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Synthesis of Main Architectures Used in Modular Active Antennas

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Abstract

As a 1st step for structuring the European Research on Array Antennas, this deliverable D1 presents a clear terminology tree for this antenna category: from passive ones to fully active, the latter using analogue or digital beam-forming with self-adaptive algorithms, via phased arrays using passive controllable devices.

According to this taxonomy, 54 array antennas, built by ACE partners, have been classified. The main characteristics are summed up in a large table (appendix B). Typical examples are shown in §4, covering a wide range of various array categories. Modelling tools are presented, and bottlenecks pointed out, providing input for further research work.

As complements to the main part, five extensive world-wide "State-of-the-art" reviews are attached: each one explains how array antennas are good answers to the requirements of a given type of Communication (and to a lesser extent: Remote Sensing) System: in Base-Stations, on Satellites, for User Terminals, and in Civil or Defence Radar.

Keyword List

Active antenna subsystems, phased arrays, beam-forming, beam-steering, control devices, low-noise (LNA) or high-power (HPA) amplifiers.

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ACE WP 2.4-1
"Optimisation of Active Antennas Architecture"
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"Synthesis of Main Architectures Used in Modular Active Antennas"

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1 INTRODUCTION

This document constitutes the first report of the ACE WP 2.4-1 "Optimisation of Active Antennas Architecture" and represents the Deliverable 2.4-D1 "Synthesis of Main Architectures Used in Modular Active Antennas".
The document describes the methodology for the work, and the results of the questionnaire that was the first item of work in this work package.

1.1 Description of Work – ACE WP 2.4-1

The description of work that was given in the Technical Annex [1] is repeated here for convenience:

1. Experience sharing, concerning practical architectures built for active antenna subsystems used in Communication, Defence and Remote Sensing applications.
   - Provide a picture of the current state of European R&D in the field.
   - Build a knowledge basis, required for making trade-offs between performance of individual functions and the reachable performance of the full active antenna (possibly providing several simultaneous beams and functions (ex: sum and difference patterns in monopulse radars and multi-channel communication).
   - Identify bottlenecks for the realisation of modular active antennas. Synthesise the current use of simulation tools for individual units & full antenna systems, and gained experience.
   - Define future need for European R&D, for solving bottlenecks and developing critical enabling technologies. Launch new research works for that, mixing self-funding, support from the NoE tools, co-funding from various National or European Agencies.

2. Antenna systems modelling, from a functional scheme, and sub-parts performance characterisation:
   - describe existing block-models and principles for them.
   - study subsystems model interfaces with a purpose to make them connectable.
   - define an overall simulation platform.

1.1.1 Deliverable

The current deliverable is:

- 2.4-D1: Synthesis of main architectures used in modular active antennas (T_o+6).

1.2 Participants

The participating entities in this work package are the following (reference numbers as in the Consortium Agreement and Technical Annex [1]):

No.	Organisation	Short Name	Country
7	Alcatel Space	Alcatel	France
10	Thales Airborne Systems	TAS	France
15	Deutsches Zentrum für Luft- und Raumfahrt E.V.	DLR	Germany
28	Universidad Politecnica de Valencia	UPV	Spain
30	Ericsson Microwave Systems AB	EMW	Sweden
31	Swedish Defence Research Agency	FOI	Sweden
36	Netherlands Organisation for Applied Scientific Research	TNO	Netherlands

Table 1.2-A Participating organisations.

In addition to these, the other entities that participate in WP 2.4-2 and 2.4-3 were given the opportunity to participate with their experiences.

2 METHODOLOGY

The main effort in this early stage of the project is to collect information about existing and planned arrays. The two methods that have been used in this case is compiling data from open sources and collecting data from the participating organisations through voluntary questionnaires. The compilations and the reviews of the state-of-the-art will hopefully give a broad picture of the global situation, whereas the questionnaires will give a subset of a European experience. The questionnaires are presumably more detailed and more up-to-date than published data, and will thus enable us to get a more complete picture.
However, this open source and voluntary input approach will have some disadvantages. The real state-of-the-art is seldom reflected in open publications, and most commercial companies would hesitate to describe their most advanced and novel systems in detail. In some cases defence secrecy would put a tough limit to information exchange. Even though the most advanced array antennas are classified, the underlying basic principles are fairly well established, and one can therefore extrapolate the technology with some confidence.

2.1 The ACE 2.4 Questionnaire

A questionnaire was designed by the participants with the activity and work package leaders as responsible. The questionnaire was generic for all the three work packages 2.4-1–3. The answers have then been used for the three separate syntheses, each focussed on the concerned WP topic. The questions in the questionnaire were the following (the full questionnaire form is appended to this report in Appendix A):

- What application? (Radar, Base-station, Satellite Terminal, Space, …)
- What kind of array? (Planar, conformal, …)
- Which architecture? (Active, passive, RX, TX, analog; digital, …)
- Block diagram
- Level of development (In TRL standard)
- Product tree
- Antenna geometry
- Beam forming techniques and algorithms, calibration, measurement
- Modelling techniques and simulation tools (commercial or internal, open source, what is lacking, …)
- Level of integration (amplifiers, …)
- Benefits and drawbacks (for techniques and tools). Critical points, open points.
- Principles and examples of Validation measurements
- Best references for associated publications

The questionnaire was sent out to all activity participants in early March 2004, with a deadline for the answers by the end of March 2004.
A total of 53 questionnaire answers were finally submitted (refs. [7] – [59]). Many of the answers had reports and articles appended to them, and the total amount of data was large, filling several binders. In order to organise and sift out the main data of this database, an Excel sheet was constructed with columns for each main data. A condensed version of this Excel sheet is contained in Appendix B of this report.

2.1.1 Statistics

There were 53 entries in total. The quantity and comprehensiveness of the answers varied a lot. Out of the entries, 10 described software, and are not included explicitly in this synthesis. The remaining 43 entries were “hardware” ones, describing arrays of various types and technology readiness. The number of entries with respect to countries is given in Table 2.1-A below.

Country	No. of Entries	Submitting Entities
Sweden	19	EMW, SES, KTH, Chalmers, FOI
Spain	8	UPM, UPV
Germany	7	DLR, TUD, UniKa
France	5	TAS, Alcatel Space
Italy	5	USi, PoliTo
UK	4	UBham
Netherlands	4	TNO
Belgium	1	KUL

Table 2.1-A Entries by country.

2.1.2 TRL Level

An adaptation of the TRL (Technology Readiness Level) method was used for assessing the technology readiness of the arrays. The TRL method was developed by NASA to classify where in the R&D chain a project or product is located (see [62]). The adapted definition of the levels (courtesy of TNO) is shown in Table 2.1-B below.

The questionnaires showed a large spread in TRL levels. The described arrays were either in the level range of 1 to 4/5 or in the upper echelon of 8/9. One can only speculate about the deficiency of mid-range systems, but one reason might be that large corporations are reluctant to release data about systems in this range, and that universities seldom move into this area.

TRL	Description
9	Actual system proven in an operational environment
8	Actual system completed and qualified
7	System prototype demonstration in an operational environment
6	System/subsystem model or prototype demonstration in a relevant environment
5	Component and/or breadboard validation in a relevant environment
4	Component and/or breadboard validation in a laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

Table 2.1-B The definition of the Technology Readiness Level (TRL) scale.

2.2 Reviews of the State-of-the-Art

As a complement to the questionnaire (which gives the 'European experience'), reviews of the main array techniques used in the world (especially USA and Japan, which are not covered by our Network) were compiled. Several generic categories were chosen, and the following reviews were prepared by participating entities.

- Defense radars (TNO and FOI) [5]
- Civilian radars (TU Darmstadt) [3]
- Spaceborne arrays (Alcatel Space) [4]
- User terminal arrays (DLR) [6]
- Base station arrays (UPM) [2]

Since the reviews are essentially self-contained, they provide a synthesis in themselves, and therefore not much of secondary synthesis is made with these as a source.

3 Structuring

3.1 A Model of a Radar or Communication System

A modern radar or communication system can be represented as a layer model as in Figure 3.1-A. The different layers that represent different functions are:

- Wave layer: Propagation and structure influence
- EM layer: Spatial integration & filtering (antenna & radome)
- Analog layer: Signal integration & filtering
- Digital layer: Signal & data processing
- Information layer: Data integration (non-coherent "fusion")

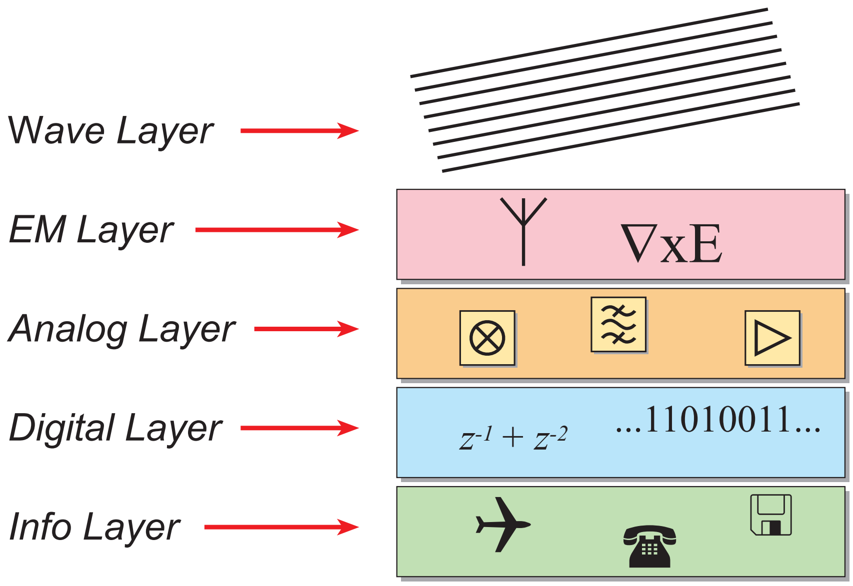


Figure 3.1-A A layer model of a modern radar or communications system.

In a classical antenna, the antenna function is located in just the upper 'electromagnetic' layer, *i.e.* the aperture *per se*. With the advent of active antennas and digital beam-forming, the antenna functions spread down through several layers. Considering non-linear and non-coherent processing of the data from the array elements, as in diversity, DOA estimation, *etc.*, all layers are now more or less involved in the antenna function. See Figure 3.1-B.

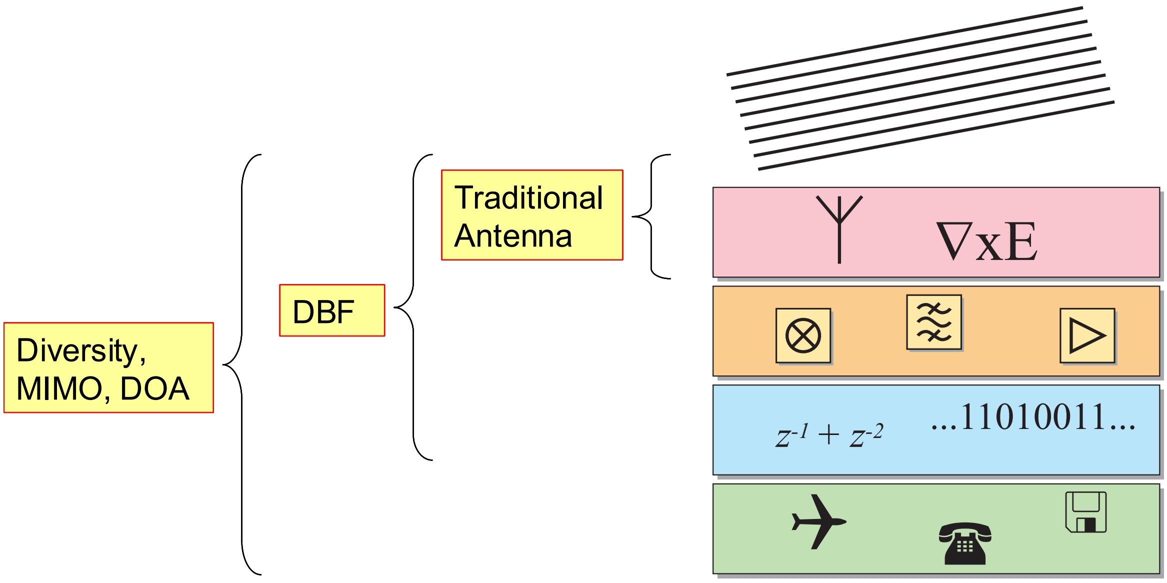


Figure 3.1-B The antenna function is now spreading into many layers.

