Design and Manufacture of a Low-Profile Radar Retro-Reflector

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ABSTRACT

A passive retro-reflector can be defined as a device which reflects most of the energy incident upon it in the direction of the illuminator. Radar retro-reflectors are often passive, but active elements can be included to enhance the backscattered signal, or to modify it in some way, such as by the introduction of modulation or simulation of range profiles. Such devices have a significant role to play in the deception of sensors used by adversaries. This paper discusses radar retro-reflectors based on a Van Atta array.

First, existing types of passive retro-reflector are compared. The relative advantages of a Van Atta array, a trihedral corner reflector, a Luneberg lens and a sphere are listed. It is demonstrated that, for certain applications, a Van Atta array is preferred.

Next, the design of such a device is considered. Parameters discussed are element spacing, type and lengths of connections, and interconnection geometry.

A Van Atta array, with a radar cross section (RCS) of 100 m² at 10 GHz, has been built and tested. Measurement results are presented, and compared with theory, and with measured data for a trihedral corner reflector with a similar physical size.

Finally, possible further developments are described. These include, in particular, the use of amplifiers to enhance the backscatter. The relationship between amplification factor, number of elements, directionality, performance, cost and size is briefly discussed.

1.0 INTRODUCTION

A retro-reflector can be defined as a device which reflects a significant amount of radar energy in the direction of the illuminator. Some of the uses of such devices are as follows:

- As a decoy, to seduce an incoming missile away from the target, or towards a less vulnerable part of it.
- For deception, e.g. to make a particular target look like another one.
- As a beacon, for navigation assistance. For example, retro-reflectors could be used to mark the edges of aircraft runways.
- For augmentation of small objects, to make them more detectable.
- For trials simulation, e.g. for incorporation into a drone to give it an RCS appropriate to a larger aircraft.
- For radar calibration purposes.

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Ideal requirements of a retro-reflector are:

- It should have a large RCS, for its size.
- It should perform over a wide range of aspect angles and radar frequencies.
- It should have a low profile. For certain applications, the retro-reflector would ideally be conformal to the surface to which it is fitted.

Also, for some applications, it would be desirable to be able to switch the retro-reflector on and off, or modify its radar signature.

2.0 COMPARISON OF EXISTING TYPES OF RETRO-REFLECTOR

Four types of retro-reflector are considered: a sphere, a Luneberg lens, a trihedral corner reflector and a Van Atta array.

2.1 Sphere

A sphere has the advantage that its RCS is independent of aspect angle, and also frequency, except when the radar wavelength is of the same order as the sphere diameter. However, most of the incident energy is reflected in directions other than that of the illuminator, as illustrated in Figure 1.

The RCS (σ) is given by:

$$\sigma = \pi r_o^2$$

where r_o is the radius.

Consequently, for an RCS of 100 m^2, the sphere radius is 5.6 m.

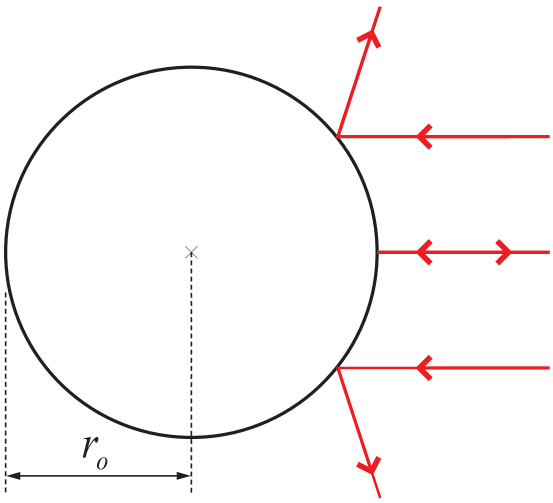

Figure 1: Sphere

2.2 Luneberg Lens

A Luneberg lens is spherical, and comprises a dielectric material, the permittivity of which is given by:

$$\varepsilon = 2 - \left(\frac{r}{r_o}\right)^2$$

where r_o is its radius,

and r defines the radius of the shell with a constant value of ε.

There is a metallised cap at the back of the lens, which subtends an angle of 2α at the centre. The value of α is typically between 45 and 90 deg. A simple diagram of a Luneberg lens is shown in Figure 2.

