A Ring-Focus Antenna Design for Simultaneous X and Ka Band with Monopulse Tracking on Both Bands

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Monopulse tracking offers excellent tracking performance and acquisition speed for Communications On The Move (COTM) satellite terminals. Furthermore, it is clear that the use of a single antenna for multiple bands is desirable for the terminal user, providing increased data rates and improved reliability without needing additional space and with the minimum increase of weight. We describe the design and performance of what we believe to be the first fully monopulse, simultaneous X and Ka band 1 metre diameter antenna. Our feed design uses a tapered polystyrene (Rexolite) rod for the Ka band within a circular waveguide for the X band. Ka band TE\(_{11}\) and TE\(_{21}\) signals are fed via circular metallic Ka band multi-mode waveguide into the dielectric rod through a tapered adapter. A mode converter is included within the Rexolite-filled waveguide run to improve E- and H-plane symmetry. The X band waveguide has a TE\(_{11}\) section for coupling of the data and a TE\(_{21}\) section of increased diameter for coupling of the X band monopulse information using an array of electric monopole probes fed via a suspended substrate network. Our reflectors use a conventional, shaped Axially Displaced Elliptical design with a rimmed 1 metre main reflector. Using a FEKO hybrid modelling approach in which the feed was modelled using MoM and the resulting aperture fields used to illuminate the reflectors, aperture efficiencies of 58% at 7.6GHz, 56% at 20GHz and 69% at 30GHz are predicted for the 1 metre monopulse antenna while WGS antenna sidelobe and polarisation specifications are still met.

Nomenclature

MoM = Method of Moments
MLFMM = Multi Level Fast Multipole Method
LEPO = Large Element Physical Optics
COTM = (satcom) Communications On The Move
ADE = Axially Displaced Elliptical (reflector antenna geometry)
Rexolite = a proprietary polystyrene dielectric material of low loss

I. Introduction

The reflector components of reflector antennas possess very wide intrinsic bandwidths. However, the same can’t be said for feed antennas: For example, a single, corrugated feed horn does not have the required bandwidth to cover both X and Ka bands which, extending from around 7.25GHz to around 31GHz, represent a two octave bandwidth. Typically, an approximate maximum bandwidth of half an octave may be achieved with a corrugated horn, due mainly to the need to have the quarter-wave corrugations near the mouth appear an approximate open circuit while those corrugations near the throat appear an approximate short circuit. Thus, a more complex design is required to cover both X and Ka band. For small COTM antennas, dichroic surfaces are probably not practical either, given the small electrical size of subreflectors, the small number of resonant elements therefore in a dichroic surface, and also the limited space in which feeds can be located without causing feed blockage. Any 1 metre design must also meet sidelobe requirements at Ka band, further constraining design options. Polarisation purity is also a strict requirement: If dual circular polarisation handedness is required, then frequency independent designs like spirals become inappropriate.

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Another dual band design option is a coaxial feed. In such designs, the higher frequency band is conveyed within the inner waveguide and the lower frequency band is conveyed between the inner and outer waveguides. The inner waveguide may be either a dielectric rod or a metallic waveguide.

However, monopulse antennas introduce an additional layer of requirements: If monopulse is to be achieved for the higher band using metallic waveguide, then either an increased diameter is required to support the propagation of higher modes, or four complete waveguides are required. Both options increase the diameter of the inner waveguide section, making the reflection matching and pattern of the annulus-shaped aperture available for the lower band more challenging. Furthermore, the increased size of the internal waveguide may increase its outer circumference sufficiently that it may approach resonance in the lower frequency band. The intrusion of the inner waveguide into the outer annulus is made worse if corrugations are introduced inside the inner waveguide.

Whilst radius variations, like steps, notches and irises can be used to improve the matching in the annulus, it is likely to be challenging to simultaneously match the monopulse information in higher modes, for example TE_{21} or TM_{01}. We describe the design and modelling of a 1m COTM monopulse antenna with the following criteria:

**Table 1 Specifications of the COTM antenna**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receive frequencies</td>
<td>7.25GHz-7.75GHz, 19.2GHz-21.2GHz</td>
</tr>
<tr>
<td>Transmit frequencies</td>
<td>7.9GHz-8.4GHz, 29GHz-31GHz</td>
</tr>
<tr>
<td>Polarization configurations</td>
<td>Simultaneous RHCP Tx and LHCP Rx or</td>
</tr>
<tr>
<td></td>
<td>LHCP Tx and RHCP Rx (software selectable)</td>
</tr>
<tr>
<td>Sidelobe masks</td>
<td>Meets MIL-STD-188-164B at Ka band</td>
</tr>
<tr>
<td>G/T</td>
<td>X band : 16dBi/K, Ka band: 21dbi/K</td>
</tr>
<tr>
<td>Polarization purity</td>
<td>AR &lt; 1dB on axis</td>
</tr>
<tr>
<td>Beam alignment</td>
<td>&lt; 0.5°</td>
</tr>
</tbody>
</table>

