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ANTENNAS FOR SATELLITE SYSTEMS - A EUROPEAN VIEW

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1. INTRODUCTION

This paper presents a brief overview of antennas for satellite systems within a European framework. Of necessity the view must be selective since more than 50 primary organisations are directly involved in the field within Europe. Their work is supported by, among others, the European Space Agency (ESA), EUTELSAT, INTELSAT, INMARSAT, national agencies and research councils, and contracts from industry both within and outside Europe.

We begin with a short review of major European satellite systems, whose requirements provide the stimulus for the antenna developments, before discussing selected antenna topics. In the past five years the authors have prepared a number of general review papers on this subject (1, 2, 3, 4, 5) and the present paper builds on these foundations.

2. SATELLITE SYSTEMS

Tables 1 and 2 identify current and planned European satellite and space systems excluding those which form part of international networks such as INTELSAT and INMARSAT although the future needs of those organisations will be mentioned. Table 1 contains details of ESA-funded satellite and space projects, while Table 2 lists a selection of national communication and/or broadcast satellites. To gauge the complexity of typical next-generation communication and broadcast satellites, we select from Table 2 the EUTELSAT III and EUROPESAT systems for comment (6). EUTELSAT III extends the services currently offered by EUTELSAT I and II, while EUROPESAT is to provide a Direct-to-Home (DTH) TV capability. However, because of the extended lifetime of next-generation satellites (typically 15 years) and the rapidity with which markets for services change, the specifications call for multimission payloads with on-board reconfigurability.

The service area of EUTELSAT III will cover Europe, including Western Russia, and some parts of North Africa and the Middle East. Services such as trunk telephony and TV distribution present no problem since EIRP and G/T requirements are easily met through the use of a European shaped beam as in EUTELSAT II (7). However, VSAT Networks and SNG require smaller antenna beamwidths with increased EIRP and /or improved edge of coverage performance. The use of an on-board processing for EUTELSAT's SMS (satellite multi-service) is being considered. The system requires a contiguous multiple spot-beam coverage of Europe. The service will be in Ku band except for the possible extension to 20/30 GHz for spot-beams and to L-band if mobile services are introduced.

Table 1
EUROPEAN SPACE AGENCY FUNDED SATELLITES AND PROGRAMMES

Project	Objectives
Hipparcos [1993]	Star mapping
Space Telescope (1990)	Cosmology
Ulysses [1995]	Solar Physics
Solar Terrestrial Science Programme (1995)	Earth plasma environment
ISO (1993)	Infrared Astronomy
Huygens (1995)	Exploration of Jupiter's Titan moon
Marecs A, B-2 [1992, 95]	Maritime Communication
Meteosat-3, -4 [1992, 95]	Meteorology
ECS-2 to -5 [1991-95]	European communication and broadcasting
Olympus [1994]	Multimission
Data-Relay Satellite = DRS (1996)	Data transfer between LEO and GEO
Artemis (1995)	Multimission communications and data relay
ERS-1, 2 [1993] (1994)	Earth observation by means of SAR Radar altimeter, etc
Meteosat Ops Programme (1989)	
Microgravity (1991)	Microgravity Experiments
EURECA (1992)	Retrievable Carrier for Microgravity
COLUMBUS/HERMES	European Manned Space Laboratories + Polar Platform
POEM (1997)	Polar Orbit Earth Observation

( ) denotes launch date [ ] denotes expected end-of-life

Table 2
COMMERCIAL AND NATIONALLY FUNDED SATELLITES

Satellite	Country/Function
DFS	German National Satellite (C and B)
Telecom 2	French Multimission (C)
Hispasat-1 and -2	Spanish Multimission (C and B)
Italsat 1 and 2	Italian (C)
Tele-X	Scandinavian (C and B)
Marcopolo (formerly BSB)	United Kingdom (B)
ASTRA-1, 1(B), 1(C), 1(D)	Luxembourg (B)
TV Sat	German (B)
TDF1	French (B)
Turksat	Turkish (C and B)
EUTELSAT II	European (C and B)
EUTELSAT III (1997)	European (C)
EUROPESAT (1996)	European (10 nation) (B)

Underline denotes in-orbit
C = Communications Satellite
B = Broadcast Satellite

The antenna options to meet the various requirements include: a small number of complex antennas radiating overlapping coverages or a large number of simpler antennas; shaped reflectors fed from either single feeds or feed clusters, or array-fed paraboloidal reflectors; a steerable/rotatable elliptical beam or a reconfigurable shaped-beam antenna; the use of larger fixed beams for all satellite positions or the use of narrower beams reconfigured for each position.

The EUROPESAT system will provide 40 TV DTH channels with 20 radiating in right-hand circular polarisation (CP) and 20 in left-hand CP with 33 dB isolation. Three identical satellites will be needed at around 19°W with one acting as a spare. The receiver coverage area covers most of Western Europe, and in view of the high G/T of 5 dBK^{-1}, a shaped-beam is expected for the up-link while the down-link will provide each country with the desired coverage. As the country coverages partially overlap there will be either a need for separate antennas for each coverage or for more complex multiple contoured beam antennas where beam overlap is achieved by feed sharing and by polarisation diversity or in some cases by dual mode BFN technology.

