# Novel multiple phase centre reflector antenna for GMTI radar

A. Damini, B. Balaji, L. Shafai and G. Haslam

**Abstract:** Adaptive cancellation of stationary clutter for a ground moving target indicator (GMTI) radar requires antenna sensing using multiple apertures. In essence, simultaneous independent observations of the target plus clutter are required. Conventionally, multiple antenna apertures can be achieved through the use of physically separated antennas, or antennas which can be controlled so that subsections are used to receive. Herein, the use of reflector antennas to effect multiple phase centres is described. Multiple feedhorns pointed laterally from the focal point of the reflector are first reviewed, with capabilities and limitations discussed. A new technique for achieving multiple phase centres with a reflector antenna is then introduced. This technique is based on the excitation and combination of TE and/or TM modes from a single antenna feedhorn. It is shown that, by proper combination of multiple TE modes from a single feedhorn, radiation patterns with separate phase centres can be produced from the same reflector. TE and TM modes can also be combined to effect the same, but this is omitted for brevity. The characteristics of the resulting radiation patterns are analysed with a view towards maximising the separation of the antenna phase centres while maintaining symmetry between the patterns and minimising the reduction in gain and constant phase beamwidth with respect to the reflector's conventional radiation pattern.

## 1 Introduction

The problem of the detection of ground moving targets using an airborne radar has been studied for several decades. This is a challenging problem partly owing to the high dependency on antenna design. Each point on the ground, at a particular range, has a Doppler frequency ($f_d$) proportional to its relative radial velocity ($v_r$); namely $f_d = 2v_r/\lambda$, where $\lambda$ is the wavelength of the radar's transmitted waveform. Further, each point is either considered to be within the antenna's main beam clutter (endoclutter) or outside of its main beam clutter (exoclutter). A narrow antenna beamwidth means that the endoclutter comprises only a small fraction of illuminated terrain. In other words, the smaller the endoclutter, the smaller the fraction of the azimuth bandwidth of the echo signal occupied by it. Fast moving targets (larger Doppler frequencies) will generally be clear of the endoclutter. However, slow moving targets will fall within the antenna's clutter Doppler bandwidth and escape detection by a conventional single-channel radar. If a fast moving target has a small radar cross-section, its detection may be complicated by the fact that it may still be masked by sidelobe clutter.

Adaptive cancellation of stationary clutter (endoclutter) may be done using two-dimensional adaptive filtering referred to as space–time adaptive processing (STAP). The application of STAP for interference cancellation (e.g. clutter or jammer) in an airborne radar has been an active area of research for over two decades [1–3]. In order to apply STAP to clutter cancellation prior to target detection, a multiple channel radar is needed. A multiple channel radar implies a radar with multiple antennas, or a single antenna with multiple phase centres.

Minimally, a multichannel radar requires two channels. A common STAP-based radar example uses the mainbeam or sum ($\Sigma$) and difference or delta ($\Delta$) channels of a monopulse antenna and is referred to as $\Sigma-\Delta$ STAP [4]. Monopulse systems were traditionally used for tracking purposes [5, 6] but have recently been proposed for ground moving target indicator (GMTI) radar. Among the attractive features of the $\Sigma-\Delta$ solution are that it is applicable as an upgrade to continuous aperture systems and implementation cost is reduced as only two receiver/digitiser channels are required. Synthetic aperture radar (SAR) signal processing using an along-track monopulse airborne radar has been shown to be useful for simultaneous moving target detection and imaging [7, 8] and for determining elevation angles in SAR imagery [9]. In conventional monopulse reflector antenna systems (see, for instance, [10, 11]), the sum and difference beams are manifested using more than one feedhorn. This, however, reduces the antenna beamwidth and gain resulting in reduction in GMTI performance. Furthermore, the multiple feedhorns are often bulky, restricting the use of the radar in an application which may require rapid antenna rotation, such as maritime surveillance.

In this paper, we discuss a GMTI radar solution based on a multiple phase centre reflector antenna which uses a single multimode feedhorn. This antenna has several advantages over the conventional monopulse implementation, and its lightweight nature enables it to be rotated rapidly, a desirable attribute for other surveillance functions. In addition, we present an overview of the GMTI

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radar solution, utilising the proposed antenna and space–time adaptive processing (STAP) to process the radar echo data from the multiple phase centres. Later, we show how antenna phase centre displacement can also be achieved by lateral pointing of feedhorns. This solution presents several implementational challenges. However, it helps the reader to understand our results, which are based on the proposed multiple phase centre reflector antenna with the single multimode feedhorn. The application of STAP to the data received from a multimode feedhorn/reflector antenna based system is herein referred to as 'multimode STAP'.