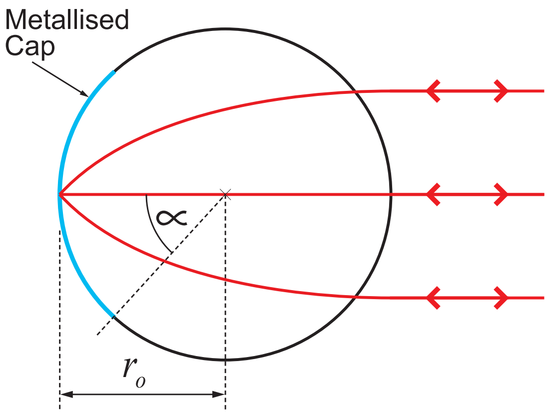

Figure 2: Luneberg Lens (side view)

For a perfectly manufactured lens, incident energy propagates along a curved path within the lens, is reflected from the metallised cap and eventually back to the illuminator. All the reflected contributions add in phase, and so the RCS is the same as that for a flat plate,

i.e. $\sigma = \dfrac{4\pi A_e^2}{\lambda^2}$

where A_e = effective aperture area

= πr_o^2 (on boresight).

In practice, the lens is manufactured from a number of shells, each with nominally constant permittivity.

The size of the metallised cap determines the shape of the polar diagram. For α = 45 deg, the RCS suddenly drops to zero when the aspect angle (θ) exceeds 45 deg. On the other hand, for α = 90 deg, the effective aperture reduces as soon as the incident direction moves away from boresight.

For σ = 100 m^2 and λ = 0.03 m, the radius r_o of the lens would be 0.16 m, i.e. 35 times less than for a sphere, with the same RCS.

2.3 Corner Reflector

A corner reflector typically consists of three flat surfaces, each of which is joined orthogonally to the other two. Each face is generally triangular, square, or the quadrant of a circle.

A simple explanation of how it works is given with reference to Figure 3, which is the side view of a dihedral corner reflector (i.e. a corner comprising two faces). The ray paths in the diagram illustrate that, for the incident direction shown, all the energy incident upon either face impinges onto the other face, and is subsequently reflected towards the illuminator. Furthermore, a simple geometrical calculation shows that all the ray paths are equal in length.

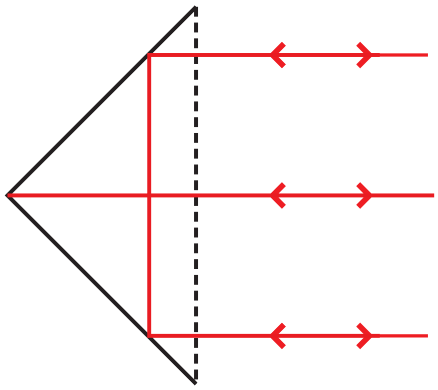

Figure 3: Side View of Dihedral

The RCS in the boresight ($\theta = 0$) direction is therefore given by:

$$\sigma = \frac{4\pi A_e^{\,2}}{\lambda^2}$$

However, as θ increases, more and more rays which are incident upon one face, fail to intersect the other, thus reducing A_e to a value which is lower than the projected aperture area.

Similar principles apply to a triangular trihedral corner reflector, the aperture of which is shown in Figure 4. It can be shown that, for the incident direction which is orthogonal to the aperture, only the incident energy within the central hexagon will impinge on all three faces (at $\theta = 0$). Consequently the effective aperture area (A_e) is reduced to $\frac{2A}{3}$, where A is the actual aperture area.

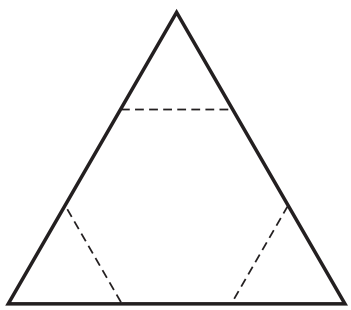

Figure 4: Aperture of Trihedral

2.4 Van Atta Array

Referring back to Figure 3, the aperture of the dihedral is shown as a broken line. If the aperture is replaced by an array of antennas, such that all the incident energy is absorbed, and if each antenna is joined to the diametrically opposite one, using connectors of equal length, then the operation of a corner reflector is simulated. The resulting device is a Van Atta array, the aperture of which is shown in Figure 5.