The above outline specification contains many details found either in whole or in part within other communication or broadcast systems of Table 2 and in requirements for the INTELSAT Follow-on Satellite (FOS-II) (8). INMARSAT III calls for seven high-efficiency spot-beams and a global beam to be addressed in a totally flexible manner; possible solutions are discussed in Section 3.2.2. Requirements for Earth Resources and Meteorological Satellites (5) are generally quite different from those above, calling, for example, for a high gain shaped beam as in the Synthetic Aperture Radar

(SAR) of ERS-1 and ERS-2, and high beam-efficiency antennas for radiometry as in AMSU-B. Data-Relay Satellites call for scanned beams, while the antenna requirements for Space-Science applications are inevitably mission-dependent.

The trends in earth-station requirements are towards low-cost, low side-lobe transportable antennas especially for VSATs and ultra-low-cost antennas for home TV reception. The latter topic, having been reviewed recently (3), will not be considered again here.

Similar trends are seen in terminals for mobiles (9) where in addition the antenna must track the satellite. In this area ESA has extensive developments for both mechanically steerable and electronically steerable antennas.

3. SATELLITE ANTENNAS

3.1 Introduction

With the exception of antennas for the data relay satellite, requiring multiple access and SAR, nearly all current and next-generation antennas for communications and broadcast satellites use reflectors. Pencil-beam antennas require a single feed but intricate shaped-beams and multiple spot-beams may be generated by means of an array excited by a beam-forming network. For certain systems these have achieved a high degree of complexity and can incorporate means for limited in-orbit reconfigurability. One trend is towards increased sophistication in BFNs and a review of this work is presented in Section 3.2. An alternative to the creation of intricate shaped-beams is to use a single feed or feed cluster and one or more shaped reflectors. The means of designing accurately shaped-beam reflector antennas by synthesis techniques has been an important development of the last decade and is described in Section 3.3. Schemes for reconfiguring shaped reflectors have been proposed and will be mentioned briefly in Section 3.4. Most satellite antennas are in a single off-set configuration and intrinsic levels of linear cross-polarisation are high. To counter this, dual-gridded reflectors have been produced with separate foci for each linear polarisation, thereby achieving a high degree of polarisation isolation. Another reflector technology involves the use of dichroic surfaces for applications in which multiple frequencies are required from a single antenna. Both these topics are discussed in Section 3.5. To complement the above designs, there has been valuable research on high performance feeds for reflectors as well as rigorous analysis of mutual coupling in feed arrays of circular and rectangular elements. This work is discussed in Section 3.6. Section 3.7 provides comments on Direct-Radiating Arrays while Section 4 contains a brief discussion on earth station antennas.

To supplement this technical review the reader may wish to consult recent ESA Workshop Proceedings (see references 6 and 7).

3.2 Array-Fed Reflector Antennas

3.2.1 Array-Fed Reflectors with a Classical BFN

Early examples of array-fed reflector antennas to produce contoured beams include INTELSAT IV and V in which a TEM-line beam-forming network is used to ensure correct excitation of each array element.

INTELSAT VI invokes three-way reconfigurability of zone-beams when different satellite positions are chosen (AOR, POR, IOR) (3). For classical contoured beam antennas, beam reconfiguration can be achieved by replacing fixed power dividers and phase shifters by variable power dividers (VPDs) and variable phase shifters (VPSs) and by possibly introducing switches. This may be implemented at various levels in the network.

- (a) Full reconfigurability where VPDs and VPSs are used throughout.
- (b) Amplitude only reconfigurability where phase is constant and only VPDs are used.
- (c) Limited reconfigurability where a few VPDs are used on the input stages to connect groups of sub BFNs.
- (d) Switched reconfigurability where switches are used instead of VPDs as in (c) above.

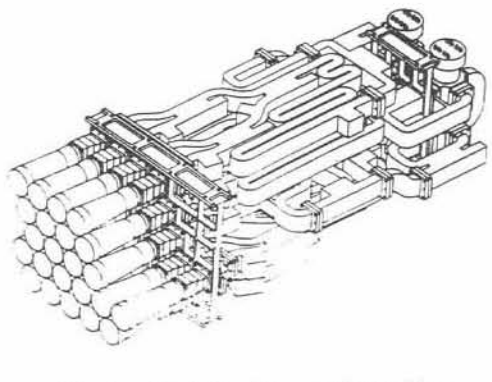

Fig 1 Switched Reconfigurable Ku-Band Feed System

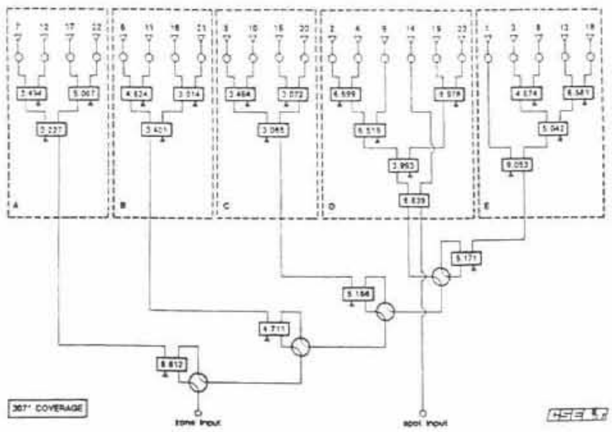

Fig 2 BFN Topology

Strategy (c) is exemplified by the INTELSAT-supported study by Alenia Spazio of the INTEL 717 specification for a Ku-band reconfiguration requirement to match a North Atlantic multi-satellite scenario(4). Figure 1 shows a view of the complete feed array comprising 5 sub-arrays which feed 23 horns. These horns illuminate a dual-gridded reflector. Electromechanical switches direct power through branchguide couplers and stub phase-shifters to achieve the desired output amplitude and phase distributions. Figure 2 shows the block-schematic enabling coverage of North America and Europe to be achieved from satellites at 307°E (sub-arrays A,B,C,D), 319°E (B,C,D), 338° (C,D) and 359° (D,E).

