RECENT EUROPEAN ANTENNA TECHNOLOGY FOR SPACE SYSTEMS

A.G. Roederer and G.A.E. Crone
European Space Technology Centre - ESA/ESTEC
PB 299, 2200 AG Noordwijk, The Netherlands
Fax: +31-71565-84999 E-mail aroedere@estec.esa.nl

1. INTRODUCTION

Space applications have been driving in the last twenty years major R&D efforts in Europe in the field of antennas and associated circuits, leading to new concepts and successful technologies.
In an invited paper at ISAP'92 by Clarricoats et al. [1], selected European developments were described, with emphasis on reflector antennas for communication satellites.
This paper reviews other European space antenna technologies, some of which are already described by Roederer et al. in a recent paper in the IEEE Antennas and Propagation Magazine [2].

2. ANTENNA TECHNOLOGIES FOR SATELLITE COMMUNICATIONS

The ESA European Mobile Service, EMS, for communications with trucks and other mobiles, will use a shaped beam payload at L-band covering Europe, to be launched in 1996 and , from 1998, a multibeam payload (LLM) on the ESA ARTEMIS satellite, allowing communications with smaller terminals.
For direct audio broadcasting, ARCHIMEDES-MEDIASTAR, with satellites covering Europe, North America and East Asia from elliptical orbits, is being studied.
Antennas for these missions and for fixed communications and satellite TV reception will be described.

2.1 Semi-active antennas for mobile communications

The ARTEMIS LLM will cover Europe with overlapping beams (see fig. 1) and flexible channel to beam allocation. For the transmit antenna (at 1.55 GHz), arrays with a taper as well as simple multifeed reflectors both require amplifiers at different levels, thus high cost or poor DC/RF efficiency.
A multifeed reflector antenna solution with each beam originating from a feed cluster and with adjacent beams sharing feed elements was found to be best to generate the beams.
A novel feeding arrangement, shown in fig. 1, where the feeds are powered via hybrid Butler-like matrices

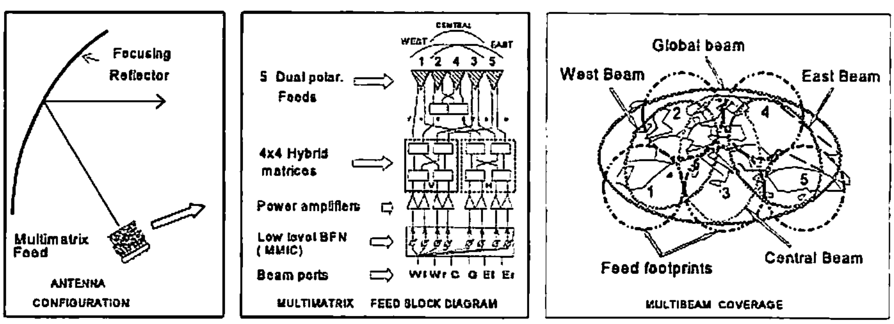

Figure 1. ESA ARTEMIS L-Band antenna diagram and multibeam coverage

from equally excited power amplifiers was proposed [3,4]. Beam steering, contouring or shaping is possible by phase-only control of the beam signals at the input of the amplifiers.
A similar configuration, but for fixed beams only, was independently derived by Spring et al.[5].

Figure 2. ARTEMIS L-band Antenna (ALENIA SPAZIO)

Each spot beam essentially originates from a cluster o feeds. For each beam, phases at the input of the twc Butler-like matrices are selected so that output signals are directed to the desired feeds. The circular polarisation is also set up through the matrices. Details on the multimatrix semi-active concept, also extended to arrays, are given in [6] and the impact of excitation errors is studied in [7].
The ARTEMIS antenna is shown in fig. 2.

Matrices of different sizes can also be used and the reflector can be slightly defocused or shaped.
The technology of the matrices, both in quasi TEM and in waveguide technologies, is mature.
Figures 3 and 4 show a 4x4 and an 8x8 bar-line Butler-like matrices for operation at 1.55 GHz, developed respectively by Alenia Spazio for ARTEMIS and by RYMSA, under ESA R& D .
The transmit-receive feed elements of the ARTEMIS L-band antenna have stringent Passive Intermodulation (PIM) requirements (see table 1).
Saab Ericsson Space in Sweden have developed fully compliant patch excited cups elements, with contact free coaxial probes. Details on ARTEMIS antennas are given by Di Fausto et al. in [8].