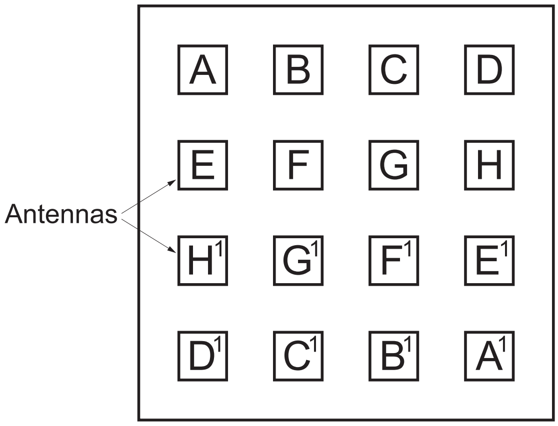

Figure 5: Van Atta Array Aperture

In this case, there are connections of equal length between antennas A and A^1, B and B^1 etc.

Provided that all the incident energy is absorbed,

$$\sigma = \frac{4\pi A_e^2}{\lambda^2} \qquad \text{for } \theta = 0$$

where $A_e = A$

(not $\frac{2A}{3}$ as is the case for a trihedral)

Furthermore, for $\theta \neq 0$,

$$A_e = A \cos\theta,$$

so the RCS does not reduce to zero until the illumination is in the plane of the aperture. The polar diagram is therefore significantly wider than it is for a trihedral, for which the RCS reduces to zero as soon as the sightline is in the plane of one of the faces.

3.0 ADVANTAGES OF A VAN ATTA ARRAY

Figure 6 contains graphs of RCS against width for the four types of retro-reflector that have been discussed. The frequency of interest is assumed to be 10 GHz.

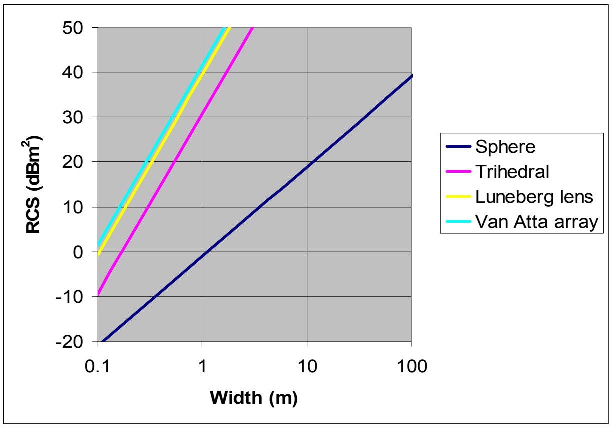

Figure 6: RCS against Width for Different Retro-reflectors

It illustrates that a sphere is a poor choice of retro-reflector, because for a given value of RCS, its size is very large. For example, a sphere of diameter 1 m gives an RCS slightly below 0 dBm^2 : 30 dB lower than for a corner reflector, and 40 dB lower than for a Luneberg lens or Van Atta array.

Table 1: Dimensions of Different Retro-reflectors Giving a Peak RCS of 100m^2

Retro-reflector	Width (m)	Thickness (m)
Sphere	11.28	11.28
Luneberg Lens	0.33	0.33
Trihedral	0.54	0.22
Van Atta Array	0.29	0.05

Table 1 lists retro-reflector dimensions giving an RCS of 100 m^2 at 10 GHz. This again illustrates that the sphere is very large compared with the other three. Also, the Van Atta array is slightly narrower than the Luneberg lens, and is approximately half the width of the corner reflector.

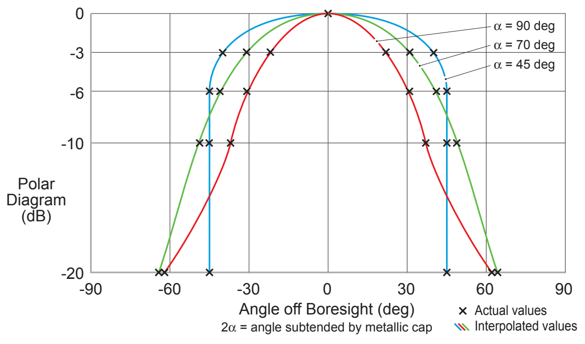

Figure 7: Polar Diagrams for Luneberg Lens with Different Sizes of Metallic Cap

The thickness is significantly less than that of a corner reflector and Luneberg lens. However, the precise thickness is dependent upon the extent to which the routing of the connections has been optimised, and the choice of connection.

The shape of the polar diagram of a Luneberg lens depends on the size of the metallised cap. This is illustrated in Figure 7. As stated in Sub-section 2.2, for α = 45 deg, the RCS drops to zero at θ = 45 deg. For larger metallic caps, the – 3 dB width drops from ± 40 deg to ± 31 deg (for α = 70 deg) and then to ± 22 deg (for α = 90 deg). However, non-zero values of RCS are achieved for θ > 45 deg.