## 2 GMTI system design considerations

STAP provides a two-dimensional adaptive filter for clutter cancellation where the apertures and pulses furnish the spatial and temporal samples. Thus, in fully adaptive STAP, received signals at each element and for each pulse in the coherent processing interval (CPI) are adaptively weighted. The weight vector can be viewed as a combined receive array beamformer and target Doppler filter. In the ideal case (e.g. when the interference covariance matrix is known), the weight vector provides coherent gain on targets while forming nulls in the angle-Doppler space to suppress the interference in the form of clutter.

### 2.1 System level description of GMTI radar

Figure 1 illustrates a two-channel radar operating in a GMTI surveillance mode. For simplicity, note that the antenna phase centre (APC) separation $d$ between APC1 and APC2, platform velocity $v$ and pulse repetition interval $\Delta T$ satisfy the displaced phase centre array (DPCA) condition $d=2v\Delta T$. Unlike DPCA [12], STAP does not require that the condition be satisfied precisely. Rather, it must be minimally satisfied, so long as the clutter rank does not increase significantly. A pulse with encoding, such as linear FM, is transmitted. The received signal is digitised and pulse-compressed through a matched filter. The input received signal is a data cube of dimension $LMN$, where $L$ is the number of range bins, $M$ is the number of pulses and $N$ is the number of apertures. The data collection is orchestrated so that for each pulse, simultaneous independent observations of the target plus clutter are effected. Space–time adaptive signal processing is performed on this data cube to suppress the clutter in each range bin as a function of angle-Doppler space. Finally, CFAR (constant false alarm rate) detection is carried out.

### 2.2 $\Sigma$–$\Delta$ STAP against multimode STAP

Systems with two phase centres have been studied in the STAP context. The most readily available two phase centre systems receive data by way of monopulse $\Sigma$ and $\Delta$ beams [4, 11]. When STAP is performed on a data cube generated from such a system, it is referred to as $\Sigma$–$\Delta$ STAP. Among the several advantages of $\Sigma$–$\Delta$ STAP over multichannel radar systems with physically separated antennas are simplified calibration, a simpler antenna, data efficiency and affordable adaptation in the context of upgrading existing hardware.

However, there are also some disadvantages. In particular, for the monopulse based reflector systems, more than one feedhorn is placed near the focus, which results in gain loss owing to both off-axis pointing and aperture blockage. We shall show that multimode STAP overcomes these problems satisfactorily. Also, unlike $\Sigma$–$\Delta$ STAP, in multimode STAP the beams are combined to form highly symmetric parallel beams which are a great asset to clutter suppression.

### 2.3 Reflector antenna feedhorn design considerations

There are several implementational and design constraints when a reflector antenna is employed on an airborne platform. First, size and weight of the reflector antenna feedhorn are particularly important for multifunction radars, which may require rapid rotation for modes such as maritime surveillance as well as a slow scan capability for