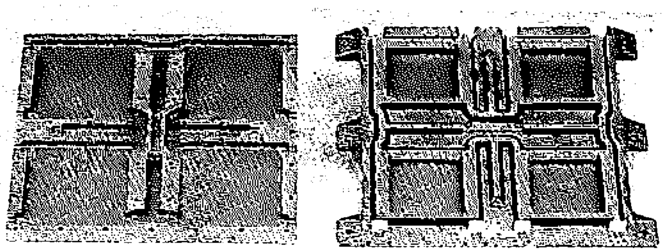

Figure 3. 4x4 Butler-like matrix at 1.55 Ghz (ALENIA SPAZIO)

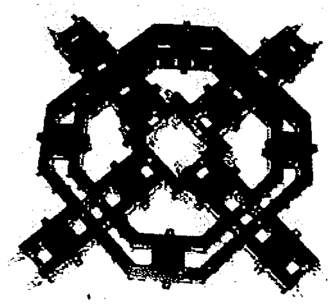

Figure 4. 8x8 Butler-like Matrix at 1.55 Ghz (RYMSA)

ARTEMIS L-BAND TX/RX FEED TYPICAL REQUIREMENTS

MISSION	:	ESA MOBILE PAYLOADS
FREQUENCIES	:	TX: 1.53 - 1.56 GHZ RX: 1.63 -1.66 GHZ
POLARISATION	:	SINGLE CIRCULAR
AXIAL RATIO	:	<1 DB IN ± 10° & <2 DB IN ± 30°
EFFICIENCY	:	> 85 % (Ge / (4 π S/λ²)
PASSIVE INTERMOD.	:	-150dBm 7th order / 2 tones@ 20 W
AMPLITUDE / PHASE Δ	:	± 0.25 DB / ± 5°
TEMPERATURE	:	-120°C TO +130°C
STIFFNESS	:	> 100 Hz
MASS	:	< 3 KG/M²
LAUNCH YEAR	:	1996 (EMS) / 1998 (ARTEMIS)

Table 1. L-band Tx/Rx feeds typical requirements

The semi-active multimatrix concept has also been retained for the INMARSAT III mobile payloads [2] and for other mobile communication satellites.

Semi-active arrays (without reflector) are being investigated for direct audio broadcast payloads [9].
Fig.5 shows the principle for a linear array, where the Butler-like matrices are hybrid couplers. Butler-like matrices of different sizes can also be selected.
An amplitude taper for low sidelobes, is achievable by phase-only control with no

taper at the power modules, which can therefore be smaller and more efficient.
The concept has been applied to the generation from an elliptical orbit of a shaped beam over Europe with low sidelobes in North America for frequency re-use. A 37 element semi-active array using one layer of hybrid couplers between the 1.8 λ radiating elements and the power modules has been optimised.

The array and the amplitude law, from phase-only optimisation at the inputs of couplers connected to selected element pairs, are shown in fig. 6. A contour plot of the beam over Europe with low sidelobes over North America is shown in fig.7.

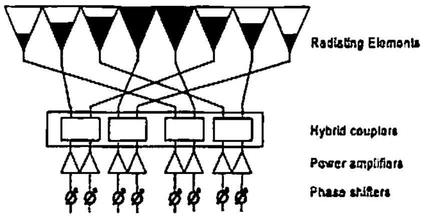

Figure 5. Semi-active linear array

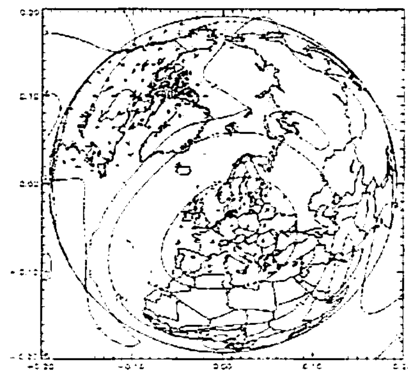

Figure 7. Semi-active array contoured beam with sidelobe control

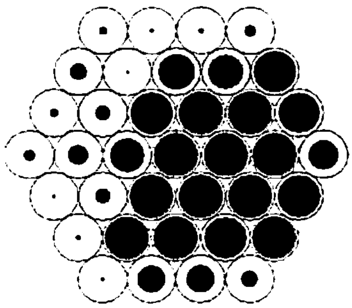

Figure 6. Semi-active planar array for radio satellite

The minimum coverage directivity of 24.8 dBi is 0.5 dB higher and the sidelobe isolation of 23.5 dB in North America is 13 dB better than is achievable with a traditional active array with the couplers removed.