3.2 Array Taxonomy

Some attempts to classify the different arrays into different generic array types in a variant of taxonomy (as in traditional *Linnæan* type botany, *cf.* [60]) are made in the following.
At the ACE workshop in Gothenburg, it was evident that there is some confusion regarding notation, *e.g.* for the term *active*. Some would understand active as something that is electronically controlled, while others would use the term for distributed active electronics. To resolve this issue, the IEEE Std. 145–1993, “IEEE Standard Definitions of Terms for Antennas” [61] was consulted. The standard says:

> ***Active array antenna system.*** *An array in which all or part of the elements are equipped with their own transmitter or receiver, or both.*
>
> *Ideally, for the transmitting case, amplitudes and phases of the output signals of the various transmitters are controllable and can be coordinated in order to provide the desired aperture distribution.*
>
> *Often it is only a stage of amplification of frequency conversion that is actually located at the array elements, with the other stages of the receiver or transmitter remotely located.*

Following this, one could therefore have active to mean that there are active elements located between the radiating elements and the beam-forming network of the array.
As an antonym to active the word ‘passive’ would be appropriate, without any negative connotations attached to that word. To annotate a case where the array is only active in transmit or receive, the word semi-active could be used. However, since this does not seem to be standardized, the terms ‘active in receive’, ‘active in transmit’, and ‘active in transmit and receive’ are used.
In order to keep an internationally accepted terminology, the terms used in the IEEE standard have been used when possible.

3.3 Terminology Tree

The terms that will be used to describe the arrays are given as in the following sections. There are essentially (at least) four dimensions in which we can classify array antennas. The ones that have been chosen here are:

- Active or passive
- Beam steering principle
- Beam-forming principle
- Simultaneous beams

Other criteria could be taken into account, such as:

- Transmit- or receive-only modes for active non-reciprocal antennas
  (TX + RX simultaneously or interleaved)
- Single or multiple band operation

However, these criteria have been put in a second order of priority, considering that the four chosen ones already provide a large set of combinations in the four-dimensional space that they span. Not all combinations are relevant, and probably about ten canonical combinations can describe most, if not all, array types (*cf.* the classification of the arrays implemented by ACE A2.4 activity partners in Section 4.1 to 4.10).

3.3.1 Active or Passive

An active array has active elements located between the radiating elements and the beam-forming network of the array. The four different combinations of active/passive in receive and transmit result in the following four classes of arrays:

3.3.1.1 Active in Transmit

3.3.1.2 Active in Receive

3.3.1.3 Active in Transmit and Receive

3.3.1.4 Passive

3.3.2 Beam Steering Principle

The principle for producing the phase or time gradient across the array, that would produce a scanned or steered beam, is the second way of classifying the arrays. If the there is no way of varying the phase gradient, the array is considered to be of the fixed beam type. One could possibly demand that the principles for changing the phase or time-delay should be based on principles that are non-mechanical, but then electromechanical systems like MEMS would have to be classified in a separate category. Thus, there are essentially three different categories for beam steering:

3.3.2.1 Phase Gradient Beam Steering

3.3.2.2 Time Delay Gradient Beam Steering

3.3.2.3 Fixed Beam

3.3.3 Beam-Forming Principle

The beam-forming principles comprise a wide variety. One way to classify these is to consider the signal type at which the beam-forming is made. Thus the three possibilities would be RF, digital, or optical. The RF type beam-forming alternatives could further be divided into either guided (transmission line) or space fed (*e.g.* 'reflectarrays'). Off-line beam-forming is also used sometimes in testbeds to assess antenna patterns, *etc.*, and should be considered as a fifth variant.
Since the beam-forming issues are more dealt in detail in another work package, we just make a crude sub-division with the following five categories:

3.3.3.1 Guided Wave Beam-Forming

3.3.3.2 Space-Fed Beam-Forming

3.3.3.3 Photonic Beam-Forming

3.3.3.4 Digital Beam-Forming

3.3.3.5 Off-Line Beam-Forming

3.3.4 Simultaneous Beams

One further way of classifying arrays is whether there are multiple (simultaneous) beams. Some beam-forming networks give the possibility to get several simultaneous beams, *e.g.*

- Butler or Blass matrices, Rotman lenses, *etc.*, for multiple fixed beams
- Controllable analogue or digital beam-formers, for multiple reconfigurable beams

Thus the classification in this case is:

3.3.4.1 Multiple Beams

3.3.4.2 Single Beam

4 Overview of Questionnaire Answers

In the following the various types of array antennas are listed in terms of classification and increasing complexity. Block schematics are given to give a word-less definition of what is meant.
The beam-forming principles are essentially reduced to either a beam-forming network or digital beam-forming in this report, since beam-forming principles are covered separately in WP 2.4-2.
Some of the questionnaire input has been tabulated in an M$ Excel document, which could serve as a multi-parameter synthesis of the raw data input. The input quantity varies from very sparse to abundant. Sometimes it is difficult to extract important parameters, but this is of course inherent in the low-end TRL array descriptions.

4.1 Array Aperture Testbed

The most basic configuration is an array aperture testbed without any beam-forming network. The array consists of a multitude of array elements, each one equipped with a port (*e.g.* coaxial connector), enabling various measurements. A block schematic sketch of this is shown in Figure 4.1-A. This array type is typically used for:

- Mutual coupling measurements
- Embedded (active) antenna pattern measurements
- Most basic validation of design tools

The array aperture testbed could be used together with off-line beam-forming, *i.e.* collected measurement data can be numerically manipulated in a computer to create a virtually beam-formed array.

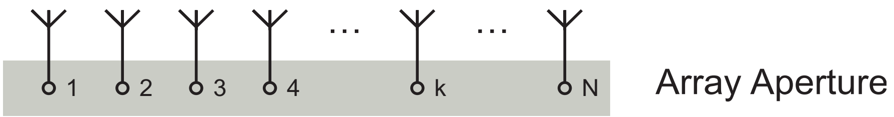
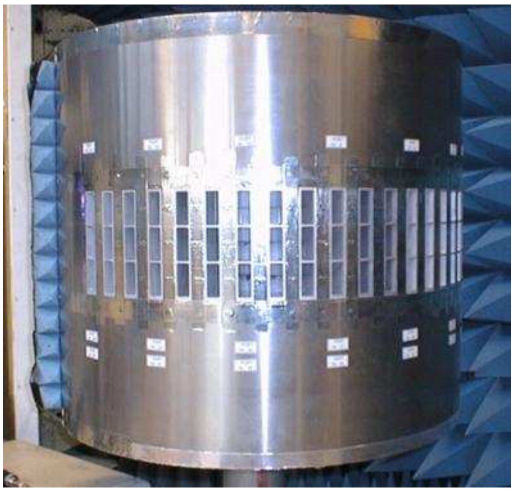


Figure 4.1-A A sketch of the principle of an array aperture testbed.

Array aperture testbeds are legion for serious research and development of array antennas. Some examples are shown in Figure 4.1-B to Figure 4.1-D below.



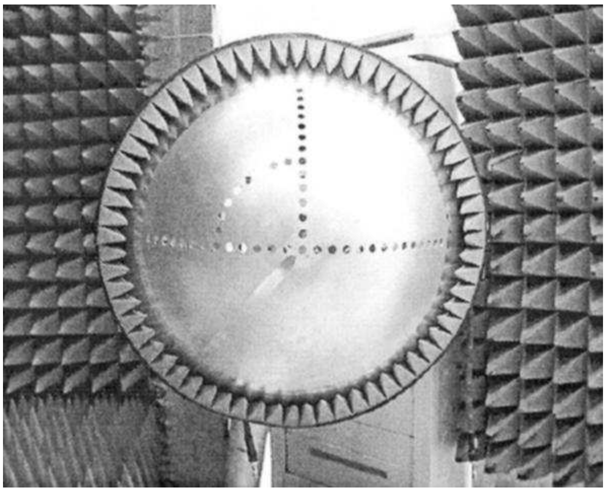


Figure 4.1-B Singly curved (left) and doubly curved (right) conformal testbeds made by Ericsson Microwave Systems and KTH ([12], [13]).

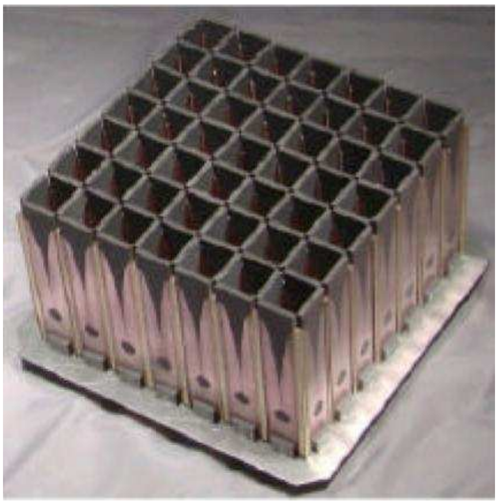


Figure 4.1-C FOI TSA array testbed [30].

Figure 4.1-D TNO open-ended waveguide array feed [52].

4.2 Passive Fixed Beam Arrays

The next step in the evolution is the addition of a beam-forming network (BFN) to an array, and thus

- Array aperture + Fixed and non-controllable BFN = Passive fixed beam array

A sketch of this canonical array type is given in Figure 4.2-A. The beam-forming network could possibly have a fixed path-length gradient across the array if a non-boresight beam is desired.

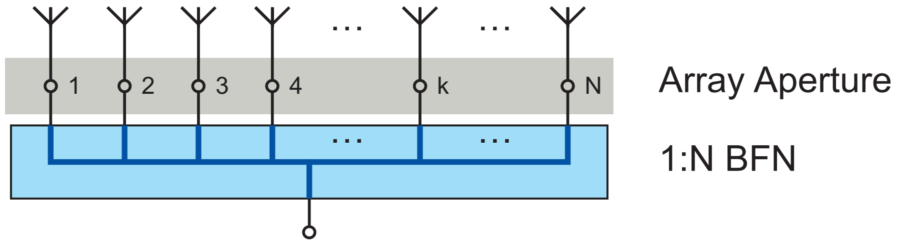


Figure 4.2-A A sketch of the principle of passive fixed beam arrays.

The questionnaire answers gave a lot of examples of passive fixed beam type arrays. In Figure 4.2-B to Figure 4.2-E some examples are shown. A somewhat difficult case to classify is the space-fed reflectarrays shown in Figure 4.2-F. Since the beam-forming issues are dealt with in a separate work package, this issue is not considered further here.

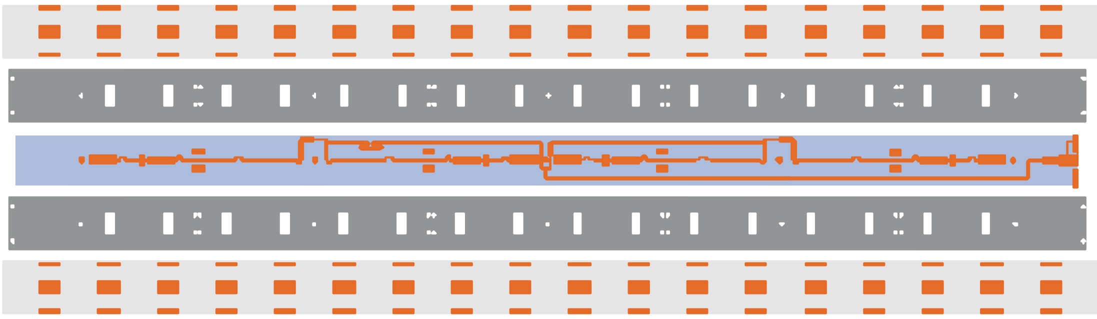


Figure 4.2-B UPM basestation sector array [50].
(Note that the drawing is rotated 90 degrees in this figure to save space.)