A summary of the BFN specification is 2 inputs to 23 outputs; switch reconfiguration; wide bandwidth (10.95 - 12.75 GHz); high power handling and low insertion loss (0.6 dB). Other examples of more complex reconfigurable BFNs using VPDs to effect both coverage and channel flexibility can be found in references 4 and 6.

3.2.2 Multimatrix Semi-Active Array-Fed Reflector

The use of the Butler matrix coupler within a BFN has been explored extensively for satellite applications in recent years and a survey has been given recently by Roederer (10). There it is shown that reflectors fed from a beam-forming system with one feed and one power amplifier per beam do not provide power to beam allocation flexibility, unless complex high power switching is employed. One solution is to use overlapping feed clusters where each beam uses typically 3, 4, 7 or 9 feeds powered via a multiport amplifier. Identical amplifiers are inserted between two identical back-to-back multiport Butler-like couplers which perform two cascaded inverse transforms, so that each low level input corresponds to a feed element and each beam is generated by proper excitation of the inputs. The disadvantage of the system is the need for two very large back-to-back matrices which, unless the coverage region contains a large number of scattered users, will result in an adverse effect on amplifier efficiency.

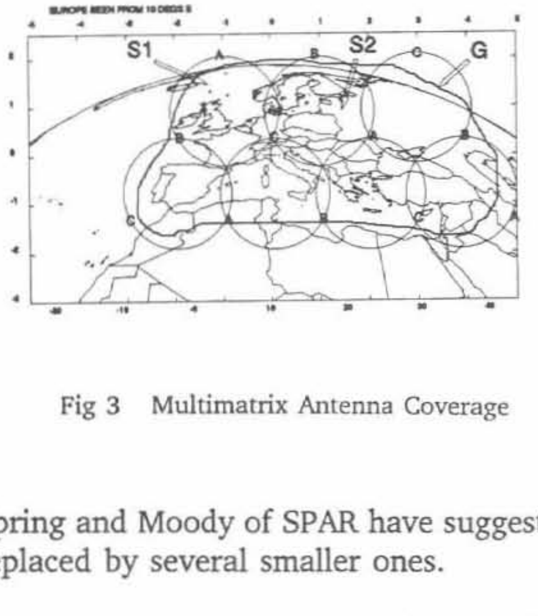

Fig 3 Multimatrix Antenna Coverage

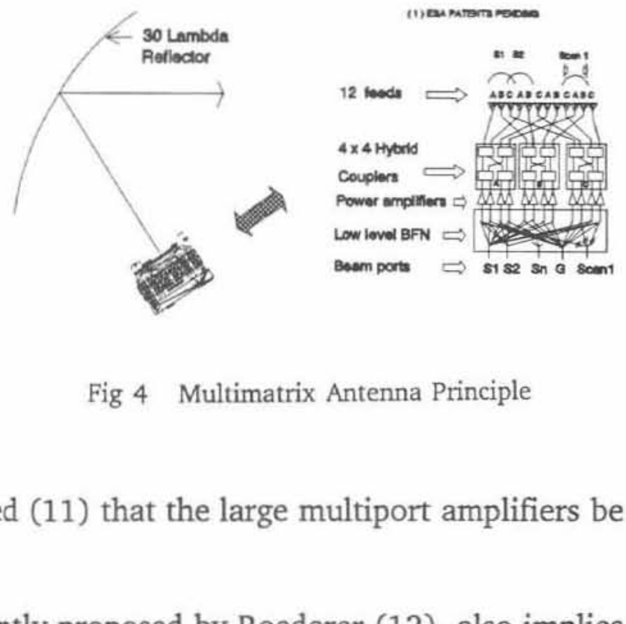

Fig 4 Multimatrix Antenna Principle

Spring and Moody of SPAR have suggested (11) that the large multiport amplifiers be replaced by several smaller ones.

A similar multimatrix concept, independently proposed by Roederer (12), also implies overlapping feed clusters (Figures 3 and 4). The feeding arrangement excludes half of the small matrices and includes fixed or variable phase-shifters for each beam. Beams originate from three feeds A,B and C powered via three 4 x 4 hybrid couplers from twelve equally excited amplifiers. Beam crossover is typically at -3 dB below peak. Full flexibility in traffic to beam allocation is available by low level switching of more or fewer channels into each beam. All amplifiers operate at maximum efficiency and once the feed clusters create a -10 dB taper at the reflector edge an aperture efficiency of 55% is achievable and with low sidelobes. Use of 4, 5, 7 or 9 feeds per beam provides better sidelobes and higher efficiency.