2.2. L and S-band feed and array element technology

Significant R&D has been funded by ESA for L- and S-band element radiators. Dual patch developments over the 1530 to 1660 MHZ band [10] were conducted at Saab Ericsson Space, Sweden. This work led to the patch excited cup feed elements of the ARTEMIS L-band antenna. They have also developed a "suspended microstrip technology" shown in fig. 8, where elements are printed on a tensioned membrane.

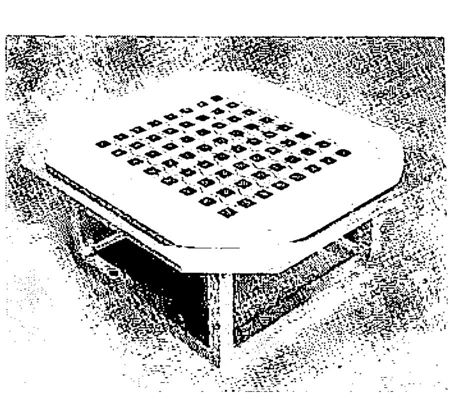

Figure 8. "Suspended" microstrip array (SAAB- ERICSSON SPACE)

Successful EM coupled annular slot designs were developed for ESA at Alcatel Espace, France [11]. This type of element is used for the MT-SAT satellite for aeronautical communications in Japan. It is also to be used scaled at Ku-band in the active antenna of the French STENTOR satellite [12].
Similar designs have been developed in Spain by CASA and DETYCOM [13] for L/S- band.
Alenia Spazio, in Italy, have also developed for ESA [14]dual polarised S-band antennas with 13% bandwidth (2.025-2300 Ghz) for communications with space vehicles via relay satellites.
These use two layers of EM coupled patches with the microstrip feed circuit on the bottom layer.
This design provides over 80% efficiency and less than 1 dB axial ratio, measured over the full band for small

arrays.
In addition to the selected developments mentioned above, ESA has innovated and supported significant R&D in the areas of antennas for mobile terminals at 1.5/1.6 GHz, ranging from new omnidirectional antennas [15] to adaptive electronically steered ones. Ref. [16] gives a review of ESA sponsored work.

2.3 Fixed communication active array at Ku-band

For future telecommunication systems with reconfigurable multibeam payloads at Ku-band, France Telecom has supported at Alcatel Espace the full development of two separate transmit and receive arrays including radiating elements, filters, amplifiers and beam forming networks [12].

ACTIVE Ku-BAND ARRAY TYPICAL REQUIREMENTS

MISSION	: FIXED TELECOM.
FREQUENCIES	: TX: 10.70 - 12.75 GHZ RX: 14.00 - 14.50 GHZ
COVERAGE	: EUROPE
NUMBER OF BEAMS	: 8 - RECONFIGURABLE
POLARISATION	: DUAL LINEAR
POLAR ISOLATION	: > 33 DB
NB OF ELEM. CHAINS	: 64
TX FILTER REJECTION	: > 90 DB IN RX BAND
POWER MODULES	: 0.5 W / 50 dB GAIN
BFN ERRORS	: 0.20 DB RMS / 3° RMS
LAUNCH YEAR	: ≈2000 (STENTOR SATELLITE)
REFERENCE	: MICHEL ET AL. JINA'94

Table 2. Active Ku-band active array data

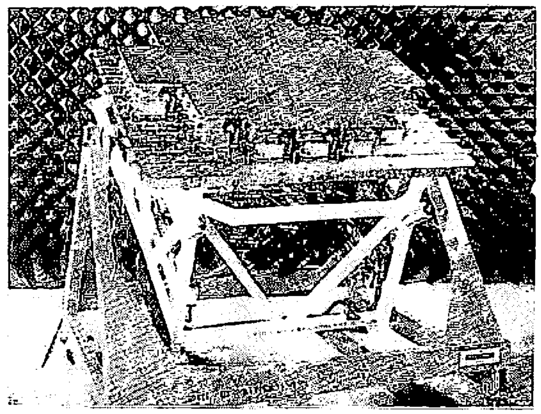

Figure 9. Active Ku-band array (ALCATEL ESPACE)

Key parameters are listed in table 2. The transmit antenna assembly is shown in fig.9.
The radiating elements are annular slots derived from those mentioned in section 2.2, described in [11]. The power amplifiers use MMIC modules and are integrated with their power supply and filter section. Only 3 of the 8 beams are generated by the beam former which includes 192 phase shifting and attenuating cells, using MMIC chips. The requirements of table 2 are met over the band and it is planned to fly technology derived from this one by year 2000 on the French satellite STENTOR.