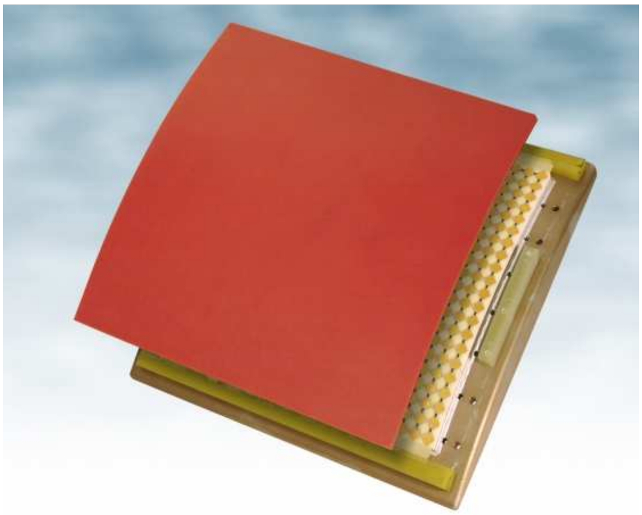


Figure 4.2-C TAS ALABAMA (Antenne Large BAnde pour Multifonctions Associées) conformal array [18].

Figure 4.2-D SES dual frequency patch antenna for GPS occultation measurements [24].

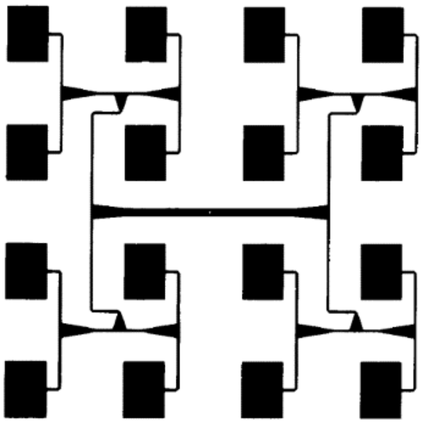


Figure 4.2-E UBham corporate feed patch array [57].

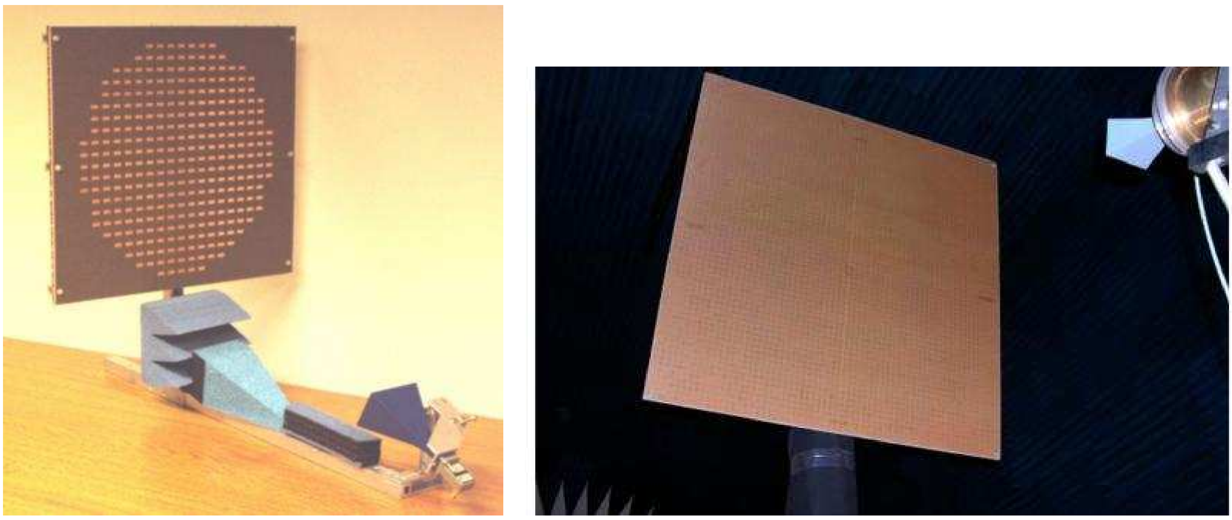


Figure 4.2-F PoliTo reflectarray [39] (left), and UPM reflectarray [44] (right).

4.3 Passive Multi-Beam Arrays

A beam-forming network with several more or less decoupled ports yields a multi-beam array. The Butler matrix is a well-known example of such a network. The principle is shown in the sketch in Figure 4.3-A. Some examples of multi-beam arrays are shown in Figure 4.3-B and Figure 4.3-C.

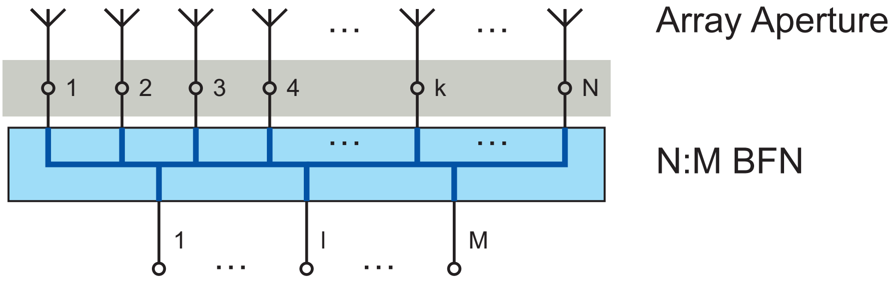


Figure 4.3-A A sketch of the principle of a multi-beam array system.

Figure 4.3-B FOI circular conformal communications testbed multibeam array [28].

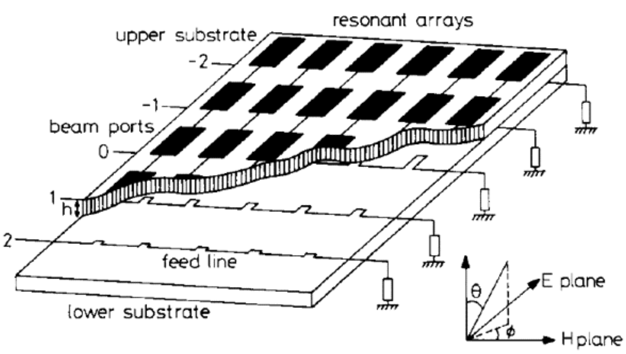


Figure 4.3-C UBham multibeam patch array [58].

4.4 Active Fixed Beam Arrays

Placing high-power amplifiers (without any phase control) in each branch of a transmitting array yields an active fixed beam (or spatial power-combining) array. A block schematic of an active fixed beam array is shown in Figure 4.4-A. An example of a spatial power-combining array is shown in Figure 4.4-B.
Even if less common, active fixed beam receive implementations are also possible, *e.g.* parallel low-noise amplifiers in each array branch to compensate for the losses of a fixed BFN. An example of this is the so-called focal array fed reflector (FAFR) antenna type used on satellites (see Figure 4.4-C).

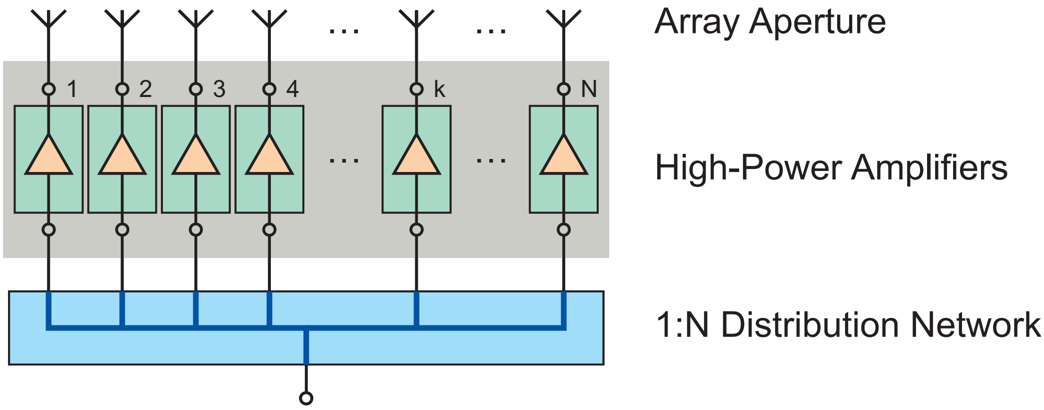


Figure 4.4-A A sketch of the principle of a power combining array antenna.

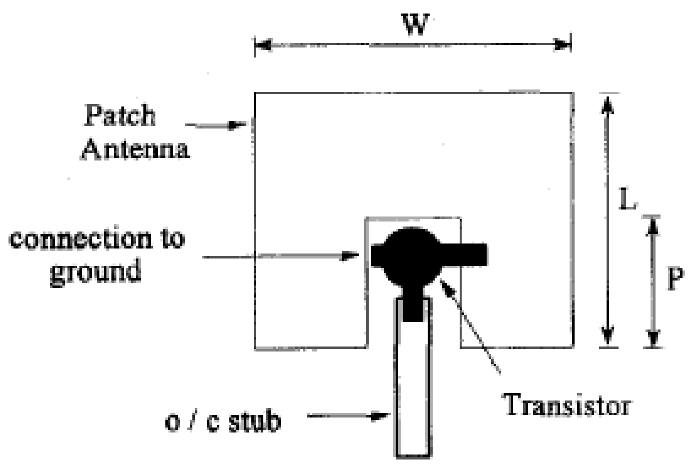


Figure 4.4-B UBham power combining patch array [56].

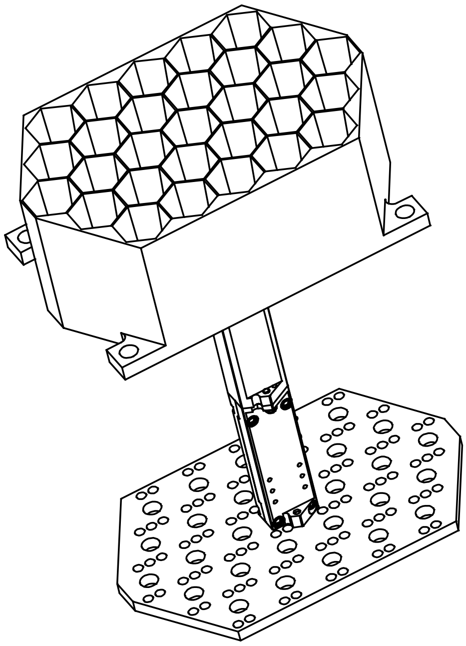


Figure 4.4-C SES MultiKaRa feed array [26].

4.5 Passive Phase Scanned Arrays

The next step up the evolution ladder is to add phase-shifters to enable beam steering through an applied phase gradient. In its simplest apparition this type of system would use passive low-loss phase-shifters (ferrite, varactor, electromechanical, *etc.*). Figure 4.5-A shows a block schematic for the combination of an array aperture, a beam-forming network, and phase shifters in each branch.
As the beam-forming network is placed after the HPA in transmit, and before the LNA in receive, it must provide very low loss. Some examples of passive phase scanned arrays with different low-loss BFN principles are:

- Space fed reflectarrays, see Figure 4.5-B.
- Waveguide beam-forming networks, see Figure 4.5-C. This antenna also utilises the principle of frequency dependent squint in a series fed waveguide slot antenna to achieve elevation beam steering.

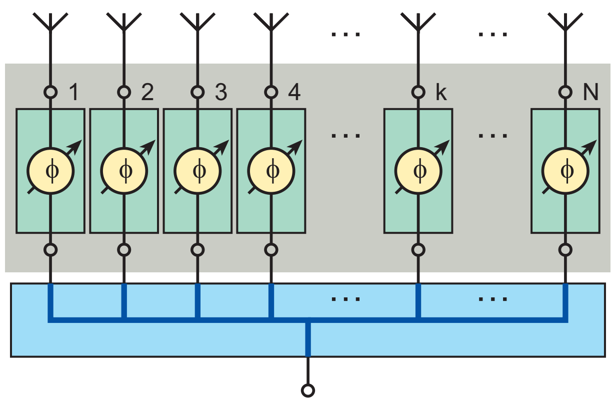


Figure 4.5-A Block schematic for a passive phase scanned array.