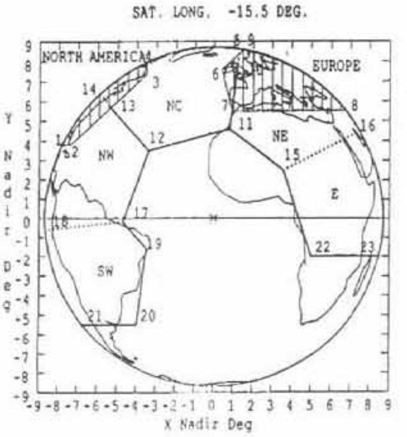

Fig 5 INMARSAT 3 Atlantic Coverage

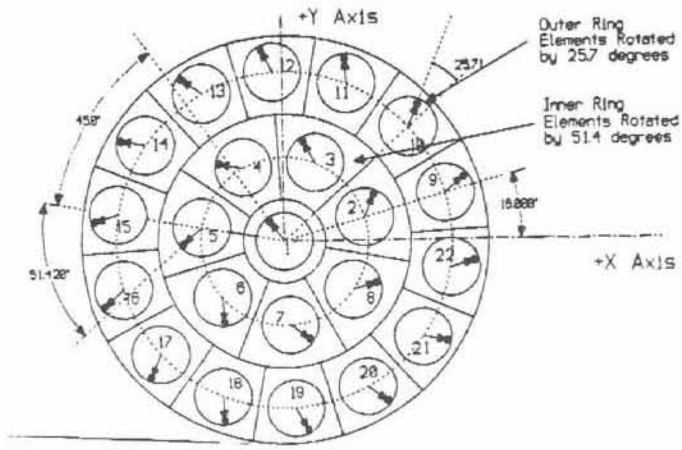

Fig 6 L-Band Multimatrix Antenna Feed Configuration

The above concept has been applied to the INMARSAT 3 payload. Figure 5 shows the coverage requirements (13) and Figure 6 the feed array. The breadboard antenna has been developed by Matra Marconi, who chose an array with sevenfold symmetry leading to 22 array elements on two concentric rings. This gave the optimum compromise between spot beam e.o.c. directivity (> 24.3 dBi) and beam-to-beam isolation (< -2O dBi). There also exists the possibility of a high directivity (> 19.2 dBi) shaped global beam.

3.2.3 Scanning Antennas

The multimatrix antennas described in section 3.2.2 can also provide fine beam hopping (10). Figure 7 shows the feed principle for scanning across Europe with a 30 wavelength reflector using 32 feeds. Depending on the user location the phases are set to power 4, 6 or 9 feeds. Four 8 x 8 couplers and 32 2-bit phase shifters allow fine beam hopping with low sidelobes and a minimum directivity corresponding to an aperture efficiency of 50%.

Frequency scanning has also been studied. ANT uses a line array, with appropriate spacing to generate the required phase delay at a given frequency, to illuminate a parabolic cylinder (14). Figure 8 shows the waveguide feed configuration developed under an INTELSAT study in which either the USA or Europe can be covered by frequency addressing in the range 11.46 - 11.69 GHz.

Other applications of frequency scanning antennas are being evaluated. One, studied by ERA (15), is for aeronautical communications over the North Atlantic at 20/30 GHz.

In another type of scanning antenna, the imaging array-fed reflector, a small feed array is magnified by optics. Single reflector systems appear to have poor efficiency, but recently, improved optics with shaped main and sub-reflectors, fed by a planar array of 32 elements, have been optimised by BAe (16). A photograph of the antenna is shown in Figure 9.

