LENS-REFLECTOR ARRAY ANTENNA FOR SATELLITE COMMUNICATIONS ON THE MOVE.

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ABSTRACT

The hemispherical lens-reflector is a well-known type of scanning antenna and has a relatively low profile compared to a dish of comparable gain. Its array variant offers further reductions in mass and height albeit with the concomitant additional complexity of an array feed network. Luneburg lenses have been used, but need not be. This paper reports an activity under ESA’s ARTESS programme to develop a lens array, initially for Ku band (and eventually Ka band) for bi-directional communications to on-the-move platforms. The lens dimensions for a two-element array have been chosen for equivalent area to a 61 cm aperture, leading to an aperture height of 220 mm (300 mm including platform). At 12.5 GHz the G/T of around 15 dB/K exceeds that of other products we are aware of with similar height constraints. For Ku band, a waveguide feed network has been developed which allows variation of the linear polarisation for both transmit and receive bands while minimising cross-polar coupling. A bi-product of the waveguide power combiner includes a monopulse difference port which may assist with azimuthal pointing error detection, augmenting a conventional step-track method.

1. INTRODUCTION.

By ‘Satellite Communications (Satcoms) on the Move’ (SOTM) we refer to bi-directional communications to terminals on vehicles and employing tracking antennas. Vehicle types and environments predominantly include ‘land mobile’ e.g. wagons for on-road or off-road use, passenger trains, aircraft (be they manned or unmanned), and ships. In maritime applications stabilised reflector antennas are well established for use at Ku band, and these types are also encountered for land mobile, notably in defence applications [1]. In contrast, airborne and rail applications are more likely to need low profile antennas and here some elliptical profile reflectors have been developed [2]. Low profile antennas can also be advantageous in other environments, e.g. military vehicles where reduced visibility and radar cross section may be sought. Besides the elliptical dish, approaches to reducing aperture height have included flat panel and array type antennas which are mechanically steered, phased arrays [3] with all-electronic beamforming, and hybrid methods.

This paper reports on variants of the hemispherical lens-reflector as a low profile antenna. Whilst not a new concept [4], increased interest in low profile scanning antennas for SOTM has inspired fresh investigations into how it might best be applied. We show how polymer stepped-index lenses can compete favourably with the more traditional Luneburg and constant index types so long as the aperture diameter is properly scaled, and how this makes the array variant attractive. Arrays of 2 or 4 lens elements are logical choices. We show how either can be suitable for Ku or Ka bands, and present a 2-element lens-array prototype scaled to be workable for both bands i.e. up to 30 GHz.

2. LENS EFFICIENCY, TRADE-OFFS, AND RADIATION CONSIDERATIONS.

The constant-index spherical lens has well known and useful scanning properties. However, its efficiency drops off for directivities above about 26 dBi owing to its mediocre focussing properties – Fig. 1(a). The efficiency roll-off is a consequence of spherical aberration. In contrast, the Luneburg lens, illustrated in Fig. 1(b), has unity efficiency at any frequency in theory – i.e. efficiency does not roll off with frequency from a consideration of optics. Of course, where a practical ‘Luneburg lens’ is really a stepped-index approximation to the ideal case, the efficiency will indeed be limited by mechanical, materials and assembly issues. We have found Luneburg lens suppliers reluctant to offer any efficiency guarantees above about 15 GHz. Between these two approaches, a two-layer polymer lens offers very useful efficiency for directivities in region 28-35 dBi (beyond this, more layers are needed), so long as very low loss materials are used. Fig. 2 summarises the trends where we see the constant-index lens efficiency falls off sharply beyond about 10 wavelengths diameter, while the two-layer lens could have about twice the diameter for an equivalent efficiency. These curves are derived from spherical wave expansion theory, which accurately accounts for scattering at boundaries and derives efficiency from the far field pattern. Dielectric loss has not been included in the upper curves, nor an accurate feed model (a dipole array is used.
instead, which further flatters the predicted gain\(^1\). The dashed curves are then best estimates for what can be realised in practice. Nevertheless the theory curves represent a best case which could be approached if all other factors (feed pattern, materials) are optimum. Data for Luneburg lenses has not been included because the discrepancy between theory (unity efficiency) and practice would be even wider, and manufacturers’ data would put the efficiency at 15 GHz in a region comparable to the constant-index lens. Fig. 2 also shows physical diameter at 3 frequencies. From the efficiency curves we can see at a glance why a number of small lenses would offer higher efficiency than a single lens of equivalent aggregate area.