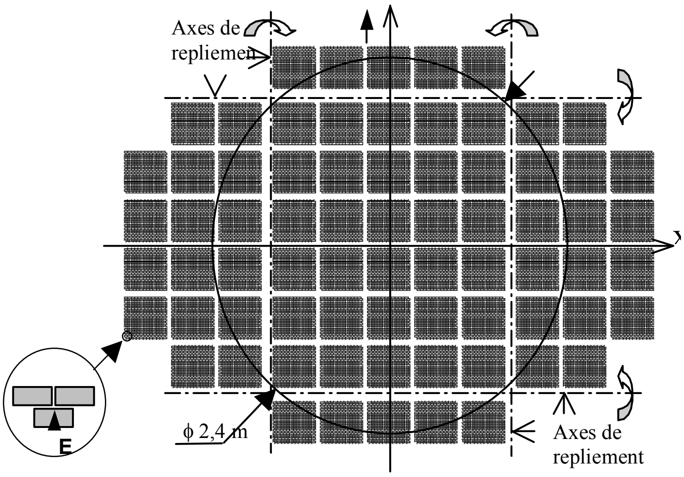


Figure 4.5-B Thales ERASP space radar array [17].

Figure 4.5-C Ericsson ARTHUR weapon locating system [15].

4.6 Digital Beam-Forming (DBF) Arrays

The currently most advanced (and most flexible) way of beam-forming is digital beam-forming. This is mainly a receive-only technique for direct radiating arrays. However, on several recent satellites (*e.g.* Thuraya, Inmarsat 4) providing phone/fax connection from/to anywhere in the world, digital beam-forming has been implemented in transmit. The digital beam-forming function is in this case comprised of a multitude of ASICs feeding the array radiating elements through solid-state power amplifiers (SSPAs), the whole array illuminating a large and lightweight reflector. This is complex, but is the only way for on-board routing connections, within a digital processor connected to TX and RX DBFNs (*cf.* fig. 2.1-c in ref. [4]).

In its purest form, see Figure 4.6-A, a DBF system would digitise the incoming antenna signals and do all the processing in the digital beam-forming processor. With *N* array elements, the dimensionality is *N* all through the system, and one can construct *N* independent beams.

However, in most cases it is not yet possible to swallow the extreme data rates that are produced by such a fully digital system, and one would typically restrict the number of digital channels to tens. The discrepancy between the number of channels and the number of array elements has to be handled in a multiple-output analogue beam-forming network, see Figure 4.6-B. The sub-arrays that are formed by such a partial digital beam-forming system will have to use beam steering, and thus there is a need for phase-shifters in all branches of the array.

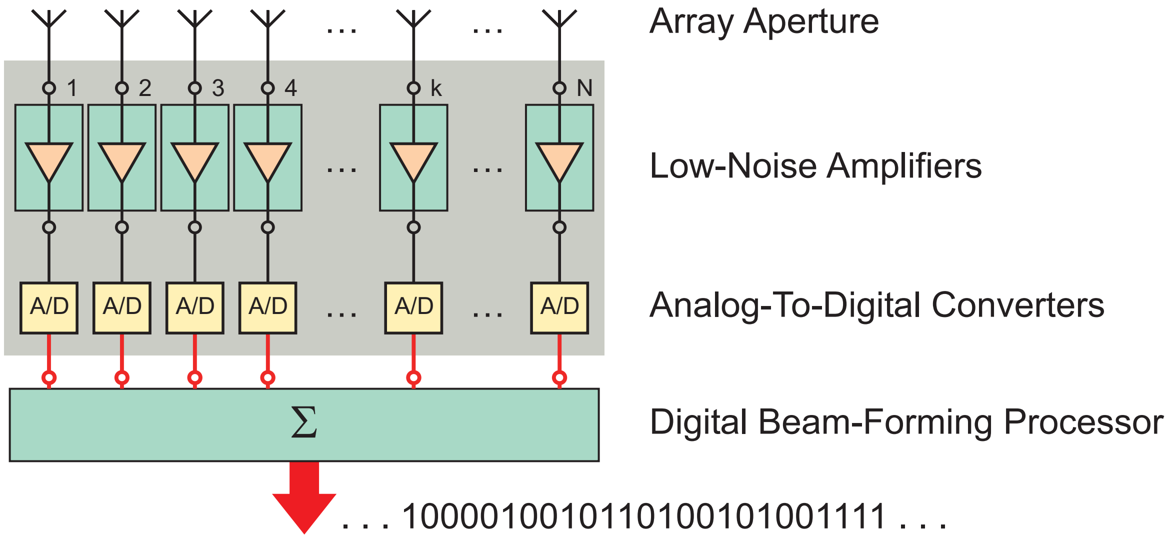


Figure 4.6-A A block schematic for a fully digital beam-forming.

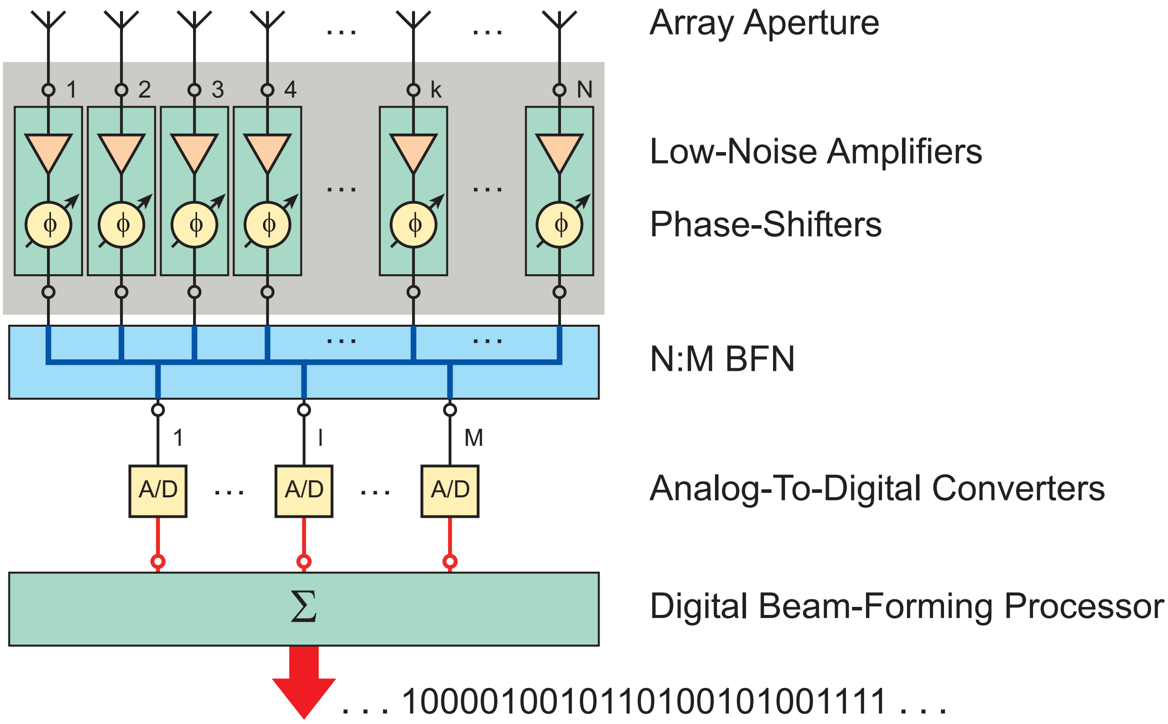


Figure 4.6-B A block schematic for a partial digital beam-forming concept.

Figure 4.6-C to Figure 4.6-J show five systems with digital beam-forming of different complexity and TRL levels. Three of them are receive-only breadboard systems.

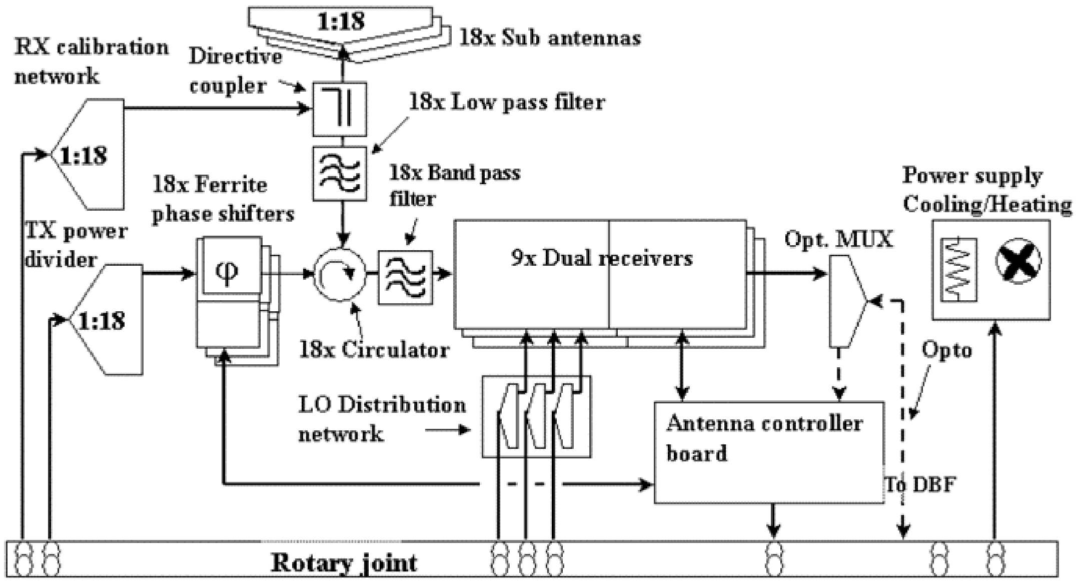


Figure 4.6-C Block schematic for the Ericsson GIRAFFE AMB antenna [16].

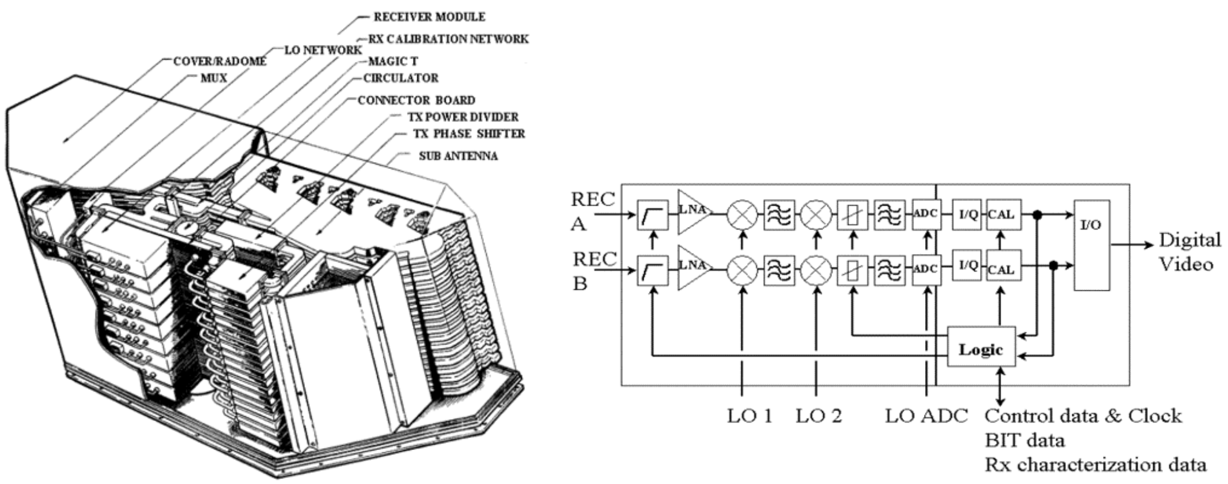


Figure 4.6-D The Ericsson GIRAFFE AMB. The mechanical layout (left) and the dual-channel digital receiver (right) [16].