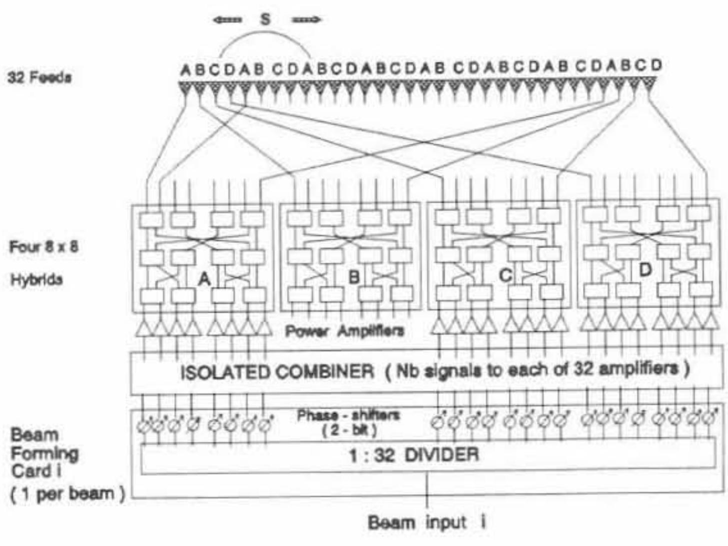

Fig 7 Multimatrix Scanning Antenna Feed

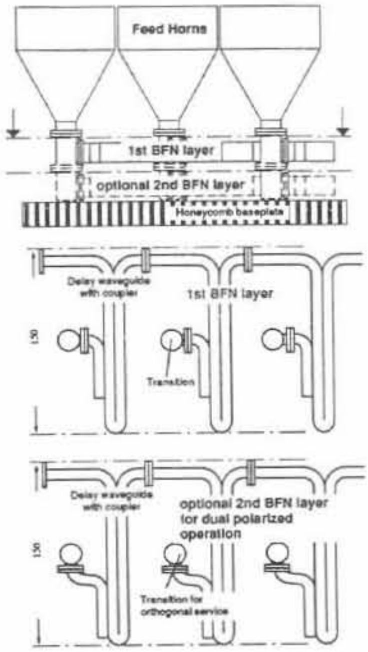

Fig 8 Ku-Band Scanning Antenna

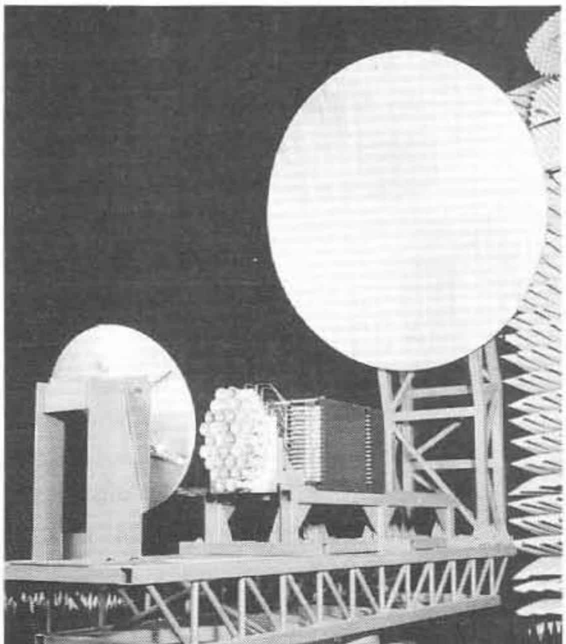

Fig 9 Imaging Array-Fed Dual Reflector Antenna

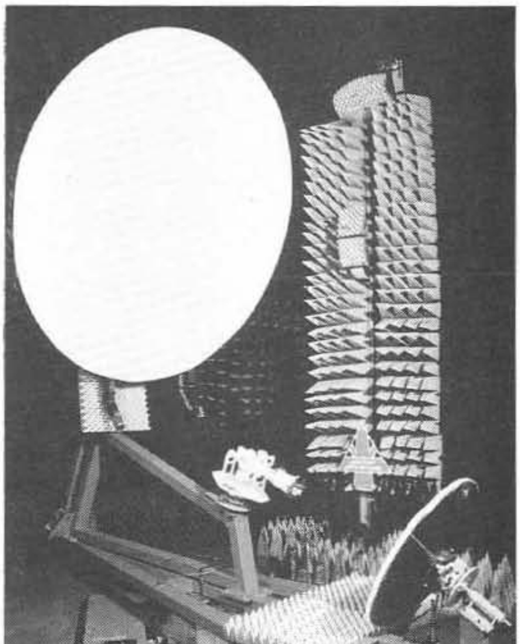

Fig 10 Dual Shaped Reflector Antenna

3.3 Shaped Reflector Antennas With Simple Feeds

In applications calling for one or two intricate coverage zones a shaped reflector fed from a single feed or feed cluster offers an alternative to an array-fed antenna. Savings associated with the mass and loss of the BFN must be traded against the absence of reconfiguration in state-of-the-art designs.

The concept of reflector synthesis based on geometric optics principles first emerged in the late 1970s (17) (18) and was soon followed in Europe by the development of alternative diffraction synthesis techniques (19), (20), (21), (22) (23) (24) and (25). These have been extensively applied in a number of studies supported by, among others, ESA and INTELSAT, and designs based on physical optics methods are now the norm. Figure 10 shows the ESA development of a 2.5m dual-reflector antenna designed and built by British Aerospace to an ASTRA IC specification (24) (25). A dual-reflector configuration enables a cross-polar level of -34 dB to be achieved within the coverage area. The reflector shell is of sandwich construction comprising CFRP skins bonded to an aluminium alloy honeycomb core. The feed is a corrugated horn of 8 cm internal aperture which provides efficient illumination with minimal spillover.

British Aerospace (26) have compared a number of their designs of both single- and dual-shaped reflectors with their own designs of paraboloid antennas using array feeds. They conclude that, so long as reconfiguration is not required, the shaped reflector offers a valuable improvement in coverage gain, together with significant mass savings.

In another study by ERA (27) against an ESA Data Relay Satellite specification, a shaped reflector was designed to provide coverage from two widely separated orbital positions with the same shaped reflector by using two feeds. The design converged on a 1m diameter single offset reflector with F/D = 0.8 leading to a minimum flux of 28.2 dBi in the 17.7 - 20.2 GHz band. Similar dual coverage requirements have also been investigated by ERA under contract from INTELSAT.

3.4 Reconfigurable Reflectors

As has been indicated above, the shaped reflector offers an optimum antenna solution when up to two coverage zones are required especially when their boundary is intricate. However, in contrast with the array-fed reflector there is no possibility of in-orbit reconfiguration as would be needed were the orbital location of the satellite to change as a consequence, for example, of changing traffic patterns or failure of another satellite in the system. Recognising this disadvantage, workers at Queen Mary and Westfield College have developed in recent years a prototype 30 wavelength diameter reconfigurable reflector antenna as shown in Figure 11 (28). The surface is made from gold-plated molybdenum mesh (supplied by MBB) and the surface shape is adjusted by attachment to stepper motors whose position is under computer control. Coverage patterns corresponding to the INTEL 717 requirement of section 3.2.2 were considered and the North American coverage achieved. Figure 12 shows a cut through the 307^{0}E pattern where good agreement is observed between patterns measured at 10 GHz and those predicted using physical-optics. The capability for null creation both within and outside coverage has been demonstrated experimentally and limited beam steering by reflector adjustment also shown. Reconfiguration is achieved by powering the motors in sequence. Following this success ESA have supported the successful development by Aerospatiale of a breadboard 1.5m antenna to reconfigure a EUTELSAT II coverage when viewed from three orbital positions (29). The mesh is similar to that used by QMW but it is tethered to a matrix of wires which are connected in turn to precision actuators. This arrangement enables a very high surface precision to be achieved.