**II. Feed Design and Modelling**

The challenges described above become less severe if a dielectric rod radiator is used for the inner waveguide: Firstly, the beamwidth and phase centre for the dielectric rod is a function of its length and rate of taper, so that an extra two degrees of design freedom are obtained; Secondly, though the dielectric rod partially supports the lower (X) band propagation, its progressive taper to zero diameter causes much less reflection of the X band wave at the feed mouth than does a metallic waveguide and its small diameter at the throat of the X band horn causes negligible effects on the pattern; Thirdly, mode-converting corrugations for the higher (Ka) band can be moved out of the way of the X band waveguide annulus and horn.
It is best if the dielectric rod is considered first in the design. A number of constraints become immediately apparent for the rod: It was chosen to be a body of revolution for manufacturing reasons and also in order to make the polarisation specifications more readily achievable. Furthermore, when the dielectric rod is in metallic waveguide, it must allow propagation of the TE$_{21}$ modes as well as the TE$_{11}$ modes. The rod design consists of 4 sections: 1) A cylindrical rod section surrounded by conducting surface where the fields are guided into the feed; 2) A mode converter section to convert the TE$_{11}$ modes in section 1 into a hybrid mode for improved E- and H-plane symmetry; 3) A constant radius cylindrical rod section where the rod is surrounded by an annulus of free space between it and the X band waveguide wall in order to adjust the position of the Ka band phase centre relative to the X band horn later included; and 4) A conical tapering section from which the radiating fields will be launched, as the diameter transitions from one in which the Poynting flux is almost exclusively conveyed inside the rod to a diameter in which the great majority of Poynting flux occurs in the free space surrounding the rod. The benefits of the mode-converter section in improving the E- and H-plane symmetry are shown in Fig. 1.

A dielectric rod of this kind was then co-axially incorporated into a conducting X band circular waveguide and horn assembly as shown in Fig. 2. Waveguide tapers are used to reduce the air-filled Ka band waveguide dimensions to the scaled dielectric-filled (Rexolite) waveguide, whilst the rod itself is tapered up in diameter to finally fill its waveguide (section 1 of the rod as described earlier). The dielectric-filled Ka band waveguide then has a corrugated mode-converter section (section 2 of the rod) before the dielectric rod emerges (section 3 and 4 of the rod) into a larger circular waveguide suitable for TE$_{11}$ propagation at X band frequencies, where 4 monopole probes introduce the data channels at X band. The four probes are phased to transmit and receive X band right and left hand circular polarizations for transmit and receive simultaneously. This waveguide then tapers to a larger diameter in which 8 monopole probes extract the TE$_{21}$ X band signal. These probes are suitably phased to receive either circular polarization of the TE$_{21}$ signal. Finally, the X band waves are radiated from an axial corrugated horn. The section 3 of the dielectric rod (where its diameter is constant) was then adjusted to cause the Ka band phase center to coincide with the X band phase center. A suspended substrate network (not shown) surrounds the X band waveguide and is used to couple and phase the probes to provide suitable polarization and modal isolation. The modeled, linear-polarized, TE$_{11}$, electric near-fields of the feed are shown at Ka band and X band in Figs. 3 and 4. Aspects of this feed form part of a patent application1.

Monopulse operation results from the ability of the feed to detect the lateral displacement of the Airy disc at the focal point. Although there are several alternatives, in this design, TE$_{21}$ mode excitation is used to convey this information deeper within the feed waveguides. In the case of the X band, it is extracted by the 8 monopole probes around the X band waveguide. In the case of the Ka band, the TE$_{21}$ energy enters the dielectric rod, passes back through the mode-converter and it coupled off from the multimode waveguide.

Figure 2. The metallic housing for the dielectric rod, shown in cross-section. The rod itself is omitted for clarity. On the left are tapers to transition the Ka band waves from air-filled waveguide to dielectric-filled waveguide. To the right of this are seen a succession of mode-converting corrugations. Two rows of X band probes are seen inside the larger waveguide, one for TE$_{11}$ and one for TE$_{21}$. On the right, the X band axial horn is seen.