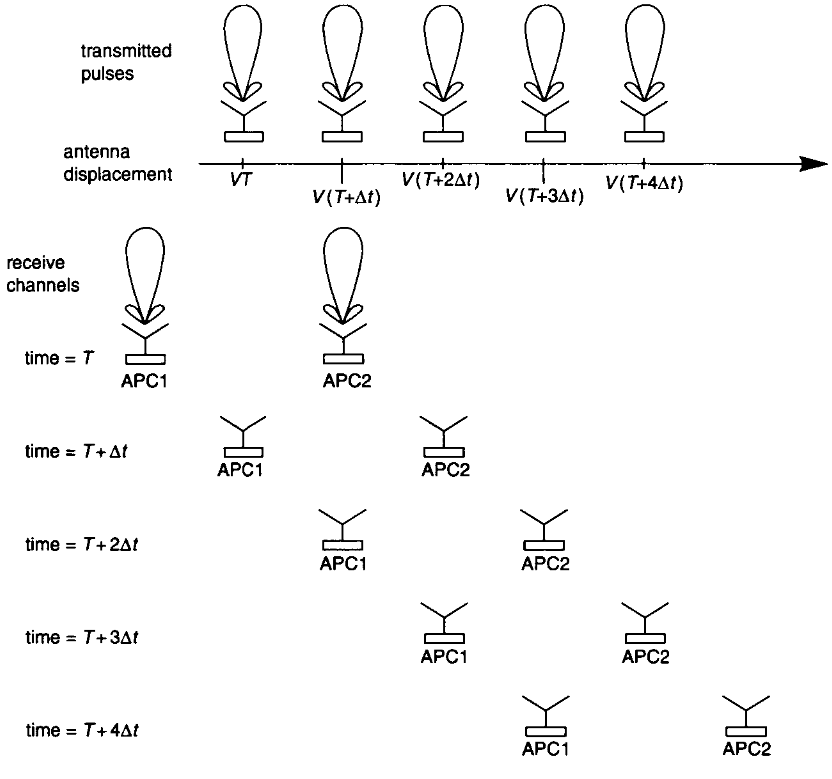

**Fig. 1** *GMTI radar with two antenna phase centres (APC)*

GMTI. Second system designers may favour a particular polarisation for a particular application. As an example, horizontal polarisation is often selected for maritime surveillance radars to minimise the return from ocean clutter. Finally, in the STAP context, it has been shown that clutter suppression performance depends on the platform velocity, pulse repetition inverval and the separation of the phase centres [2]. In particular, larger phase-centre separation results in better clutter suppression performance. To this end, the reflector antenna feedhorn should simultaneously maximise the separation of the phase centres and the constant phase beamwidth for the parallel beams, while ensuring that the beams are symmetrical and minimise any loss in gain of the parallel beams. Thus, there is a need for a tradeoff in choosing the optimum antenna feedhorn design with respect to both the laterally pointed feedhorn method and the single multimode feedhorn concept presented herein.

In the following Sections, we present design results based on a set of parameters for an offset feedhorn reflector antenna listed in Table 1 for both laterally pointed feedhorns and a single multimode feedhorn.

## 3 Feed pointing method

In this Section, we study the reflector antenna phase-centre displacement as a function of the feedhorn pointing angle. We investigate the far-field pattern in the plane of feed tilt. In our application, we are most interested in the phase-centre separation along this plane, so we highlight the corresponding phase distribution. This is useful in understanding results in the following Section, which introduces the use of the single multimode feedhorn for effecting multiple phase centres from a reflector antenna.

### *3.1 Phase-centre displacement, gain and constant phase beamwidth*

One approach to shifting the phase centre of a reflector antenna is to point the feedhorn away from the centre of the reflector. In the following, we use a feedhorn with a Gaussian beam, having a 10 dB taper over the reflector aperture. The phase centre of the horn physically coincides with the conventional focal point of the reflector (for maximum gain), while the horn itself points at a certain angle away from the centre of the aperture. The resulting beam pattern then has amplitude maximum at 0° but with a phase centre shifted away from the antenna's traditional phase centre by a distance dependent upon the feed pointing angle. To understand the phenonemon, we view the reflector as an aperture antenna. When the feedhorn is pointed towards the centre of the reflector, the phase centre of its far-field pattern is at the centre of the aperture. As the feedhorn is aimed progressively away from the reflector centre, the peak intensity of the aperture field moves away from its centre. As a result, most of the radiation comes from the portion of the aperture that contains the peak intensity, and the phase centre of the aperture moves to that side. In general, unlike a point source, which would have a well defined, unique phase centre (constant phase for all angles), an antenna having a large aperture (the reflector) compared to the wavelength will not have a unique phase centre for all azimuth angles (for instance, see [13, 14]).

**Table 1: Reflector antenna parameters**

| | |
|---|---|
| Centre frequency | 10 GHz |
| Instantaneous bandwidth | 1 GHz |
| Gain | 33 dBi minimum |
| 3 dB beamwidth | 2.4° horizontal, 4.5° vertical |
| Power handling | 50 kW peak, 500 W average |
| Reflector horizontal width | 1.01 m |
| Reflector height | 0.66 m |
| Focal length | 0.381 m ($f/d$=0377) |
| Reflector offset | 0.13 m |

Next, the antenna is analysed for various feedhorn pointing angles to study the phenomenon of phase centre movement. The method for obtaining the phase centres is as follows. The co-ordinate origin for calculating the far-field is moved to the location of the amplitude peak on the reflector aperture, and the far-field phase is calculated. The phase must be constant over the main beam if the origin of the co-ordinate system is coincident with the actual phase centre. In our analysis, some iterations were necessary to locate the phase centre accurately, for constant far-field phase and for any given feedhorn pointing angle.