Thus, in a certain regime, a two-layer polymer lens implemented as an array will offer better efficiency than a single lens of equivalent area. It remains to then choose dimensions and for the present exercise a 610 mm equivalent aperture was selected, realised as two lens apertures each of 432 mm diameter.

\[ \varepsilon_r = 2 \left( \frac{r}{R} \right)^2 \]

![Figure 1 Approximate ray tracing in spherical lenses (a) constant index and (b) Luneburg.](image)

If operation at only Ku band was required (<15 GHz) there would be very little efficiency benefit in two lenses over one. At Ka band the case is very different and the array approach is considered essential. At 20 GHz (receive) the efficiency is adequate to maintain healthy G/T, while at 30 GHz the efficiency short-fall could be mitigated by spending a little more on the Tx power amplifier. Thus the 610 mm equivalent occupies a good compromise region for the two-element array and both frequency bands. A four element array remains attractive for Ka band but would occupy more lateral space and we have not pursued it.

Grating lobes are usually perceived as a disadvantage, but since these are manifested as lobes within the spatial envelope of the radiation pattern for the individual aperture, they can be acceptable, as seen in Fig. 3. Here a measured lens pattern, scaled by a typical EIRP figure for a sub-2 Mbit/s link as used operationally on trains, falls within the Eutelsat Standard M off-axis radiation requirement.

![Figure 2. Trends in spherical lenses, constant index and two-layer stepped index cases.](image)

This pattern falls in the elevation plane and so the pattern should be compliant for any latitude, including equatorial regions, where other low profile antennas with more extreme pattern asymmetry may fall short owing to excessive beamwidth in the elevation plane. The hemisphere-reflector reported scores well here because the elevation beam arises from an aperture whose equivalent height is twice the physical height. Also, by inference, the grating lobes of the azimuth pattern will peak at the envelope of the elemental pattern of Fig. 3. (See also the measured array patterns.)

![Figure 3. Radiation pattern for individual lens compared to Eutelsat Standard M for small terminals (< 2Mbits/s).](image)

The array will also exhibit lower mass and lower height than the single aperture. To capitalize upon these

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\(^1\) Since the above analysis was completed, the SWE method has been extended to include realistic feed patterns.
advantages, an efficient array power combiner must also be used. Fig. 4 shows that antenna gain tends to be proportional to height but that the lens array deviates from the usual trend.

Figure 4. Trends in scanning antennas, Ku band.

The range of elevation scan angles is another important metric for this class of antenna. Low elevation is limited by two mechanical issues: (i) the lowest proximity of the primary feed to the ground plane and (ii) the lateral extension of the ground plane on the opposite side from the feed. The role of the ground plane is vital in producing a mirror image of the hemisphere which recovers the full spherical-equivalent aperture. Its dimension cannot be infinite, and so will lead to scanning loss below some elevation threshold [5]. We have chosen mechanical scan down to 15° and the loss-free threshold of 20° for operation on ground vehicles at European latitudes. Satcoms-on-the-move is in any case highly problematic at lower elevation angles owing to line-of-sight obstructions. The ground plane extension of (almost) the lens diameter leads to a rotational swept footprint of around 1165 mm. This lateral growth of an antenna’s occupied space is an inevitable consequence of reducing the aperture’s height, and occurs in other low profile configurations.

Maximum elevation is not particularly limited since the feeds may be positioned at or beyond 90°, but two detrimental effects should be considered: (i) at high elevation the feeds will begin to contribute to occupied height – this drove the development of a ‘folded’ waveguide feed chain, and (ii) aperture blockage by the feed chain will begin to degrade the radiation pattern. Targeting European latitudes, we have designed for a maximum scan elevation of 50° - this is not a hard limit and could be extended by various measures, such as inclining the ground plane.