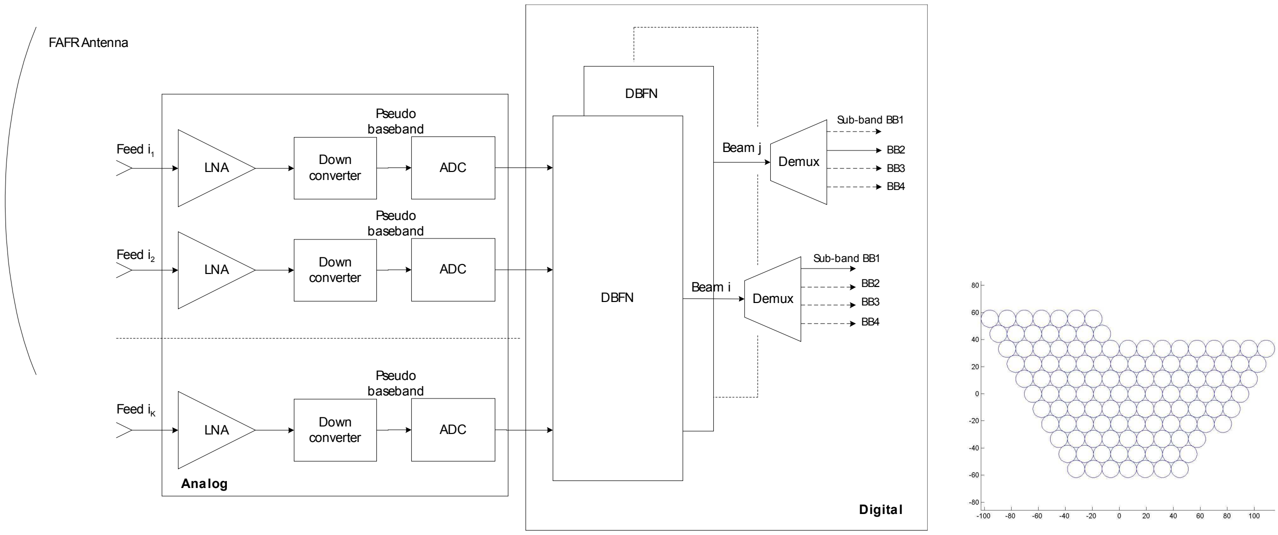


Figure 4.6-E Alcatel Space FAFR digital beam-forming focal plane array [21].

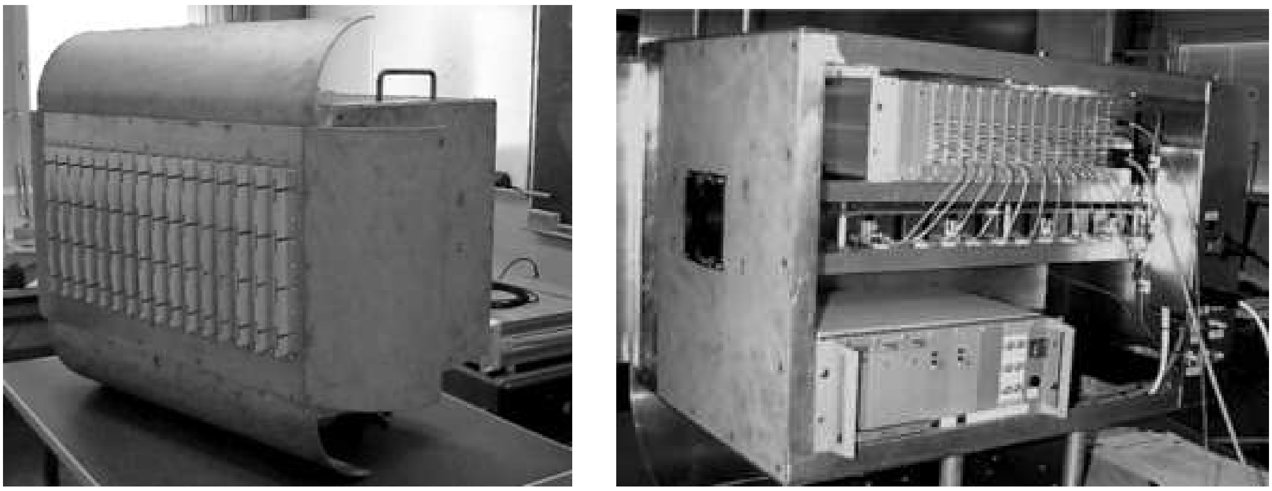


Figure 4.6-F FOI DIGANT radar testbed [27].

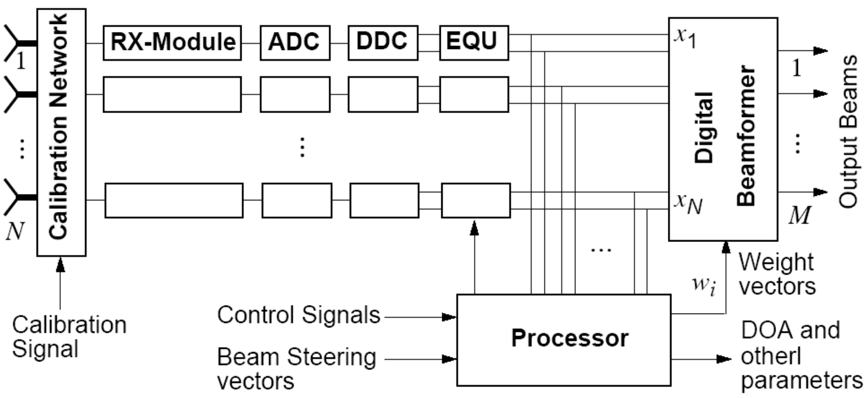


Figure 4.6-G FOI DIGANT block schematic [27].

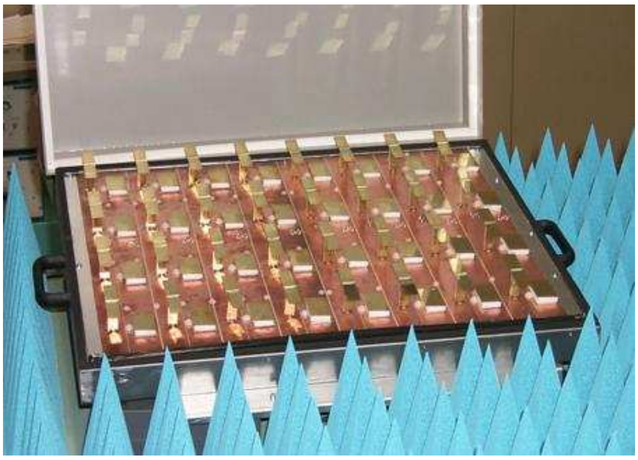


Figure 4.6-H PoliTo UMTS channel sounder (smart antenna prototype) [40].

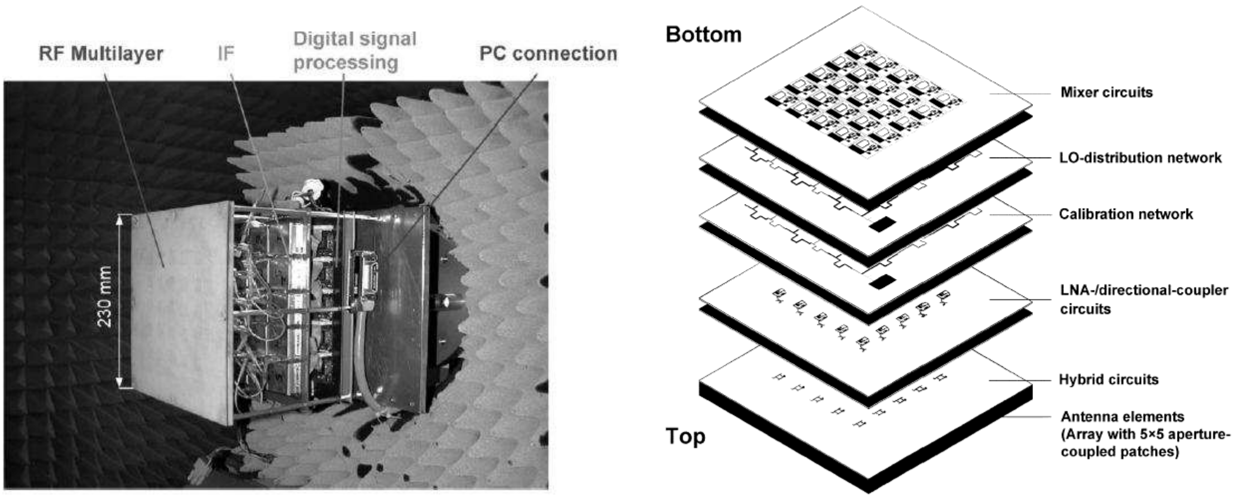


Figure 4.6-I DLR active DBF breadboard for satellite navigation and communication [33].

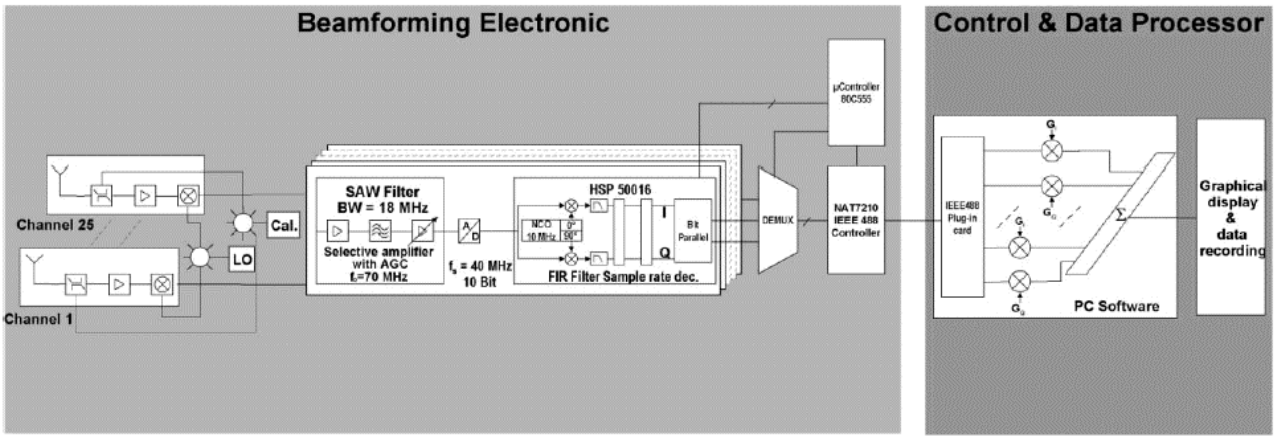


Figure 4.6-J DLR active DBF breadboard block schematic [33].

4.7 One-Way (Transmit or Receive) Active Phased Arrays

An array can be utilised for transmit- or receive-only operation (*e.g.* for telecommunications to/from satellites), or might be a hybrid type where only one of these functions is implemented with active circuits (*e.g.* in some radar antenna systems). In these cases, such antenna systems can be termed semi-active or one-way active, and block schematics of such systems are given in Figure 4.7-A and Figure 4.7-B. Two such satellite antenna systems for transmit-only missions are shown in Figure 4.7-C through Figure 4.7-F.

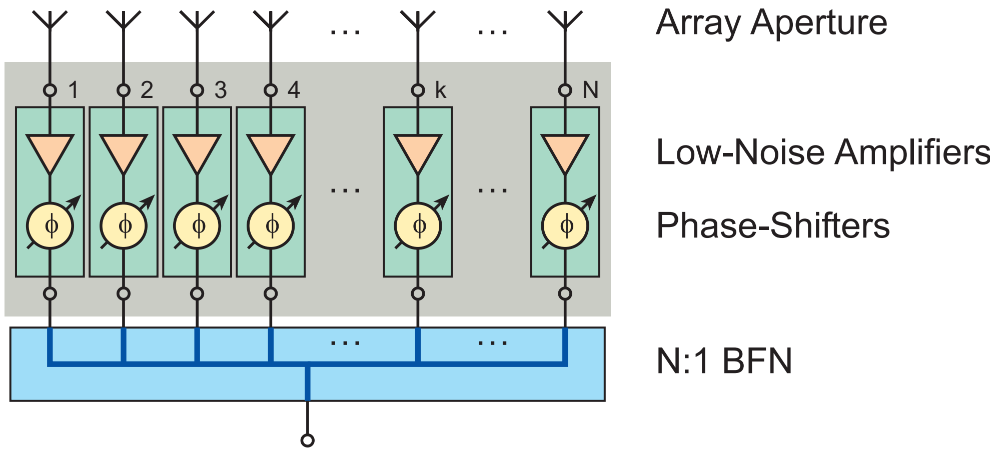


Figure 4.7-A A block schematic for a phased array which is active in receive.