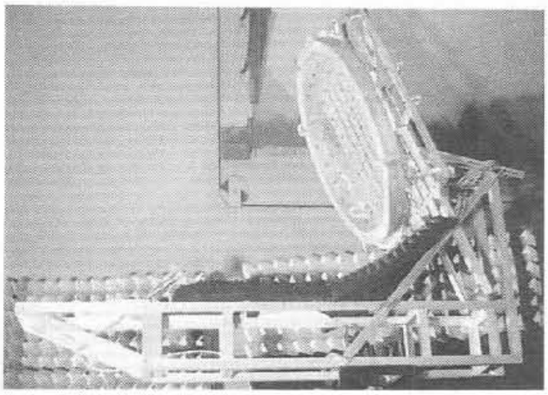

Fig 11 Reconfigurable Reflector Antenna

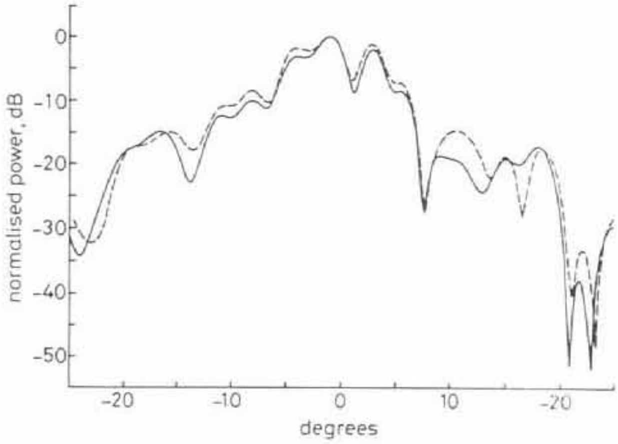

Fig 12 Measured and Predicted Pattern for Antenna of Fig 11

3.5 Polarisation Sensitive- and Dichroic-Reflectors

3.5.1 Polarisation Sensitive Gridded Reflectors

A single offset reflector has inherent linear cross-polarisation levels of order -25dB relative to the peak of co-polar, a level which is unsuitable for dual-polarisation frequency re-use applications. While a dual-reflector satisfying Mitziguchi conditions offers a solution to this problem, in some cases accommodation on the spacecraft bus inhibits this solution. An alternative is the use of polarisation sensitive reflectors (PSR) and this solution offers high Transmit/Receive isolation. For example, MBB (30) have developed a dual-gridded 2m-diameter polarisation-sensitive reflector for a Chinese Communication Satellite DFH-3. Grids are laser-etched on to aluminium-coated Kevlar honeycomb and two identical reflector shells are mounted one behind the other, each with a focal length of 2.1m. The offset planes are rotated by 16° (31) with respect to each other and the back reflector shifted by 17 cm in the axial direction. Aerospatiale, who manufactured the gridded reflectors for EUTELSAT II (32) employ a mechanical cutting/etching process.

3.5.2 Dichroic Reflectors

The use of multiple frequencies on a single antenna in future payloads has stimulated a number of studies in Europe of dichroic (or frequency selective, FSS) reflectors. A trade-off study performed by CSELT (33) finds that rings are more suitable as elements compared to crossed-dipoles, Jerusalem crosses and square loops. The basic electrical requirement in the ESA dual-reflector antenna study was for the dichroic sub-reflector to be transparent in Ku band 10.95 - 12.25 GHz and reflective in Ka band 18.2 - 20.2 GHz. Both Ericsson and Alenia have performed parallel developments for this application. In the Alenia design, the double-gridded sub-reflector is formed from a triple Kevlar sandwich and measured, and predicted results (34) found to be in good agreement. The following represents a summary: Gain loss <-0.4 dB in both reflection and transmission bands, sidelobe level <-25 dB in transmission and <-20 dB in reflection, cross-polar level <-25 dB in transmission and <-36 dB in reflection.

3.6 Feed Systems

3.6.1 Hybrid Feeds

Because of their inherent low cross-polarisation and pattern symmetry, circular cross-section feeds which support a hybrid HE_{11} mode or which synthesise the field from pure mode combinations are preferred when accommodation will allow. This is nearly always the case with singly fed reflector antennas when the corrugated horn is a standard choice. Compact dual-mode feeds have been used in arrays. Excellent software is available from many sources enabling very accurate prediction of electrical performance.

An example of a dual-mode compact feed is the SCRIMPHORN (Figure 13), developed by MBB (35) for the array-fed AFSAT reflector antenna. The re-entrant coaxial line supports the coaxial TE_{11} mode which together with the TE_{11} and TM_{11} mode in the feed aperture leads to a very low cross-polar (<-35 dB) compact feed.