It is instructive to study the far-field phase distribution for lateral feedhorn pointing angles. The phase-centre displacements for various pointing angles are shown in Fig. 2. Figure 3 shows the gain performance for the reflector antenna for the same angles. Unsurprisingly, the phase-centre displacement is a monotonically increasing function of the pointing angle, and the reflector gain decreases as

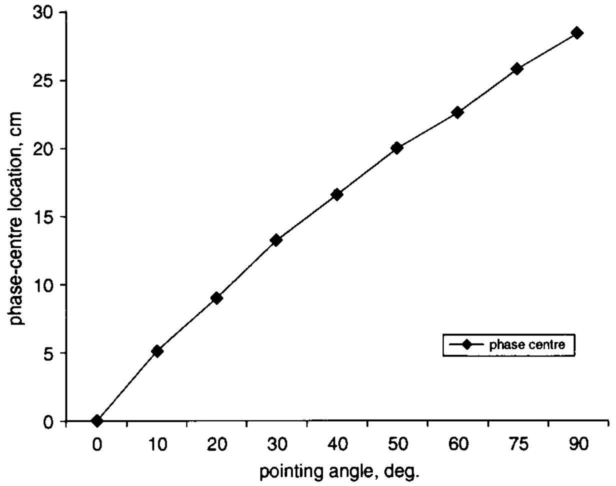

**Fig. 2** *Phase-centre displacement from the centre of reflector aperture as a function of feedhorn pointing angles*

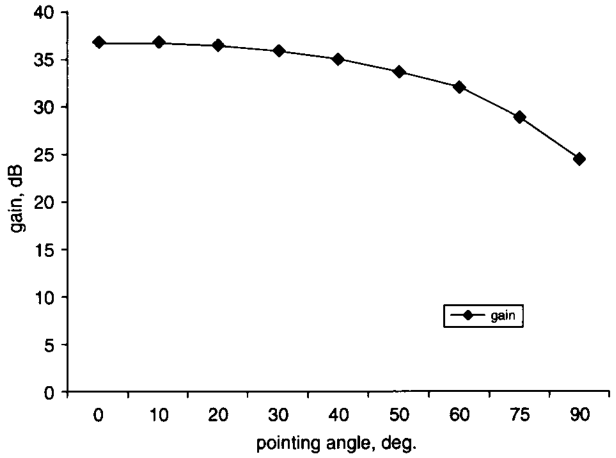

**Fig. 3** *Gain performance of the reflector as a function of feedhorn pointing angles*

only part of the reflector aperture is illuminated. However, this impacts the constant phase beamwidth (CPBW), the beamwidth over which the phase is constant. For example, the azimuth far-field CPBW is reduced to 2° for a 30° pointing angle, as opposed to 5° for a 0° pointing angle. This is because the antenna geometry is very complex, so that the offset phase centre becomes even less like a point source.

From the above results, it can be seen that significant phase-centre separation can be achieved by pointing the feedhorns laterally. The far-field beam pattern remains at 0° relative to the reflector boresight. However, a decrease in the gain performance is observed as the feedhorn pointing angle increases. Therefore, a compromise is required to obtain efficient antenna performance while maximising phase-centre displacement. Another phenomenon that is noticeable is that CPBW decreases as the feedhorn pointing angle is increased. This must also be considered when assessing efficient antenna performance as a function of the phase-centre separation.

### 3.2 Limitations

We have shown that phase-centre displacement in reflector antennas can be obtained by pointing the feedhorns appropriately. In order to obtain multiple phase centres simultaneously, more than one feedhorn needs to be placed near the focus. This approach has several shortcomings.