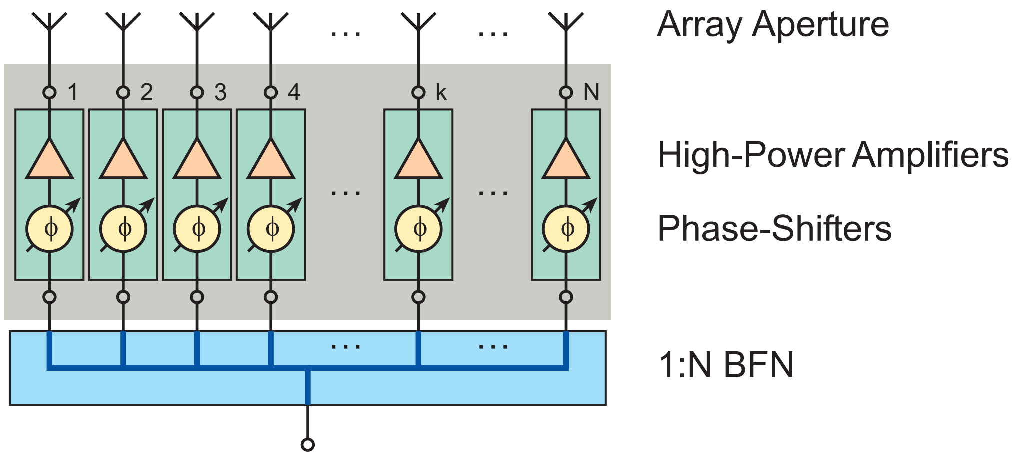


Figure 4.7-B A block schematic for a phased array which is active in transmit.

Figure 4.7-C Alcatel Space conical conformal array [19].

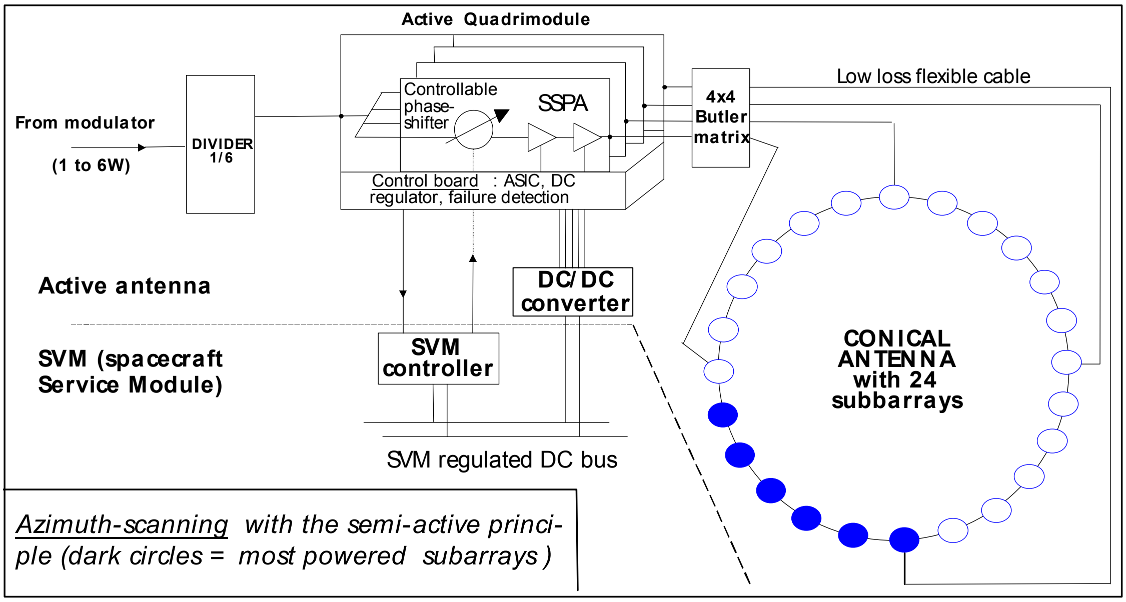


Figure 4.7-D Alcatel Space conical conformal array block schematic [19].

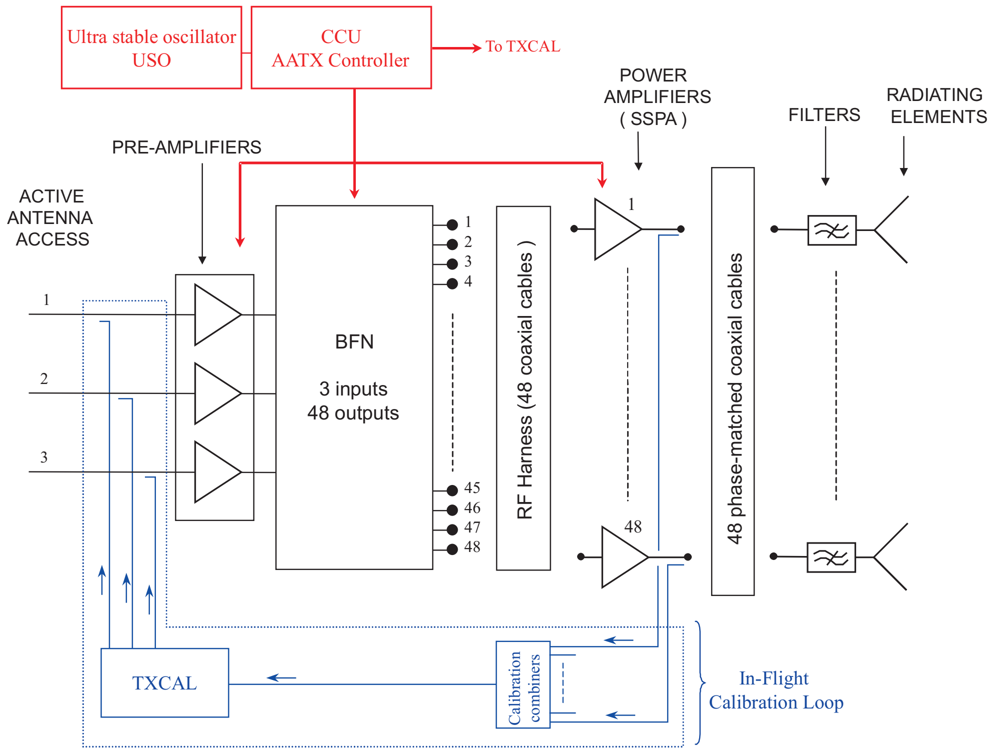


Figure 4.7-E Alcatel STENTOR DRA block schematic [20].

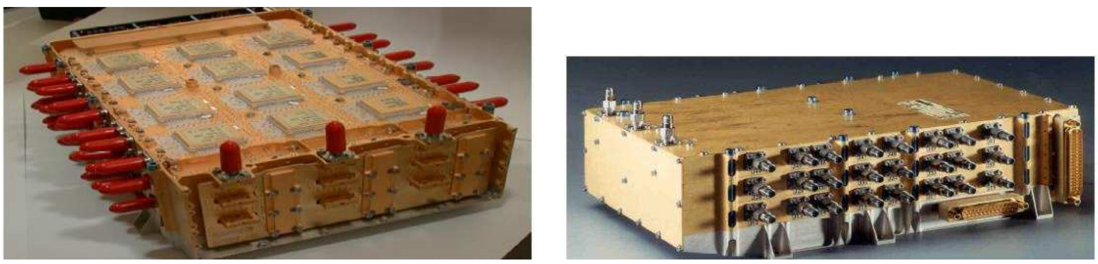


Figure 4.7-F Alcatel STENTOR DRA [20].

4.8 Two-Way Fully Active (Transmit and Receive) Phased Arrays

For a two-way antenna, the highest level of beam steering is achieved with a system that is fully active in both transmit and receive. In both radar and communication systems there would have to be some kind of duplexing scheme, since the transmit and receive functions share the same antenna array elements. This duplexing is typically achieved through the use of:

- Switches or circulators (time-division duplex, as in pulsed radar systems).
- Filtering (frequency division duplex, as in communication systems, where the TX and RX frequency bands are separated by a significant percentage).

A block schematic of a two-way fully active phased array system is shown in Figure 4.8-A. In a real-life system, the block schematic is of course much more complex than this, but in terms of function this simplified form is suitable. A more complete block schematic is introduced later in Section 6.1.
A few examples of systems of this kind are shown in Figure 4.8-B to Figure 4.8-D.

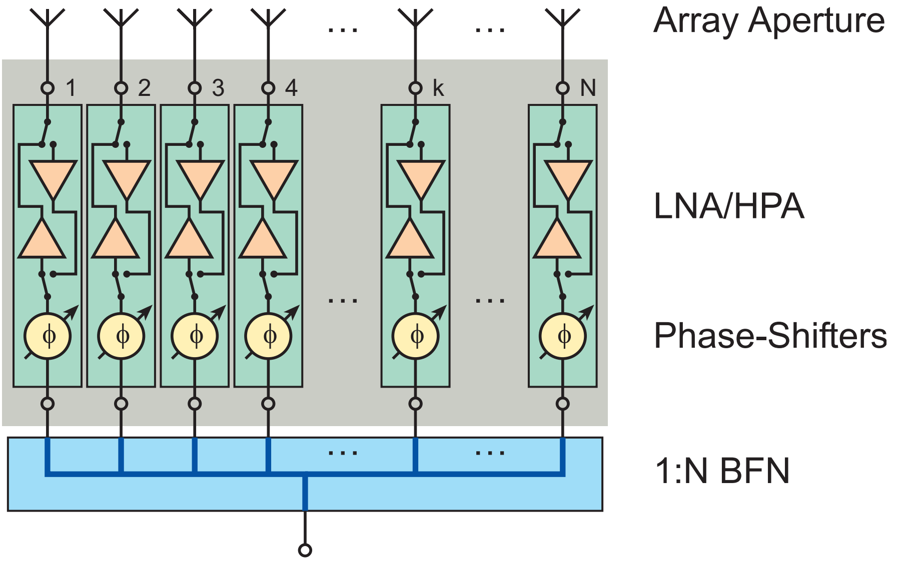


Figure 4.8-A Block schematic of a phased array that is active in both transmit and receive.

Figure 4.8-B TNO/TNN APAR naval defence radar [53].

Figure 4.8-C Ericsson ERIEYE airborne early warning radar dorsal unit [14].

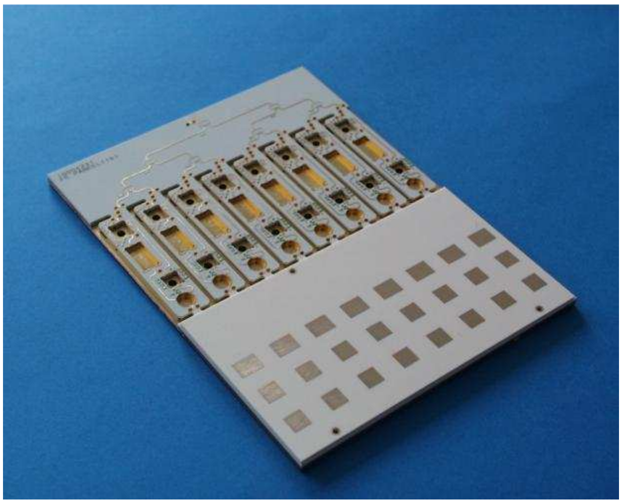


Figure 4.8-D TNO MiniSAR active X-band small array [55].

4.9 True Time Delay (TTD)

For real (instantaneous) wideband operation we need true time-delay (TTD) instead of phase-shifters. These systems have additional requirements on *e.g.* group delay, and non-dispersive beam-forming networks are needed to get true time-delay performance over a large instantaneous bandwidth. Figure 4.9-A shows a block schematic for a time-delay beam steering system. Figure 4.9-B shows a wideband testbed for time-delay beam steering.