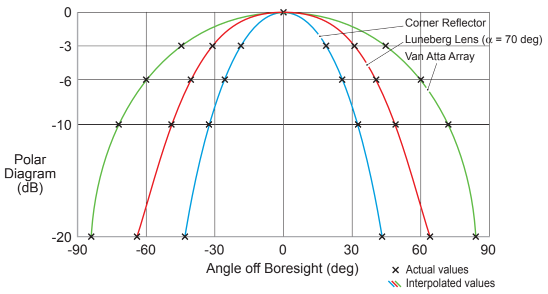

Figure 8: Polar Diagrams for Different Retro-reflectors

α = 70 deg has been chosen for the Luneberg lens polar diagram reproduced in Figure 8, for comparison with those of a corner reflector and a Van Atta array. The lens polar diagram is significantly wider than for a corner reflector, but significantly narrower than for a Van Atta array.

Characteristics of the four different types of retro-reflector are summarised in Table 2. A sphere, for almost all applications, can be ruled out, because of its physical size. A Luneberg lens or corner reflector would be a good choice if a wideband retro-reflector is required. However, if the frequencies (and polarisations) of interest can be accommodated by an appropriate choice of antenna, a Van Atta array should be used. This is not only smaller than the other two, it also has a polar diagram which is significantly wider.

Table 2: Summary of Performance of Retro-reflectors

Retro-reflector	Width	Depth	Polar Diagram	Bandwidth	Polarisation	Comments
Sphere	Very large	Very large	Very wide	Wide	Any	Unsuitable for many applications, due to size
Luneberg Lens	Small	Greater than Trihedral or Van Atta array	Good	Wide	Any	A good wideband retro-reflector
Trihedral	Greater than Luneberg lens or Van Atta array	Comparatively small	Narrowest	Wide	Any	A good wideband retro-reflector
Van Atta Array	Small	Potentially very shallow	Second to sphere	Limited by choice of antennas	Limited by choice of antennas	Potential for i) electronic switching ii) inclusion of amplifiers iii) simulation of range profiles

A Van Atta array also has potential for:

- Electronic switching.
- Inclusion of amplifiers, thus increasing the RCS of an array of a given dimension.
- Simulation of range profiles, which could extend off the back of the target, by increasing the length of the connections.

4.0 DESIGN CONSIDERATIONS

4.1 Element Spacing

Antenna elements should be separated by a distance which is sufficiently small to ensure that most of the incident energy is absorbed, and that grating lobes are not formed by the coherent addition of the signals re-transmitted from the antennas. However, they should be far enough apart to minimise the number of antennas required for a given array area.

For microstrip patch antennas, the optimum separation between centres is of the order of 0.6 λ.

4.2 Lengths of Connections

It is necessary to ensure that all the reflected signals add in phase. The best way to achieve this is to make all connections equal in length. This implies that the length of the connections must be at least equal to the maximum diameter of the array. Consequently, connection of two antennas close to the centre of the array becomes inconvenient.

For any given frequency, it is sufficient that the lengths of connection differ by an integral number of wavelengths. However, if the retro-reflector is required to operate over a narrow bandwidth, it may be acceptable to vary the lengths of connections by a few wavelengths, without significantly degrading its performance at the band edges.

4.3 Type of Connection

Two types of connection are considered: semi-rigid co-axial cable, and microstrip.

Semi-rigid co-axial cable has a loss of 0.06 dB/λ for a diameter of 3.6 mm, and 0.09 dB/λ for a diameter of 2.2 mm. Loss is greater for microstrip, and is dependent upon impedance, and also the thickness, permittivity and loss tangent of the substrate.

Semi-rigid co-axial cable is therefore preferred for most cases, although there may be applications for which the need for a very thin retro-reflector is such that the additional loss can be tolerated.

4.4 Interconnection Geometry

Straight lines joining pairs of antennas, which need to be connected, all pass through the centre of the array. For two antennas close to the array centre, the connection needs to be the same length (for a broadband retro-reflector), consequently one option is to make the device thicker at the centre, than at the extremities. For a Van Atta array of constant thickness, careful routing of the connections is necessary. In order to achieve an optimum thickness, use of routing software may be appropriate, especially if the array is large.