- Gain: Since more than one feedhorn cannot be placed exactly at the focus, there will be a loss in the gain of the resulting beam patterns. Multiple feeds increase aperture blockage, further reducing the gain and increasing sidelobes, resulting in GMTI performance loss. Finally, CPBW for the off-focal point phase centres will be smaller, further degrading GMTI radar performance.
- Fixed phase-centre separation: The phase-centre separation for any given laterally pointed feedhorn is fixed and can only be changed mechanically.
- Mutual coupling: Placement of more than one feedhorn in close proximity will lead to significant mutual coupling effects.
- Mechanical: Radar antennas often require rotation at high angular velocities. This will present a major challenge to mechanical stability and maintainance of a fixed pointing angle.
- Electrical: The feedhorn network (and the associated electronics) required for multiple feedhorns becomes increasingly complex and difficult to calibrate.

These limitations stimulate further study of the concept of using a multimode feedhorn to effect a multiple phase-centre reflector antenna. It suggests that any scheme that is able to illuminate different parts of the reflector antenna would achieve the desired result of phase-centre displacement. The following Section introduces the concept of a single multimode feedhorn for accomplishing this.

## 4 Multimode design

Reflector antenna feedhorns are normally fed by circular waveguides that can propagate TE and TM modes. Conventional feedhorns use the dominant $TE_{11}$ mode. The higher-order modes are usually used for beam shaping or tracking. Also, high efficiency feedhorns use corrugations to improve the symmetry of the amplitude pattern. This complicates their geometry, and numerical methods must be used to determine their far-field radiation patterns. Here, to demonstrate the concept, we use a circular horn fed by a circular waveguide. The horn aperture diameter is selected to be 4 cm to allow the propagation of both $TE_{11}$ and $TE_{21}$ modes at 10 GHz and to provide suitable far-field patterns for illumination of the GMTI reflector. Other modes can also propagate in the horn, but for simplicity are not included in the analysis since they are not used in the target application. It will be shown here that by manipulating the amplitudes of the dominant and secondary modes in the circular waveguide, two physically separated phase centres are realised.

### 4.1 Beam shaping using multiple modes

The main idea behind the use of multimode techniques is to implement secondary modes in order to control the radiation characteristics of the feedhorn [15]. Here, we use them to displace the reflector phase centre. For simplicity, we use the far-field patterns of the waveguide feedhorn modes radiated from its open end. In the illuminated portion of the reflector, i.e. angles less than 50°, these beam shapes are a good representation of the reflector feed patterns and can be used for demonstration of the concept. For a GMTI radar, the main design criterion requires separation of the phase centres without significantly compromising the gain, symmetry and CPBW of the parallel beams. This provides simultaneous independent observations of the target plus clutter, which is required for clutter suppression using STAP. The $TE_{21}$ mode in combination with the $TE_{11}$ mode can accommodate this design specification.

The multimode feedhorn is shown in Fig. 4. The $TE_{21}$ mode is symmetrically excited from the sides of the circular waveguide while the $TE_{11}$ mode is excited from the end of the waveguide. As we shall demonstrate, the $TE_{11}$ and $TE_{21}$ modes can be assigned amplitude and phase weightings and combined to achieve identical parallel beams. The main idea behind this technique is to achieve a phase-centre displacement phenomenon by implementing multiple modes in a single feed, instead of multiple feeds with single TE modes, as in the previous Section. In the following, we concentrate only on the case of two-phase centres formed by combining the $TE_{11}$ and $TE_{21}$ modes.