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III. Reflector Design and Modeling

We selected the Axially Displaced Elliptical (ADE) dual reflector design as the basis of a shaped reflector antenna. The ADE is desirable for small monopulse satellite antennas, since it can accommodate a wide beam-width feed pattern due to the absence of feed blockage. This is advantageous since, typically, the feed is designed with the data-carrying, sidelobe- and G/T-determining $\text{TE}_{11}$ modes as the highest priority whereas the patterns of the pointing-error-sensing $\text{TE}_{21}$ or $\text{TM}_{01}$ modes are of lower priority and therefore have less controlled and usually wide beam widths. Thus, in order to capture as much as possible of the higher mode feed pattern, a sub-reflector subtending a wide angle is desirable. In a conventional Cassegrain design, this could cause unacceptable feed blockage of the rays traveling between the sub-reflector and main-reflector, or unacceptable aperture blockage.

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A major disadvantage of an ADE reflector pair, is that typically the aperture field strengths near the main reflector center are down by around 10dB, due to their derivation from the weakest fields of the feed (originating from the edges of the feed pattern) due to the ray inversion associated with the real image produced by the sub-reflector. This causes a weakness in the aperture fields near the optical axis which creates high first side-lobes. Correcting this is a trade-off with exact ADE reflectors, since in order to reduce the sub-reflector spill-over and scattering side-lobes, very low fields of the feed must be intercepted by the sub-reflector edge (which at around -10dBi, are 25dB below the feed maximum) and directed to the main reflector central region, thus exaggerating the inner side-lobes due to the low near-axial aperture fields. Conversely, improving the first sidelobes will increase the sub-reflector spill-over side-lobes. Although this variation of field strength at the aperture center is partly compensated by the ADE geometry (since large angles of the feed field are mapped to small radii of the main reflector aperture), it is still problematic and leads to high side-lobes. The sub-reflector curvature need only deviate very slightly from the basic ellipse to dramatically alter the field distribution at the main reflector: For example a little less concave curvature at the sub-reflector outer edge will bring the rays closer together at the main reflector. This is the motivation for reflector shaping.

A simple iterative Matlab script was written to shape the reflectors with the aim of reducing side-lobes and improving bore-sight gain. This script assumes a feed pattern of $E \propto \cos^6 \theta$, which is a good fit to the feed pattern of the feed at Ka band. It starts with an ADE reflector pair cross-sectioned in 2D, and maps the field strength across the main reflector aperture by discretising it into around 40 rings. Energy conservation is used to equate the power in a spherical angle between adjacent ray angles from the feed to the power in the corresponding annulus at the main reflector. The mapping is achieved using ray tracing. Then, the shape of the sub-reflector is slightly adjusted to redistribute the power contained between the rays over the main reflector to achieve a desired field distribution, including tapering. Now that the sub-reflector is no longer an exact ellipse, the main reflector must be altered in shape slightly to restore the total path lengths of all the rays to uniformity. This is done iteratively using a polynomial perturbation function added to the axially-displaced parabola of the ADE design. A shaped reflector pair with a 150mm sub-reflector diameter and 1m main reflector diameter is shown diagrammatically in Fig. 5 together with the ray paths from the feed phase center to the aperture. Some bunching of rays is seen towards the inner and outer parts of the main reflector; This represents the extent of aperture field upward adjustment resulting from the shaping aimed at improving the field uniformity across the aperture and gradually tapering it at the outer edge. Also apparent, is the blurring of the intermediate ring focus into a focal region.

**Figure 5. Rays traced from the feed phase center after a 1 metre ADE reflector pair has been shaped to improve aperture field uniformity for improved sidelobe levels.**

**IV Reflector Antenna 3D Modeling**

The reflectors were modeled using Multilevel Fast Multipole Method (MLFMM) on the sub-reflector and Large Element Physical Optics (LEPO) on the main reflector using the commercial EM modeling software FEKO. The feed illumination was introduced to the reflector model via an aperture field computed by the MoM modeling of the feed in isolation. After some iterations, it was noted that a rim added to the main reflector was required to reduce main reflector spill-over lobes below the required masks.
The $\text{TE}_{11}$ gain patterns are shown for the antenna in X band (7.6GHz) Ka band receive (20GHz) and Ka band transmit (30GHz) in Fig. 6. The on-axis gains achieved correspond to aperture efficiencies of 58%, 56% and 69% respectively.

![Figure 6. The modeled far-field H-plane patterns of the 1metre, shaped, ADE, antenna fed with the feed as described, shown at 7.6GHz, 20GHz and 30GHz. The inset image shows the reflector pair and the square region over which the sampled pre-computed feed field is reconstituted as Huygen's sources to illuminate the sub-reflector, instead of modeling the feed and reflectors is a single attempt.](image)

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