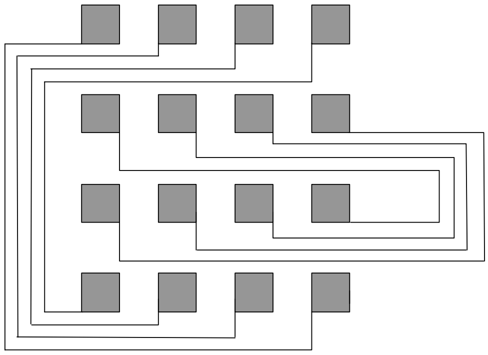

Figure 9: Possible Geometry for Microstrip Interconnections

Similar problems occur for microstrip connections, for which a possible scheme, for a 4 x 4 array, is illustrated in Figure 9. This design could, of course, also be applied to co-axial cable connections.

4.5 Use of Amplifiers

Amplifiers may be used to enhance the RCS above that otherwise possible from a retro-reflector of a given size.

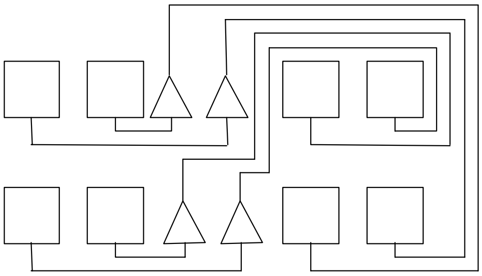

Figure 10: Use of Amplifiers, with Separate Transmit and Receive Arrays

Figure 10 shows a possible configuration, incorporating amplifiers between two 2 x 2 arrays. This configuration doubles the total size of the array. Consequently, the RCS increase, by the use of amplifiers, is G-6 dB (where G is the gain of each amplifier), compared with the (increased) array size without amplifiers.

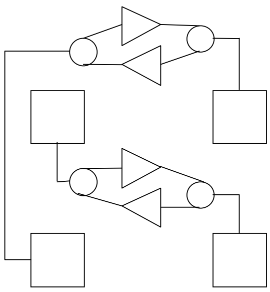

Figure 11: Use of Amplifiers in a Single Array

Figure 11 shows a configuration which does not require duplication of the array. In this case, two amplifiers and two circulators are required per link. About 20 dB is the maximum amplification that can be considered if regenerative feedback (leading to oscillation) is to be avoided.

4.6 Parameters of Selected Design

A Van Atta array has been built and tested. The device was designed to have an RCS of 100 m^2 at 10 GHz, and a bandwidth of ±5%. This gave an array size of 0.3 m x 0.3 m, 20 x 20 microstrip patch elements, and 200 semi-rigid co-axial cable connections.

5.0 MEASUREMENT RESULTS

5.1 Van Atta Array

The experimental retro-reflector is shown in Figure 12. The main contribution to the volume of the device is the matrix of cables required to connect the antennas. At present, the cables extend beyond the printed circuit board by up to 25 mm, and add up to 75 mm to the thickness. An aluminium alloy case has subsequently been added to the rear of the retro-reflector, to protect the cable matrix.

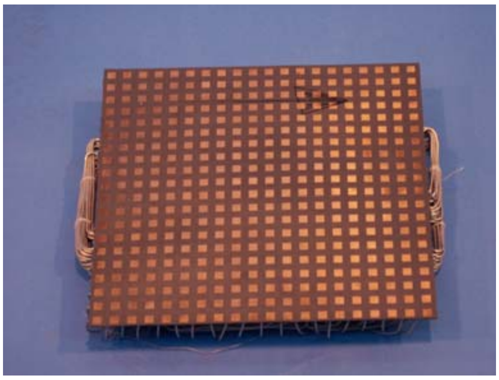

Figure 12: Front Face of Low-profile Retro-reflector

The performance of the retro-reflector was measured at the Hutton Moor Indoor Measurement Facility, near Weston-super-Mare, operated by Thales Communications UK. Measurements were carried out from 8 to 12 GHz, and at –30, 0 and 30 deg elevation, with the polarisation of the antennas of the measurement system, and the retro-reflector itself, rotated by 90 deg between sets of measurements. Consequently, data was only obtained using the single linear polarisation for which the retro-reflector was designed.