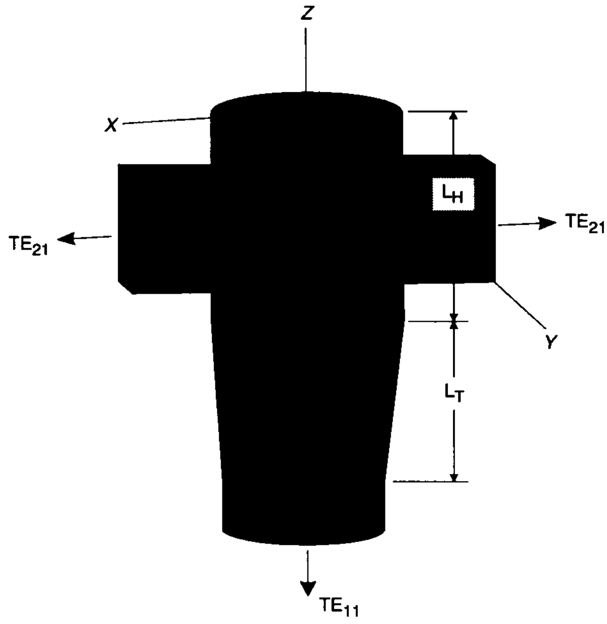

**Fig. 4** *Schematic drawing of a multimode feedhorn ($L_T = 0.03$ m, $L_H = 0.08$ m)*

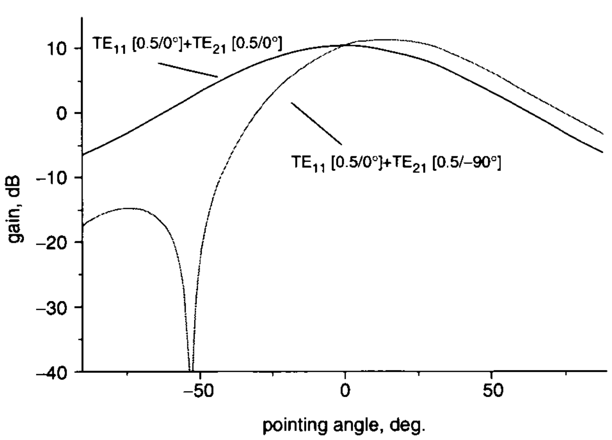

**Fig. 5** *H-plane radiation patterns (gain against angle) for $D = 4$ cm circular waveguide for combined $TE_{11}$ and $TE_{21}$ blue: $0.5(TE_{11}+TE_{21})$ green: $0.5(TE_{11}+TE_{21}j)$*

Figure 5 illustrates the combining of the $\mathrm{TE}_{11}$ and $\mathrm{TE}_{21}$ modes with equal power but different phasing. This Figure captures the TE modes as they are emitted from the circular feedhorn, not reflected from the antenna aperture, i.e. the far-field of the feedhorn. It is seen that the single multimode feedhorn radiation pattern's peak moves away from its axis when the two modes are ±90° out of phase. These results are analogous to the feedhorn pointing technique.

### 4.2 Shift in reflector antenna phase centre using multiple modes

So far we have shown only the waveguide feedhorn patterns; now we will study the resultant reflector antenna beam patterns. Ultimately, we are interested in the radiation patterns of the reflector antenna. For a GMTI radar application, the $\mathrm{TE}_{11}$ mode forms the transmit beam. The received beams are implemented via a combination of $\mathrm{TE}_{11}$ and $\mathrm{TE}_{21}$ modes in the multimode horn. The corresponding radiation characteristics of the combined modes yield the received patterns. Again, the received TE modes are combined algorithmically eliminating the need for separate feeds to achieve multiple phase centres. During transmission, power is applied to the $\mathrm{TE}_{11}$ port exciting only this mode. Upon reception, energy is extracted from both the $\mathrm{TE}_{11}$ and $\mathrm{TE}_{21}$ ports.

An appropriate complex power ratio is used in software to combine the $\mathrm{TE}_{11}$ and $\mathrm{TE}_{21}$ modes. The phase centre moves away from the origin as the power contributed by the $\mathrm{TE}_{11}$ mode is decreased and the contribution of the $\mathrm{TE}_{21}$ mode is increased. The goal is to find the combination which results in acceptable compromise between radiation performance and phase-centre separation. For each complex power ratio, the phase-centre location is determined as the point where the CPBW of the main lobe is maximum. For instance, the H-plane pattern for the $0.6\ \mathrm{TE}_{11}+0.4j\ \mathrm{TE}_{21}$ combination is provided in Fig. 6 and the corresponding phase distribution is provided in Fig. 7.

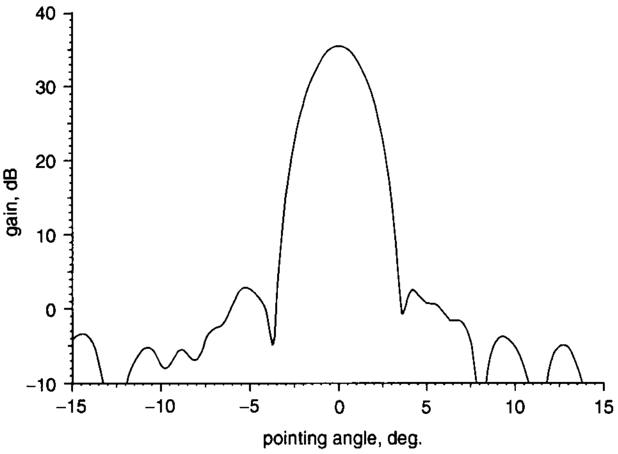

**Fig. 6** *H-plane reflector antenna radiation pattern for $(0.6\ TE_{11}+0.4jTE_{21})$ excitation, $D = 4$ cm circular horn at the focal point*