2.4 Antennas for satellite TV reception

WAVEGUIDE FED SATELLITE TV ANTENNA PERFORMANCES

FREQUENCY BAND	: 10.70 - 12.75 GHZ
POLARISATION	: DUAL LINEAR
CROSS POLARISATION	: > 26 DB
CHANNEL ISOLATION	: > 20 DB
OHMIC LOSS	: < 0.5 DB
G/T	: >12.7 DB/K (0.8 DB LNB NF)
RETURN LOSS	: >12 DB
NB OF ELEMENTs	: 12x12
TECHNOLOGY	: MOULDED PLASTIC
REFERENCE	: SHELLEY.. ESA WPP- 051, 1993

Table 3. DBS TV receive antenna performance

Unlike in Japan, where most antennas are designed for 11.7 to 12.1 GHz, a broader band, from 10.7 up to 12.75 GHz is assigned in Europe. Thus, arrays have difficulty to compete with single or dual beam reflector antennas.
The low tolerance circular slot design of Rammos [17,18], using circular holes excited by stripline corporate feed networks, is on sale for over 1 GHz bandwidth, and in preparation for 2 GHz.
One promising design by ERA [19] uses square apertures fed by two low loss waveguide corporate networks, one per polarisation, employing E plane dividers. A 12x12 array, shown in fig.10, has been built and tested over the 10.7 to 12.75 GHz band.

With uniform illumination, the array is oriented diagonally to lower sidelobe interference. Performances are listed in table 3.

3. ANTENNA TECHNOLOGIES FOR EARTH OBSERVATION

ESA is active in several earth observation programmes involving microwave instruments such as synthetic aperture radars (SAR), cloud and rain radars, scatterometers, altimeters, radiometers and limb-sounders.
ESA's ENVISAT 1, shown in fig.11, to be launched in 1999, is part this programme.
The next sections cover antennas for active SAR's and for millimetre wave sounders.

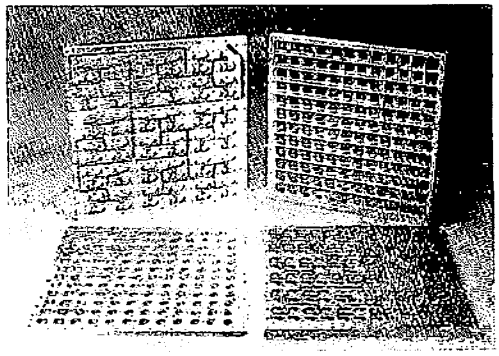

Figure 10. Satellite TV receive array antenna

3.1 Antenna technologies for synthetic aperture radar

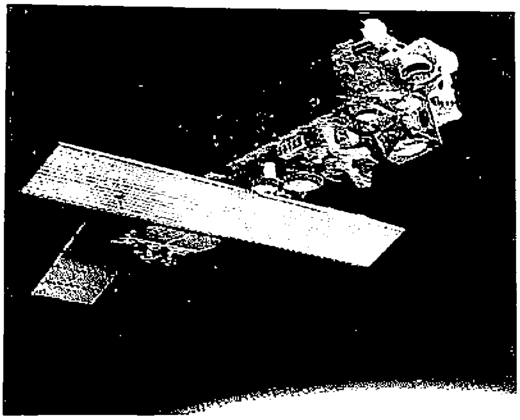

Figure 11. Artist's view of ESA ENVISAT 1

C BAND PRINTED ANTENNA TYPICAL REQUIREMENTS

MISSION	:	SYNTHETIC APERTURE RADAR
FREQUENCY	:	5300 MHZ ± 75 MHZ
POLARISATION	:	DUAL LINEAR (H/V)
CROSS POLARISATION	:	< -25 DB WITHIN ± 15°
RETURN LOSS	:	< -15 DB IN ORBIT
OHMIC LOSSES	:	< -1.0 DB / METRE
ELEMENT EFFICIENCY	:	> 85% (Ge / [$4\pi Se/\lambda^2$])
TEMPERATURE RANGE	:	-80°C TO +55°C
MASS	:	< 2 KG/M² (EXCL. STRUCTURE)
LAUNCH YEAR	:	1999