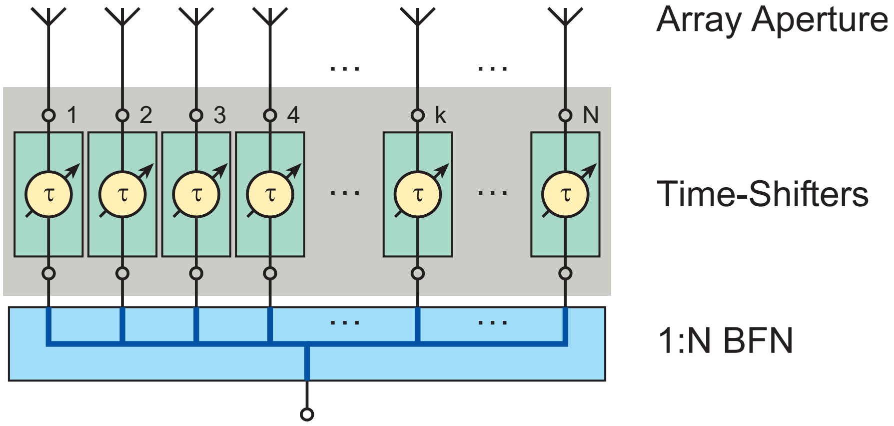
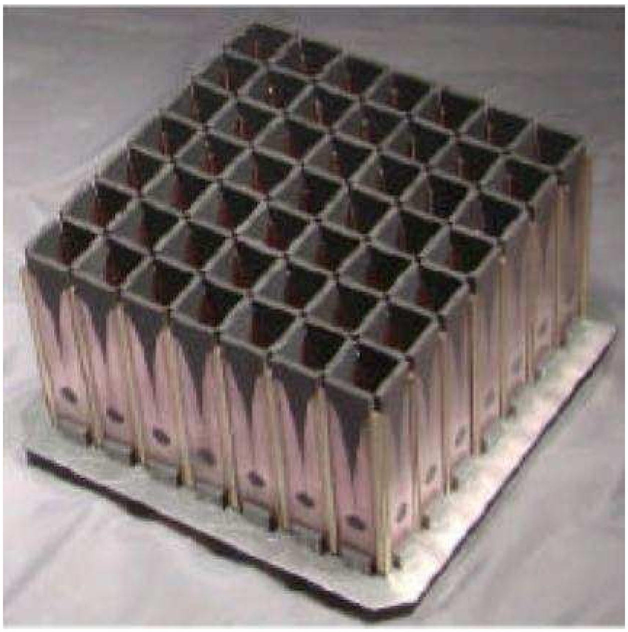


Figure 4.9-A A sketch for time-delay beam steering.



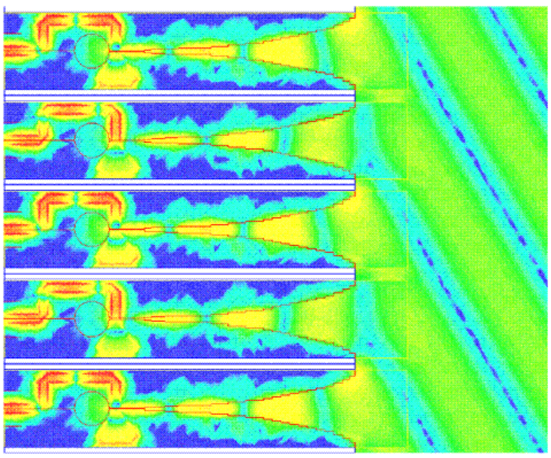


Figure 4.9-B FOI TSA ultra-wideband array testbed (left) and time-domain field calculation results (right) [30].

4.10 Photonic Arrays

Photonic arrays would use optical methods to do the beam-forming. One example is shown in Figure 4.10-A below.

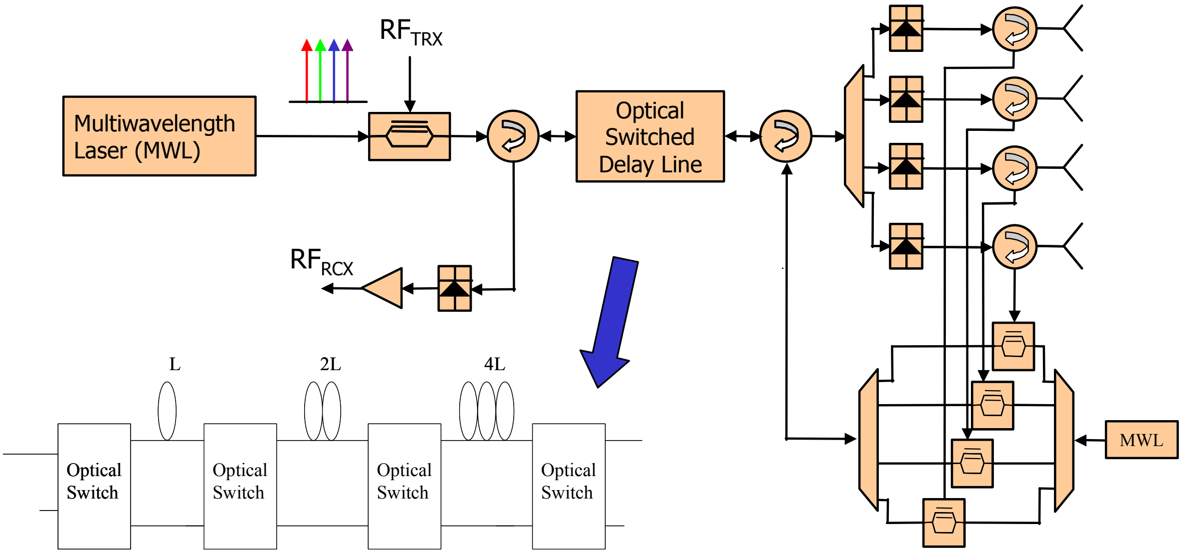


Figure 4.10-A UPV basestation for fixed and mobile broadband wireless access (BWA) using optical beam-forming [51].

5 OTHER PARAMETERS

Except for the array architectures *per se*, the questionnaires also asked questions about the radiating elements, calibration methods, *etc.* that were used in the reported systems.

5.1 Radiating Elements

There are certain favourites for the array radiating elements which is clearly shown in the following table:

Radiating Element	No. of Cases
Patches (single and stacked)	19
Open-ended waveguide apertures	7
Dipoles	4
Slotted waveguides	3

Table 5.1-A The array radiating elements ranked by popularity.

The number of array radiating elements ranged from single up to > 10000.

5.2 Calibration

One important aspect of active antennas is calibration and characterisation, *i.e.* the procedure of finding out the real phase and amplitude characteristics of the array antenna and its modules. The terminology is somewhat fuzzy, but active calibration stands for measurements while the system is operating, whereas characterisation is measurements made during manufacture and system integration. If the system is stable over time, characterisation data can be used for correcting the deficiencies and variations of the arrays. The two main types of calibration and characterisation are conducted or radiated mode, where the way the reference signal is distributed to the antenna is the basis for the notation. One term that is common is path-per-path (PPP), which means that all signal paths in the array are measured separately.

The calibration or characterization strategies in use according to the questionnaire were:

- Active conducted mode calibration.
- Radiated mode characterisation.
- Path-per-path at 0 degrees.
- Path-per-path characterisation.
- Conducted mode path-per-path characterisation, and radiated mode calibration in flight.
- Conducted and radiated mode path-per-path characterisation.
- Conducted and radiated mode time-domain characterisation.

5.3 Measurements

The measurements performed on the arrays spanned a wide range. The typical measurements that were made are listed in the following, with the most common measurement parameters listed first.

- Return loss
- S parameters and mutual coupling
- Radiation patterns
  - Array patterns
  - Isolated element patterns
  - Active element (embedded) patterns
  - Gain
  - Cross-polarisation discrimination (XPD)
- Active antenna parameters
  - Effective isotropically radiated power (EIRP)
  - Gain to noise temperature ratio (G/T)
  - Intermodulation (IM)
  - Signal to noise ratio (SNR)
  - Effective isotropic conversion loss (EICL)
- Miscellaneous
  - Direction of arrival (DOA)
  - Group delay

5.4 Modelling & Simulation

An increasing part of the research and development of array antennas involve computer modelling and simulation, both for the electromagnetics part and the systems part. A lot of money is either spent on licenses for commercial software, or in-house development of software. In some cases more advanced functions in commercial software can be unavailable due to export restrictions (especially RCS functionality), which makes national and/or in-house efforts necessary.

5.4.1 Commercial Tools

The commercial tools that are used according to the questionnaire answers are given in the table below, ranked by the number of answers. The 'big elephants' HP/Agilent and Ansoft totally dominate the market, and can be said to constitute 'industry standard'. For systems calculations, Matlab is also totally dominating.

Software Name	No. of Answers
HP/Agilent Momentum	10
Ansoft Ensemble	9
HP/Ansoft HFSS	7
Matlab	6
Agilent ADS	5
Designer	4
HP/Agilent MDS	3
Pagoda, Libra, Omnisys, QW3D, NEC, EESof, IE3D, MWO, GRASP, …	>=1

Table 5.4-A The commercial software used according to the questionnaire answers.

5.4.2 In-House Tools

Almost all participants have developed specialised in-house software. Some major efforts outside the universities can be mentioned:

- Thales
  - "Antenna Design (AD™)" FEM
  - "ADR2™" FEM infinite array
- TNO
  - "Multimode Equivalent Network (MEN)" integral equation MoM
  - "PHASIM" phased array simulator
- FOI
  - FDTD with phase/time boundaries
  - Cylindrical FDTD

5.5 What Is Lacking – Bottlenecks

Some of the bottlenecks which were listed in the questionnaires are:

- Modelling finite (but large) arrays accurately
- Modelling antenna in surrounding
- Faster codes
- Recalibration in operating conditions
- Polarization control for wide-angle scan
- Combining EM and non-linear circuit simulators

6 SYNTHESIS

The previous sections have shown the wide variety of architectures for arrays that represent 'a European experience'. The reviews of the state-of-the-art (references [2]–[6]) essentially show the same trends elsewhere.

6.1 Typical Active Array Module Block Schematic

Using the compiled information, one could now devise a more or less 'typical' active array module block schematic. The different array architectures studied have a wide variety of complexity, but a good starting point would probably be the block schematic in Figure 6.1-A. Most other array types would be subsets of this generic type. On a higher level, a complete array is the cascading of an array aperture and a beam-forming network (or DBF processor) with a collective of modules as in the generic block schematic in Figure 6.1-B.

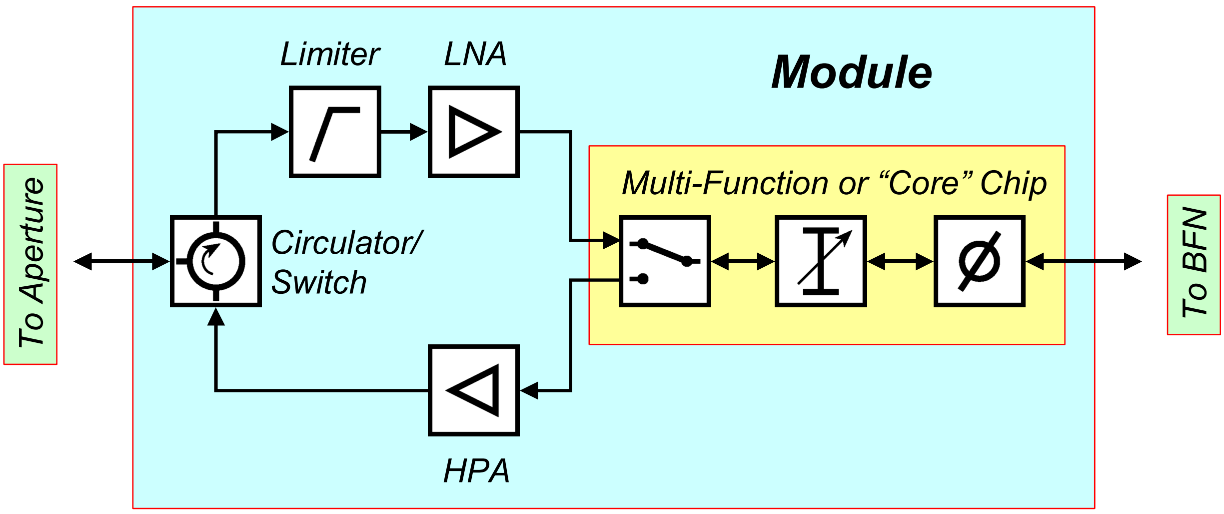


Figure 6.1-A A block schematic for a 'typical' active phased array module.