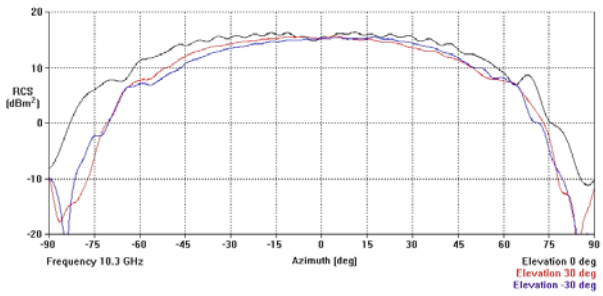

Figure 13: RCS as a Function of Aspect for a Low-profile Retro-reflector

Figure 13 shows plots of the measured RCS at 10.3 GHz, over the azimuth range –90 to 90 deg, and for elevation angles of –30, 0 and 30 deg. The results were very encouraging in that the beamwidth (± 45 deg at the –3 dB points) agreed with theory, and the bandwidth (± 10 %) exceeded expectations.

The interconnecting cables were approximately 0.5 m long, and made of 2.2 mm diameter aluminium alloy semi-rigid co-axial cable. About 1.5 dB of attenuation may be expected in these cables, reducing the expected RCS from 113 m^2 to 80 m^2, i.e. 19 dBm^2.

The measured RCS was 3 dB lower than this. This reduction is thought to have been caused by up to 4 mm of distortion of the printed circuit board, caused by stresses introduced during soldering. However, the measurements were made without the aluminium alloy case fitted. It is anticipated that the distortion has been significantly reduced, now that the case has been fitted.

5.2 Corner Reflector

A trihedral corner reflector, with edge length 0.3 m, was also measured, for comparison. This is shown in Figure 14, and corresponding RCS data, at 10.3 GHz, is contained in Figure 15. This shows that the peak RCS is 6 dB lower than for a Van Atta array, and the –3 dB beamwidth is 50% less.

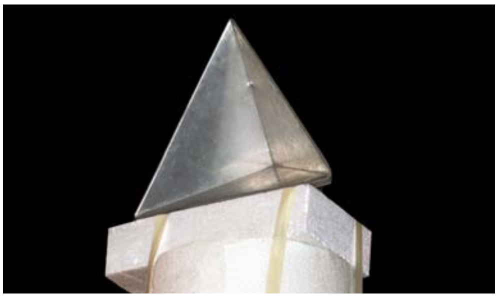

Figure 14: Corner Reflector on Polystyrene Column

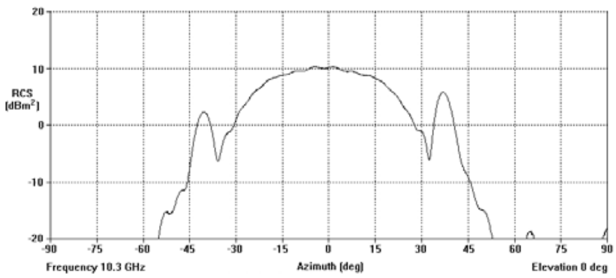

Figure 15: RCS as a Function of Aspect for Corner Reflector

6.0 CONCLUSIONS AND POSSIBLE FUTURE DEVELOPMENTS

6.1 Conclusions from Work to Date

A low-profile retro-reflector has been designed, manufactured and tested. The results were very encouraging:

- The beamwidth agreed with the theory,
- The bandwidth exceeded expectations,
- The peak RCS was 3 dB lower than theory.

However, it is anticipated that the peak RCS is now higher, having reduced the amount of distortion of the printed circuit board by the addition of the aluminium alloy case.

6.2 Possible Future Developments

Possible future developments include:

- Incorporation of electronic switching,
- Inclusion of amplifiers,
- Simulation of range profiles,
- Introduction of doppler into the reflected signal,
- Use of broadband antennas,
- Making the RCS programmable.

6.3 Incorporation of Amplifiers

For a given radar frequency, the RCS of a Van Atta array is related to the number of antennas (n) and the gain of the amplifiers (G):

$$\sigma \propto Gn^2$$

In order to determine the optimum values of G and n, the following factors need to be considered:

- Beamwidth: the larger the array, the narrower the beamwidth of the transmitted signal will be,
- Amplifier power output: for a given choice of amplifier, this will be limited to a maximum value,
- Health and Safety: this could be a problem, for large values of G,
- Feedback between the transmit and receive arrays may cause difficulties, in certain circumstances,
- Cost,
- Size,
- Type of connection: the additional loss associated with microstrip connections may be acceptable if a thin retro-reflector is required.

6.4 Final Conclusion

A Van Atta array, with amplifiers, acts as a very effective, small radar retro-reflector, which could have a varying or programmable RCS. If required, doppler could be simulated in the reflected signal. Alternatively, the device could be used to simulate range profiles.

7.0 ACKNOWLEDGEMENT

This work has been carried out with the support of the Ministry of Defence, who provided funding for manufacture and testing of the retro-reflector.