Table 4. SAR antenna typical requirements

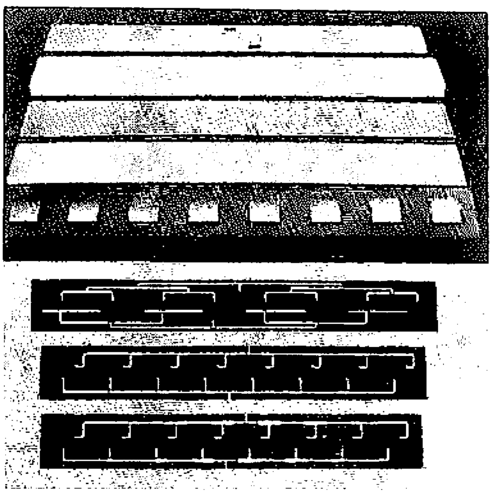

Fig.12. Sub-array of slot coupled patches (DORNIER-DBS+U. KARLSRUHE)

After the successful operation of ESA's ERS1 and ERS2 C-band SAR's, dual polarised active arrays will be flown with the typical requirements listed in table 4, for which several designs compete.
One configuration, developed by Baracco at ESTEC [20], uses two almost independent radiating strip etched on the two faces of a substrate each EM coupled by open-ended microstrip lines.
Recently, Dornier-DBS with University of Karlsruhe [21], using slot coupled patches, have achieved results well exceeding the requirements of table 4. This C-band antenna is now being developed in space technology. Figure 12 shows a breadboard of a sub-array.

3.2 Antenna technologies at millimetre wave frequencies and above

3.2.1 High accuracy reflector technology

Millimetre-wave and submillimetre-wave passive instruments and infrared telescopes require reflectors with micrometre accuracy in space environment with diameters up to a few metres.
ESA has supported the development of carbon fibre reinforced plastics as well as carbide silicate reflector technology to meet these requirements.
Fig.13 shows an all graphite/epoxy test panel developed by Dornier-DBS in Germany for operation up to infrared. Its key characteristics are summarized in table 5.

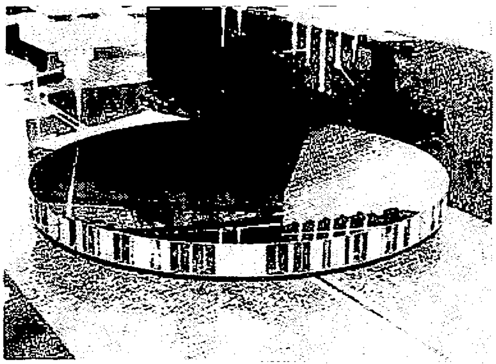

Figure 13. High accuracy reflector panel (DORNIER-DBS)

HIGH ACCURACY REFLECTOR TECHNOLOGY		
APPLICATIONS	:	FAR INFRARED RADIOASTRONOMY
	:	MM & SUB-MM WAVE SOUNDERS
GEOMETRY	:	UP TO 3 METRES IN PANELS 100 MM THICK SANDWICH / ALL CARBON FIBRE/ GOLD PLATED
SURFACE ERROR	:	5 - 10 µM RMS
MASS	:	15 KG/M²
CRITICAL AREAS	:	ACCURACY/THERMAL CONTROL
STATUS	:	1.1 M BREADBOARD (5µM RMS MANUF. + 2µM THERMAL)
REFERENCE	:	DORNIER: HIGH PRECISION ANTENNA STRUCTURES ESA CONTRACT No 8556

Table 5. High accuracy reflector characteristics

3.2.2 Millimetre wave feed technology

ESA supports the development of antenna technology for application to stratospheric chemistry (from 10 to 100 km altitude) by radiometry from 90 to 1000 GHz, in particular for monitoring of the ozone. Present requirements for the millimetre wave limbsounder antenna are outlined in table 6.

MILLIMETRE WAVE SOUNDER ANTENNA REQUIREMENTS		
MISSION	:	CHEMISTRY OF HIGH ATMOSPHERE (OZONE...)
SATELLITE / ORBIT	:	SUN-SYNCHRO. @ 800 KM
FREQ. BANDS A,B,C,D (GHZ)	:	199-207 / 296-306 318-326 / 342-348
COVERAGE	:	LIMB SOUNDING
BEAM POINTING ACCURACY	:	DISTANCE: 1 KM - AZ: 1 DEG
BEAM EFFICIENCY	:	A: 85% / 4.5 KM 98% / 9 KM B/C/D: 85% / 3 KM 98% / 6 KM
MAX. DIMENSIONS	:	2.5 METRES
ENVIRONMENTAL	:	ARIANE 5
LAUNCH YEAR	:	2005