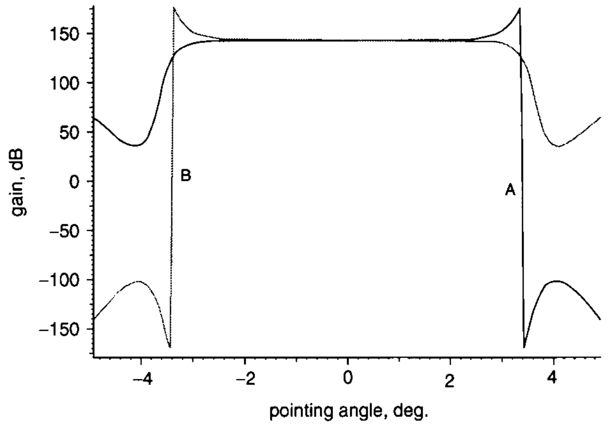

**Fig. 7** *Phase distribution of the far-field for $(0.6\ TE_{11} \pm 0.4j\ TE_{21})$ excitation when the co-ordinate origin is moved on the reflector aperture to the phase-centre location near the peak field intensity (± correspond to A, B)*

From the above results, it can be seen that phase-centre separation is achievable with the single multimode feedhorn technique. For the above case, a phase-centre separation of $d = 20.4$ cm was obtained between the two parallel beams. The gain of the reflector antenna drops to about 35.5 dBi, which is a decrease in gain of 1.4 dBi in comparison with the beam associated with the pure $\mathrm{TE}_{11}$ mode of operation. Remarkably, the CPBW remains about the same as for the pure $\mathrm{TE}_{11}$ case (i.e. about 5°). The amplitudes of the two beams resulting from the $0.6\ \mathrm{TE}_{11} \pm 0.4j\ \mathrm{TE}_{21}$ combination are identical because of the symmetric characteristic of the reflector antenna aperture and the manner in which it is illuminated by the single multimode feedhorn.

Several cases of the feedhorn are analysed by altering the amplitude distribution between the $\mathrm{TE}_{11}$ and $\mathrm{TE}_{21}$ modes. The dependence of reflector antenna phase-centre displacement and gain as a function of mode power amplitude ratios are summarised in Figs. 8 and 9, respectively. From Fig. 8, it can be observed that a significant phase-centre separation can be achieved with the multimode technique. However, this comes at a cost. As the phase centre moves away from the origin, antenna gain is decreased. The gain drops significantly as the phase centre moves towards the edge of the reflector. Furthermore, CPBW starts decreasing and the parallel beams become less symmetric in amplitude. Therefore, a compromise is required in the selection of the mode power amplitude ratios to achieve the best possible phase-centre location without significantly affecting the radiation characteristics.

### 4.3 Multiple phase centre reflector antenna summary

We have demonstrated that phase-centre separation can be more effectively obtained by using multiple modes in a single feedhorn, as opposed to a single mode in multiple laterally pointed feedhorns. For instance, a single circular waveguide or circular horn permitting propagation of the $\mathrm{TE}_{11}$ and $\mathrm{TE}_{21}$ modes can act as the feedhorn of a reflector antenna. This reflector antenna is then equivalent to a two

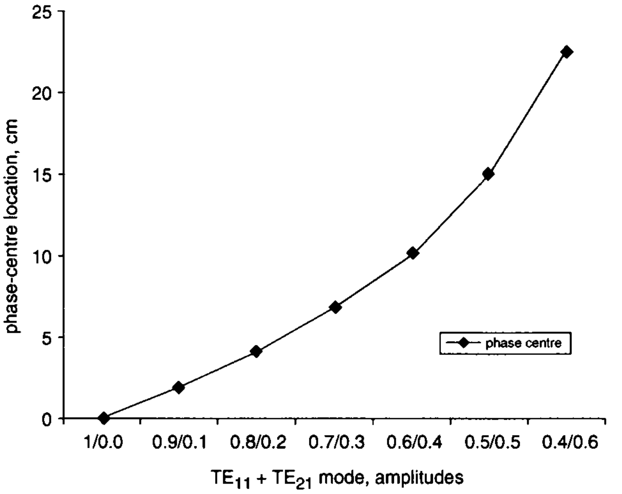

**Fig. 8** *Phase-centre locations (i.e. displacements from the aperture centre) as a function of $TE_{11}$ and $TE_{21}$ mode power amplitude ratios*

