a digital beamformer. As the price, weight and complexity of a digital beamformer are currently high and directly proportional to the number of channels then this array, which uses only half the number of channels of conventional dual-polarised arrays (such as the prototype array), this is an ideal match for this technology.

In applications where the array needs to be stealthy it can be made collapsible through the use of a few rotating joints as shown in Figure 15.

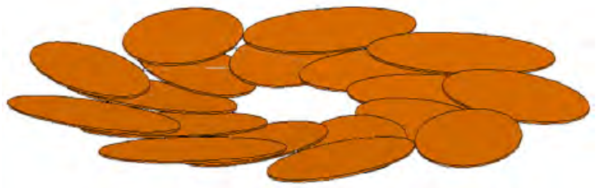

Figure 15: Collapsed Inward/Outward facing array

With the arrangement shown in Figure 15 the array can be collapsed such that it is conformal to the surface of the vehicle on which it is mounted and so significantly reducing its RCS when not in use.

The only limitation of the array is that the phase centres for the elements do not move with wavelength which limits the bandwidth of the array. However, like the high frequency array, more elements can be slotted into the array to reduce element phase-centre spacing as required albeit at the expense of reduced gain.

6 Acknowledgements

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James Fisher at Roke Manor Research Limited produced the original dual-polarised array concept.

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