Table 6. Millimetre wave antenna requirements

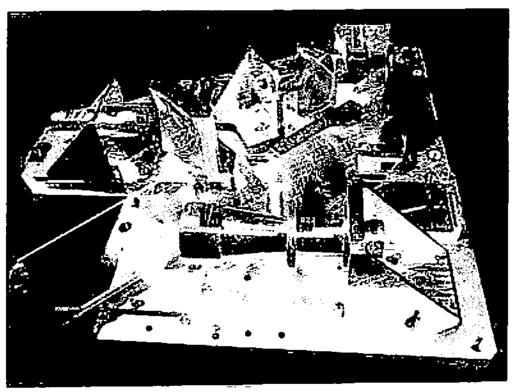

Figure 14. Millimetre wave feed (MMS-F)

ESA started funding critical technologies in frequency bands from 61 GHz to 207 GHz. This work, reported in [22,23], has resulted in the quasi-optical focal plane network described in table 7 and fig. 14.

MILLIMETRE WAVE SOUNDER ANTENNA DESCRIPTION

ANTENNA TYPE	:	GREGORIAN OFFSET
REFLECTOR	:	2 M x 1 M SHAPED
REFLECT. TECHNO.	:	FULL CARBON FIBRE REINFORCED PLASTICS
SUB-REFLECTORS	:	OFFSET PARABOLOIDS FOR BEAM MAGNIFICATION OFFSET ELLIPSOIDS FOR BEAM TRANSFER
FREQUENCY FILTERS	:	DICHROIC PLATES: GOLD PLATED/ PHOTO-ETCHED RINGS ON FUSED SILICATE SUBSTRATE
POLAR. FILTERS	:	POLARIZER PLATES: GOLD PLATED & PHOTO-ETCHED
FEEDS	:	CORRUGATED HORNS
BEAM EFFICIENCY	:	95 TO 98 % FOR COMPUTED SECONDARY PATTERNS
OHMIC LOSSES	:	0.5 DB - 0.7 DB (FROM COMPONENT LOSS MEASUREMENT)
REFERENCE	:	G.PADOVAN, ICAP 93 p. 925

Table 7. Millimetre wave sounder antenna first breadboard description

The requirements listed in table 6 will drive the next development phase which will cover the complete limbsounder breadboarding, including reflectors and receivers.
The high beam efficiency requirement leads to a dual offset shaped reflector design with a common waist size of 8 millimetres for each band. Reflectors, wiregrids and dichroic plates are used to separate the four frequency bands.
The dichroic technology is gold plated photo-etched ring patches on a fused silicate substrate. The wiregrids use the same technology with the patches replaced by parallel lines on both sides of the substrate.
Key features of the demultiplexer, developed in France by Matra Marconi Space, are listed in table 7.

4. Other areas of antenna R&D for space applications

ESA and other institutions have supported a large number of software developments:

- for reflector antennas, in particular at TICRA (Denmark), ERA and QMWC (UK)
- for feeds, in particular at CNET (France) and CSELT (Italy)
- for printed antenna arrays, in particular at LEMA-EPFL (Switzerland), Katholieke Universiteit Leuven (Belgium) and Université de Limoges (France)
- for the analysis of antenna interactions with spacecraft, in particular at the Technical University of Denmark, TICRA (Denmark), Matra Marconi Space (France), Mothesim (France) and IDS (Italy)

Some of these programmes are now used worldwide.
Recently an effort has been undertaken with IDS (Italy) to develop an "Antenna Design Framework", equipped with facilities, allowing to interface and run a number of antenna software tools together.

ESA has also promoted the early development of antenna test techniques and facilities with high accuracy spherical near field techniques at the Technical University of Denmark, a 12x4 metre planar near field facility at Saab Ericsson Space (Sweden) and a dual reflector compact test range with a 5x7 metre quiet zone in ESTEC.
References on these and other European developments are given in [2].

4. Conclusions and trends

From the above review of antenna design tools and technologies, it is clear that Europe, after two decades of intensive R&D, has developed areas of excellence in space antenna engineering and technology (reflector and printed microstrip antenna modelling, shaped reflectors, antenna feed systems...).

Much work remains to be done to improve the accuracy and speed of modelling tools with as objective to reduce the number of breadboarding iterations and to limit costly antenna testing.
Consolidation of existing technologies towards lower cost and use of larger apertures, extension up to submillimetre waves , development of integrated active antennas, possibly with optical components and digital beam formers, are some of the challenges for the satellite antenna designers of the next decades.

6. Acknowledgments

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