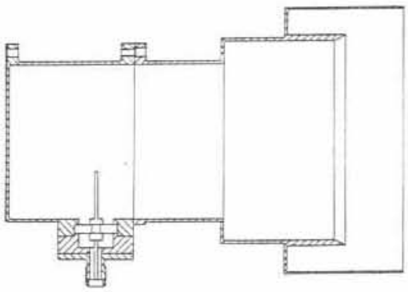

Fig 13 SCRIMPHORN

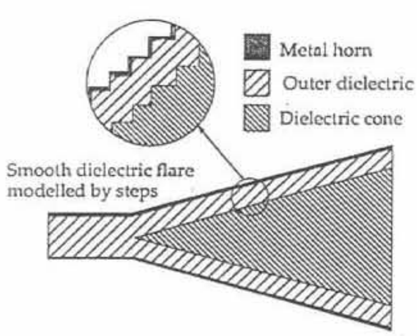

Fig 14 Dielectric Loaded Horn

Another example of a multi-mode feed (36) is provided in the ERA-designed electronic beam-squint antenna for in-orbit communications between the EURECA spacecraft in low earth orbit and the geostationary OLYMPUS spacecraft. There is a need to track over a wide angular sector and accommodate receive linear polarisation whose orientation varies by ±40°. The tracking system operating in the 20/30 GHz band employs a conical horn supporting two orthogonal TE_{21} modes in addition to the TE_{11} mode. The mode generator comprises a specially profiled circular taper with four circumferentially disposed side ports, each consisting of a transmit band reject filter, a PIN switch and a plane short circuit.

In an attempt to reduce the mass and manufacturing complexity of the corrugated horn, workers at QMW (37) have made a comprehensive investigation of low mass dielectric loaded conical horns as in Figure 14. The prototype structure was devised at QMW in 1983 and it offers potential for use in satellite applications, especially when metallisation is used on the outer dielectric. Very accurate design procedures have been developed in which the inhomogeneous conical section is treated as a series of step discontinuities and modal matching used to determine the propagation characteristics and fields of the composite horn. A performance comparison with a similar-sized corrugated horn at Ku band shows a peak cross-polarisation of about -30 dB for the dielectric horn compared with -38 dB for the corrugated horn. Although there is a poorer electrical performance there is a significant weight saving of 0.23 kg compared with 1.73 kg.

3.6.2 Mutual Coupling Between Feeds

Early in the use of horn feeds in arrays, the influence was recognised of the effect of mutual coupling on the cross-polar characteristics of the embedded element. Pattern symmetry was also found to be affected. Studies of both these phenomena have been conducted at several European laboratories, and software now exists to predict accurately primary patterns for finite arrays of both circular and rectangular apertures. The results (38) for a triangular lattice of 23 square elements are in Figure 15, which compares the co-polar pattern of a single horn (Figure 15a) with that of the embedded element in the array (Figure 15b). The next step is to integrate these models into existing antenna design software so that the designer can optimise every module from the BFN input to the reflector parameters including the effects of mutual coupling in the array and its interaction with the beam-forming circuits.

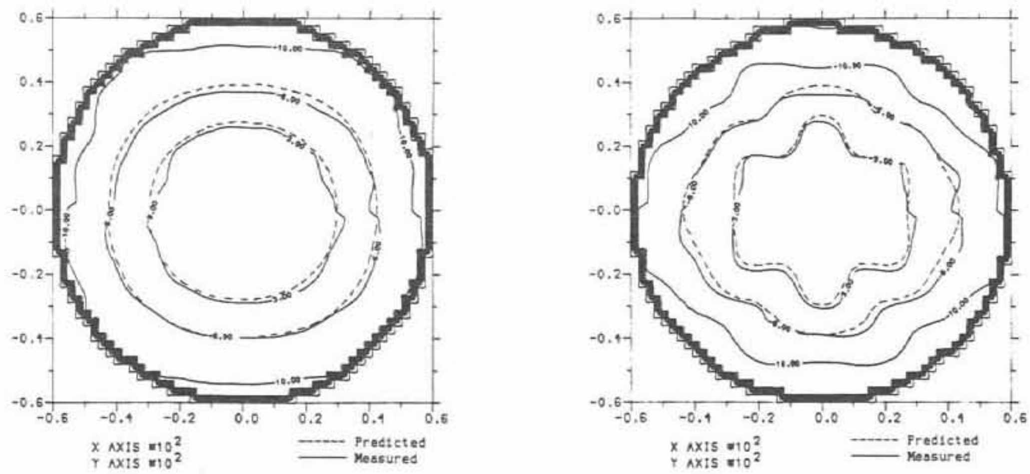

Fig 15a Horn Pattern

Fig 15b Embedded Horn Pattern

3.7 Direct-Radiating Arrays

One of the best examples of a direct-radiating array is the SAR antenna on ERS-1 developed for use in the ESA Earth Observation Programme. The antenna, which was designed and built by Ericsson and Dornier Systems, is a 10m x 1m slot array generating a 100 km swath from a satellite orbiting at about 785 km. The above concept has been extended by Ericsson (39), who use a passive array antenna to generate two simultaneous beams from a common aperture. Tests have been performed with a 1m x 1m model which comprises 24 waveguides containing 24 slots fed by means of a Blass matrix. Figure 16 shows measured elevation patterns which will be the same as for the full-size antenna which would comprise ten identical panels. The estimated gain for the near beam of the full array is 38.5 dBi and for the second beam 43 dBi.