3. WAVEGUIDE FEED CHAIN AND ARRAY POWER COMBINER.

Various strategies could be attempted to combine the RF power from the two lens apertures. The challenges to be addressed include: overall combiner efficiency, control of linear polarisation while providing for transmit and receive signals, attaining adequate cross polar discrimination, and minimising antenna height. In one approach, each aperture could use a conventional feed, OMT and transmit/receive electronics chain, with power combining possibly carried out at intermediate frequency. Each OMT would then rotate about the feed axis to set the local polarisation vector. This approach was rejected on account of its cumbersome layout. Instead, RF power combining was selected using an all-waveguide method prior to single Tx and Rx ports. A polariser is used in each side of the feed chain. Fig. 5 shows the components developed for this purpose, prior to the addition of the mechanical actuators which set (i) feed elevation and (ii) polarisation angle. Quite abrupt 90° bends are integrated into the primary feed waveguide section so as to minimise the encroachment into headroom, by the feed chain, which tends to occur at high elevation angles. These bends can have a strong and undesirable effect on cross polar coupling, and necessitated very close attention to the internal waveguide structure. We refer to this layout as ‘folded’ waveguide on account of the OMT running orthogonally to the radiating feed axis. Also in Fig. 5 the transmit reject filter and LNB (entirely conventional items) have yet to be added to the Rx port.

Figure 5 Lens array and waveguide feed chain.

We propose a short length of flexible coax to connect Tx power amplifier to the Tx waveguide port. (An all waveguide interconnect might be feasible, via rotary joints, but we have not yet addressed this.)
A spin-off benefit of the array and power combiner is the addition of a 3rd port for the receive difference channel, which may assist with azimuth angle error detection (monopulse) in the implementation of tracking. A very similar waveguide layout could be used for Ka band (20/30 GHz) where circular polarisation is commonly used; this obviates the need for the linear polarisation actuation stage.

4. MEASUREMENTS AND RESULTS.

Following intensive design efforts aided using the commercial EM solver CST Microwave Studio, development versions of the waveguide components were fabricated, then measured using an anechoic chamber. Feed patterns were as expected, but their inclusion here would not be of great interest. In contrast, cross polar (XP) coupling presents a thorny challenge and arises from the polarisers and waveguide bends. This was examined in detail but found difficult to measure to XP discrimination (XPD) levels below about -35 dB owing to limitations of anechoic chambers. This figure is also the most stringent usually specified for operation where it contributes to co-satellite XP interference, and was achieved for the transmit band. During summer 2011 the first feed-lens measurements were made using a single, non-folded primary feed and an inclinable jig (Fig. 6) so that different elevation angles could be used.

However for a very symmetric pattern, such as we expect the lens to exhibit, a single cut can be sufficient. A far field transform written for this purpose showed a good agreement both with theory and later measurements (Fig. 7). Also, the lens was found to not contribute to measurable XPD, which is also expected from consideration from its symmetry, unlike, for example, an offset-fed reflector. Later, the same lens and jig was measured using a small planar near field scanner, which is a much better facility for an electrically large, directive antenna. In this suite of measurements, gain was by-and-large in line with expectation, but sidelobes were observed to be highly variable – Fig. 7 shows one of the nastier examples. These distortions were thought likely to be caused by poor primary feed alignment, ground plane curvature, and air gaps, and so the temporary jig was not further used. Instead, efforts then focussed on completion of the prototype ('breadboard') where more careful attention was paid to feed chain alignment with respect to the lens array. The ground plane used is a commercial grade double-skinned aluminium ‘honeycomb’ type (Fig. 5).

The final suite of measurements was carried out in August 2012 at MDA Space Mission’s near field measurement facility at their Montreal site. A proper calibration for gain was made. A large number of measurements were carried out for: each individual lens, parts of the feed chain, the lens array, the various OMT ports, various polarisation states, and at different feed elevation angles. At the time of writing the results from these measurements are being processed, but some preliminary findings are presented. Firstly, individual lens gain was seen to be quite healthy at 70-60% over the
frequency range 10.7-14.5 GHz including ohmic losses of the order 0.6 dB, thought to be dominated by dielectric loss. The erratic sidelobe behaviour observed with the first test jig was absent (Fig. 8), indicating that the breadboard ground plane and the feed-to-lens alignment procedure were effective.