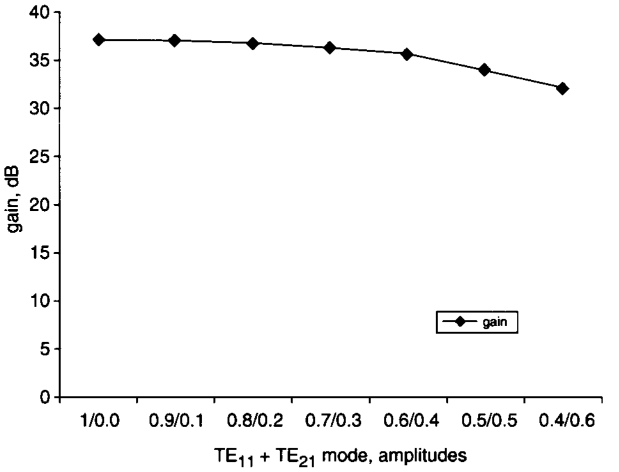

**Fig. 9** *Gain performance of the reflector antenna as a function of $TE_{11}$ and $TE_{21}$ mode power amplitude ratios*

phase centre antenna and hence is suitable for GMTI radar applications. By adjusting the power combination of the $TE_{11}$ and $TE_{21}$ modes in software the phase-centre locations can be altered. The phase associated with the $TE_{21}$ mode can be switched to either a positive or a negative value ($\pm j$) to obtain phase-centre locations on either side of the antenna focal point. In other words, this multimode feedhorn provides two offset parallel beams without the use of two feeds. The effectiveness of the multimode feedhorn technique is confirmed by comparing Figs. 2 and 8. For instance, feedhorn pointing of about 22° provides a 10 cm phase-centre displacement, similar to the multimode case with feedhorn diameter of 4 cm and mode combinations of $0.6\ TE_{11} + 0.4j\ TE_{21}$.

Finally, a multimode feedhorn can also be designed to operate using the dominant $TE_{11}$ and higher-order $TM_{01}$ modes. The latter mode does not radiate the azimuthal $E_\phi$ component, and its $E_\theta$ component can be used, as in the previous case, to shift the radiation beam peak to one side of the reflector aperture. The resulting effect will be similar to the previous case and details of its study are omitted for brevity.

## 5 Conclusions

The theory behind a multiple phase centre reflector antenna which uses a single multimode feedhorn was presented. Conventionally, phase-centre displacement is achieved either through the use of physically separate antennas or, in the case of a single reflector, by lateral pointing of multiple feedhorns. It is shown that by proper combination of multiple TE modes, parallel radiation patterns with separated phase centres can be produced from the same reflector. TE and TM modes can be combined to effect the same result. For a GMTI radar, it is desirable to maximise the separation of the antenna phase centres, while maintaining symmetry between the radiation patterns and minimising the reduction in gain and constant phase beamwidth with respect to the reflector's conventional radiation pattern. Analysis of an X-band reflector antenna/multimode feedhorn with one GHz bandwidth indicates that two separate phase centres, with radiation patterns minimally degraded from the reflector's conventional transmit pattern, are indeed achievable. Non reflector-based GMTI radar antennas (e.g. microstrip or slotted waveguides) often use subsets of the full transmit aperture for receiving so that the resulting receive patterns have a wider beamwidth than the full aperture allowed for transmit. A further positive note from the GMTI radar perspective is that the two receive radiation patterns for a multimode feedhorn based multiple phase centre reflector antenna depend on the full reflector aperture so that the beamwidth, and hence clutter bandwidth, are not unduly increased. The two phase centres allow simultaneous independent observations of the target plus clutter reflectivity field. The multiple phase centre reflector antenna thus enables the concept of multimode STAP for clutter cancellation and subsequent target detection.

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