In the future, some direct-radiating arrays can be made active. For example, in a single beam array, each element or sub-array is connected to a transmit/receive module including phase-shifter, T/R switch, low noise amplifier and power amplifier. Beam-forming is by computer command to phase-shifters, VPDs and possibly variable gain amplifiers. This is typically the case in a SAR antenna. For adaptive arrays, control must take place in a closed loop and advantage is found by clustering elements into sub-arrays phased to produce medium gain in the wanted direction. In multi-beam arrays, several beams are activated simultaneously, generally at different frequencies and with different codes. Since the frequencies are closely spaced, and as the beams are not generally orthogonal, such arrays must be active. They have been studied for ESA in relation to L-Band mobile communications (40) and for multiple-access data-relay at S-Band (41). Here they are state-of-the-art with aperture sizes up to a few square metres. For all these applications ESA is supporting an extensive programme on microstrip patch antennas which has not yet been reported in the open literature.

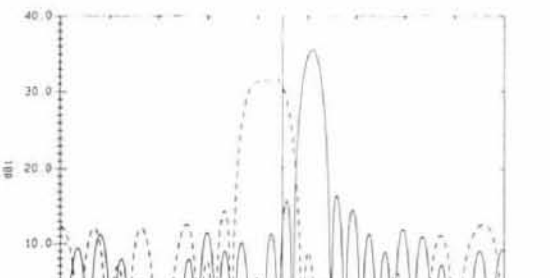

Fig 16 Measured Pattern of Dual Beam Array

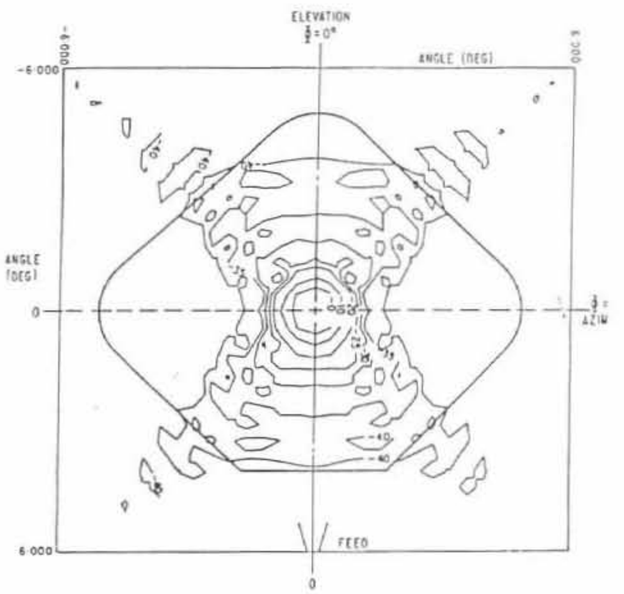

Fig 17 Measured Contours of Single Offset Reflector

In summary, the major advantages of direct-radiating arrays are: high efficiency; phase-only beam-forming; graceful degradation; and distributed amplification. The major disadvantages are: complexity and mass; illumination taper for low sidelobes;

unsuitability for contour beams; sensitivity to interference; deployment and thermal control problems; also losses in cables.

4. EARTH STATION ANTENNAS FOR VSATs

With major improvements in spacecraft antenna EIRP, new Earth station antennas belonging to the principal networks have decreased in aperture size while essentially conforming to the design philosophy developed in the 1970s. Innovation is to be found among antennas for VSATs and for mobile earth stations. Particular emphasis has been placed on the achievement of low sidelobes, especially in the geostationary plane, because of the move towards 2° inter-orbital satellite spacing. Several designs take advantage of a novel reflector shape to achieve this goal.

The diamond antenna developed at ERA (42) is an example. Figure 17 shows the co-polar radiation pattern of a 2.4m single offset reflector superimposed upon the perimeter of the reflector. The antenna has a measured performance of 48.2 - 59.3 dBi gain in the band 11.7 - 14.0 GHz and sidelobes which are generally lower than 25 - 25 log θdBi in the azimuth plane. The boresight cross-polarisation is less than -40 dB and the antenna operates with up to 1 kW cw at either of the linearly polarised ports. It is entirely suitable for transportable transmit/receive satellite terminals.

CONCLUSIONS

The paper has presented a selected overview of research and development in Europe in the field of antennas for satellite systems. The growth of technology associated with array-fed antennas is evident, albeit that space constraints in the paper have forced us to exclude discussion of digital beam-forming and optical beam-forming methods. There is a clear trend towards efficient reconfigurability, in response to changing traffic patterns during the extended lifetime of next generation spacecraft. For coverage requirements which exclude reconfiguration and which demand no more than two zones, the shaped reflector offers an improved solution with higher coverage gain and lower mass than is found in array-fed reflectors.

Active direct-radiating arrays offer an efficient solution for future missions, subject to the availability of power amplifiers with above 30% efficiency over a 6 to 10 dB dynamic range. Also, thermal control problems are among those which remain to be solved. Semi-active multi-matrix antennas are state-of-the-art and will shortly be used in L-band payloads such as INMARSAT III. Frequency-scanned antennas will also find a place since they offer simple multiple access capability. Research continues on feeds and array feeds in particular, leading to much improved optimisation techniques stretching from the BFN input to the reflector pattern. High-performance earth-station antennas for VSATs are also now state-of-the-art, including types which lend themselves to ease of transport for applications such as news gathering and national emergencies.

A move towards higher frequencies is occurring in some systems, spurring new technologies. This is particularly the case where current technology has been biased towards frequencies in Ku band and below. International interest in earth observation will ensure substantial investment in programmes for future remote-sensing satellites including those monitoring the earth's atmosphere, while ESA programmes such as HORIZON 2000 and CORNERSTONE 2000 will provide significant long-term challenges for the antenna engineer concerned with spacecraft antennas (43).

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