**Elevation scan.** Scan performance was examined with emphasis on the low elevation regime, where ground plane truncation limits performance. The design envelope for the current version of the antenna is a mechanical range of 15° to 50° with zero scan within 20° to 45°. The lowest angle investigated was 17°, but even at this low angle scan loss was hardly measurable. The results of Fig. 9 were derived from a single lens, but later measurements on the array confirmed that the array elevation pattern follows that of the individual lens, as expected. A little sidelobe growth is observed as scan angle reduces; for the target applications at mid-to-high geographical latitudes these sidelobes tend to lie quasi-orthogonally to the geostationary arc.

**Array patterns.** As expected, the array pattern is seen in azimuth cuts and manifested as a product of the lens pattern and array factor – Fig. 10. Gain is expected to increase by up to 3dB above the single lens case. In practice, the array pattern exhibited a slight pointing offset, or ‘squint’, which (i) detracts from the array directivity and (ii) leads to asymmetric grating lobes. The cause of this squint is still under investigation. So far, it is thought to be inherent to the waveguide power combiner and is tractable to EM simulation, and a solution may be found from a slight offset of the OMT ports.

Nevertheless, the measured directivity and gain of the array is healthy. Measured gain at 12.5 GHz is 35.7 dBi, from which we infer a G/T figure of merit in the region of 15 dB/K at the LNA input.

The polarisation strategy was tested by manually adjusting the polarisers since electro-mechanical actuation has not yet been implemented. Polarisation angle can be varied continuously, with the Tx and Rx ports’ polarisation remaining orthogonal.

Cross polar discrimination (XPD) was measured by capturing two orthogonal probe polarisations and post-processing to find the null, a good example of which is seen in Fig. 11 where polarisation is vertical. However, XPD figures can be degraded for intermediate polarisation...
angles as the weak energy in standing waves between the polarisers and ‘folded’ primary feeds couples between waveguide modes. These effects are also frequency dependent.

![Diagram of waveguide feed chain and power combiner](image)

**Figure 11. Typical cross-polar pattern for lens array in transmit band.**

5. ACTUATION, TRACKING AND CONTROL

Although this paper primarily concerns the RF aperture, the mechanical platform, which is under continued development, warrants some commentary. Target tracking accuracy of better than 0.1° is driven by the azimuth half power beamwidth which would apply at 30 GHz of about 0.6°. This is thought stringent but not unrealistic. The azimuth stage is driven by a servo motor via reduction gearbox and timing belt – backlash in this drive is expected to be a limiting factor, but all steps have been taken to minimise this within a reasonable cost. Elevation actuation of the feed chain is via another motor and control arms. Our approach to combining gyros/inertial sensors for acquisition, and RF step-track, is conventional, but may be augmented by azimuth monopulse angle error detection.

6. CONCLUSION

The RF aperture for a low profile tracking antenna has been developed, using a two-element array of hemisphere lenses above a common ground plane. The equivalent aperture diameter of 610 mm arises from two 432 mm apertures, the height being just 216 mm. The present version of the azimuth stage contributes a further 80 mm to antenna height, while the aperture will fit within a radome of footprint 1160 mm diameter. The azimuth stage could be sunk beneath a vehicle’s roof line, limiting radome height to little more than the lens height. A waveguide feed chain and power combiner has been developed for Ku band, while we propose the lenses can be used successfully also at Ka band (20 & 30 GHz). From a measured gain of 35.7 dBi at 12.5 GHz we infer a G/T figure of around 15 dB/K at the LNA input. The properties of bandwidth, linear polarisation control, cross-polarisation, and transmit-receive signal path separation are all comparable to those achieved with a waveguide-fed reflector antenna, since a novel waveguide feed network is used. The antenna height is less than one half of the equivalent reflector height.

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8. REFERENCES.