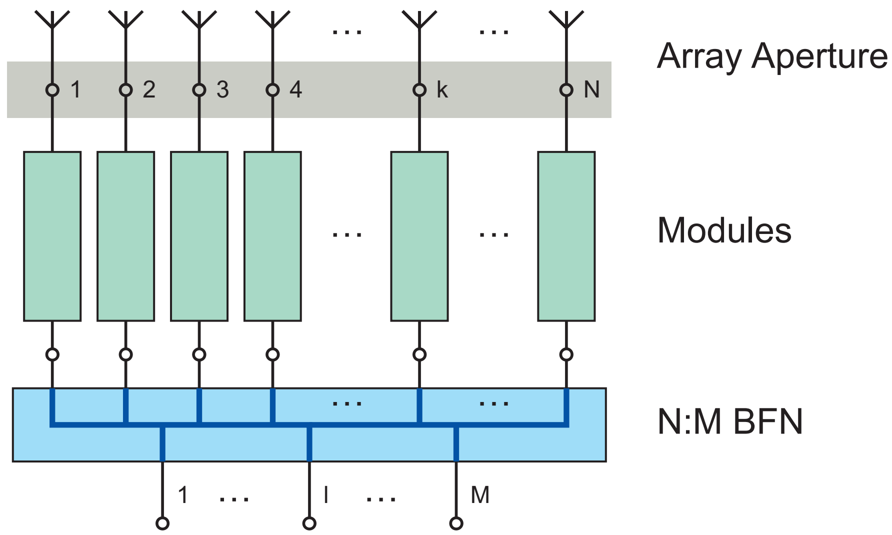


Figure 6.1-B A high-level block schematic of a generic active phased array.

6.2 Items for Modelling

In the following sub-sections, examples are given for various research topics that could be of interest for this work package (or a future extension of it). The topics listed are not definite, but should rather serve as 'food for thought'.

This report and the reviews should thus be used as a basis for further discussions.
The next step to be taken within our workgroup is to identify:

- Which are the important bottlenecks?
- What relevant optimization criteria should be used?
- Which topics are feasible to model and solve within our framework?
- What should we prioritize?
- Who does what?

6.2.1 Aperture

Aperture models are fairly mature for infinite arrays, where generalized MoM/FDTD or specialized fast MoM solvers can be used. However, finite (but large) arrays are still tricky to analyse. There exist some openings for these difficult arrays, *e.g.* using specialized geometries or truncation methods. The development of these models is beyond the scope for this work package, but certain issues that pertain to the interfacing of these models to the rest of the array could be listed:

- Non-50-ohm interfaces
- Multi-mode modelling
  - ➢ Non-TEM interfaces
  - ➢ Phased array scan impedance
  - ➢ Differential feeds (mixed-mode parameters)
- Angular scan range *vs.* bandwidth trade-offs

6.2.2 Active Parts to Aperture Interaction

Some issues that pertain to the actual performance of the active parts when they interact with the array aperture can be addressed:

- Scan impedance *vs.* optimum active gain or noise performance
- Non-linear modelling
  - ➢ Stability outside band of interest (isolators will not help in general)
  - ➢ Spatial power combining

6.2.3 Active Phased Parts

The active parts themselves have several parameters that could be modelled:

- Attenuator/phase state properties (*e.g.* in terms of tolerances and bias)
- Channel equalization
- Bandwidth
- Group delay

6.2.4 Beam-Forming Networks

Analogue beam-forming networks pose their own catalogue of potentially unresolved issues:

- Modelling of large multi-port structures (*e.g.* tolerances)
- Terminated *vs.* unterminated hybrids in the networks
- Dispersion properties (for wideband systems)

6.2.5 Digital Beam-Forming

Digital beam-forming poses some problems which are borderline between an analogue world and a purely digital information world. Some examples of issues that are relevant to the antenna properties could be given:

- ADC quantization and linearity effects
- Spurii and intermodulation

7 References

[1] ACE Annex I, "Description of Work".

[2] ACE 2.4 Review, "Review of Array Architectures Used in Base Stations", UPM, Spain.

[3] ACE 2.4 Review, "Review on Antenna Technologies for Commercial and Civil Radar Applications", Jens Freese and Rolf Jakoby, TUD, and Josef Wenger, DaimlerChrysler AG, Germany.

[4] ACE 2.4 Review, "Review of State-of-the-Art in Spaceborne Arrays", Gerard Caille, Alcatel Space, France.

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[7] ACE 2.4 Questionnaire Answer #1, "G1DMULT software", Zvonimir Šipuš, Chalmers, SWE.

[8] ACE 2.4 Questionnaire Answer #2, "G2DMULT software", Jian Yang, Chalmers, SWEDEN.

[9] ACE 2.4 Questionnaire Answer #3, "Hybrid UTD-MoM software for Conformal Arrays", Björn Thors, KTH, Sweden.

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[13] ACE 2.4 Questionnaire Answer #7, "Doubly curved conformal array testbed", Maria Lanne, Ericsson Microwave Systems, Sweden.

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[20] ACE 2.4 Questionnaire Answer #14, "STENTOR DRA satellite array", Gerard Caille, Alcatel Space, France.

[21] ACE 2.4 Questionnaire Answer #15, "FAFR with DBF focal plane array", Roland Baudin, Alcatel Space, France.

[22] ACE 2.4 Questionnaire Answer #16, "Cup satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

[23] ACE 2.4 Questionnaire Answer #17, "Remote sensing satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

[24] ACE 2.4 Questionnaire Answer #18, "GPS occultation satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

[25] ACE 2.4 Questionnaire Answer #19, "Dual-pol SAR satellite array", Hans Ekström, Saab Ericsson Space, Sweden.

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[29] ACE 2.4 Questionnaire Answer #23, "AMALIA Radar testbed", Aziz Ouacha, FOI, Sweden.

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[56] ACE 2.4 Questionnaire Answer #50, "Active integrated", Peter Hall, Univ of Birmingham, United Kingdom.

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8 LIST OF ACRONYMS

The following list of acronyms is by no means complete, but tries to list most of the common (or uncommon) acronyms that are used in this document. Trademarks and project/product acronyms are not included.

ADC .... Analog-to-digital converter
ASIC .... Application specific integrated circuit
BEL............. Belgium (ISO code)
BER .... Bit error rate
BFN .... Beam-forming network
Chalmers .... Chalmers Tekniska Högskola AB
CM.............. Conducted mode
DBF .... Digital beam-forming
DBFN.......... Digital beam-forming network
DEU............ Germany (ISO code)
DLR .... Deutsches Zentrum für Luft- und Raumfahrt E.V.
DOA............ Direction of arrival
DOA............ Direction of arrival
EICL .... Effective isotropical conversion loss
EIRP .... Effective isotropically radiated power
EM .... Electromagnetic(s)
EMW........... Ericsson Microwave Systems AB
EP............... Element pattern
ESP .... Spain (ISO code)
FAFR .... Focal array fed reflector
FDTD.......... Finite difference time-domain
FEM............ Finite element method
FOI .... Swedish Defence Research Agency
FRA .... France (ISO code)
GBR............ United Kingdom (ISO code)
G/T .... Gain to temperature ratio
HPA .... High power amplifier
IEEE .... Institute of Electrical and Electronics Engineers
I/H............... In-house
IM .... Intermodulation
ITA.............. Italy (ISO code)
KTH .... Kungliga Tekniska Högskolan
KUL .... Katholieke Universiteit Leuven
LNA .... Low-noise amplifier
MEMS......... Micro-electromechanical systems
MIMO.......... Multiple input – multiple output
MoM............ Method of moments
N/A.............. Not applicable (*or* not available)
NASA .... National Aeronautics and Space Administration
NLD .... Netherlands (ISO code)
NoE............. Network of Excellence
PoliTo .... Politecnico di Torino
PPP .... Path-per-path
RCS .... Radar cross-section
RF .... Radio frequency
RL .... Return loss
RM .... Radiated mode
RP............... Radiation pattern
RX............... Receiver
SES .... Saab Ericsson Space AB
SNR .... Signal to noise ratio
SSPA .... Solid-state power amplifier
SWE .... Sweden (ISO code)
TAS............. Thales Airborne Systems
TBC .... To be confirmed/checked
TD............... Time-domain
TEM .... Transverse electromagnetic
TNN .... Thales Naval Netherlands
TNO .... Netherlands Organisation for Applied Scientific Research
TRL............. Technology readiness level
TSA............. Tapered slot antenna
TTD............. True time-delay
TUD .... Technische Universität Darmstadt
TX .... Transmitter
UBham........ University of Birmingham
UniKa .... Universität Karlsruhe
UPM............ Universidad Politecnica de Madrid
UPV .... Universidad Politecnica de Valencia
USi.............. Universita degli studi di Siena
WP.............. Work package
XPD .... Cross-polarisation discrimination

9 APPENDICES

9.1 Appendix A

"2.4 activity questionnaire – Best ACE Partners Experience Array Description"

9.2 Appendix B

"ACE 2.4 Questionnaire Synthesis"
Excel sheet with the condensed data from the questionnaires
Updated 2004-11-23

2.4 activity questionnaire – Best ACE partners experience
Array description

Please answer, within the table-lines below, the questions in a single group for each topic, numbered 0 to 7. For a clearer presentation, please use one table-line blank between the questions and your corresponding answer group.

0/ Partner

- *Contact name + e-mail (possibly specific for any complementary question concerning the described array)*

1/ General

- *What application (radar, base-station, Space antenna, satellite terminal, testbed…); TX and/or RX; Frequency band?*
- *What kind of array (planar/conformal, passive, phased, fully active…); Which type of radiating elements (R.E.)?*
- *If the array is conformal, what geometry, why was it chosen ?*

2/ Architecture & Beam Forming

- *Block-diagram, geometry; No. of independent paths (sub-arrays); No. of R.E.*
- *Beam-forming (B.F.) principles (how are commands computed? adaptive algorithms?)*

3/ Main hardware characteristics

- *Product tree (list of independent blocks); Integration level; Main technologies used (including active elements)*
- *Development level (1 to 9: see TRL standard in Appendix)*

4/ Modelling

- *Simulation/optimization tools used at basic block level and whole antenna: commercial ?if internal, what advantages, and how it was validated? what analysis method for R.E.? specific sofware if conformal antenna?*
- *What is lacking?*

5/ Calibration & Test

- *Path-per-path calibration? Conducted or radiated mode? Dispersion compensation? At one or several frequencies, temperatures, angles…?*
- *What is finally measured? Patterns, absolute gain, G/T or SNR, EIRP, intermodulation…? Please give typical results in Annex.*

6/ Synthesis of your experience

- *Advantages and drawbacks (for the chosen architecture, B.F. technique, and simulation tools)?*
- *Critical or open points? Possible ideas: "how to solve them ?"*

7/ Publications

- *Report here only the title and reference (review, conference)*

- Put the best synthetic publications concerning this array (in PDF form) + your filled questionnaire answer in Word 97 format in the same ZIP archive

---

Please send 1 filled questionnaire per main array-type you developed, before end-March, simultaneously to the Activity leader + the 3 WP-managers:

gerard.caille@space.alcatel.fr
joakim.johansson@ericsson.com
roland.baudin@space.alcatel.fr
zvonimir@elmagn.chalmers.se

3 syntheses will be performed, focused on the subjects of each WP, and sent back to all who answered.

Appendix: Technology Readiness Level (TRL), product status

TRL	Description
9	Actual system proven in an operational environment
8	Actual system completed and qualified
7	System prototype demonstration in an operational environment
6	System/subsystem model or prototype demonstration in a relevant environment
5	Component and/or breadboard validation in a relevant environment
4	Component and/or breadboard validation in a laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

N°	Entity	Array Name	Array function	Reporting person	Country	TRL	Fq Band	Type (cf definitions §3,3)	Rad El	No of el	Calibration	Analysis tools	Measurements
1	Chalmers	G1DMULT	Software	Zvonimir Sipus	SWE	1	N/A	Conformal Software	Rectangular patches & waveguide apertures	N/A	N/A	G1DMULT	RP, S-para, Z
2	Chalmers	G2DMULT	Software	Jian Yang	SWE	1	N/A	Conformal Software	dipoles, patches apertures	N/A	N/A	G2DMULT	RP
3	KTH	Hybrid UTD-MoM for Conformal Arrays	Software	Björn Thors	SWE	1	N/A	Conformal Software	Rectangular waveguide apertures	N/A	N/A	UTD/MoM Hybrid	RP, S-para, RCS
4	KTH	Hybrid UTD-MoM for Conformal Arrays	Software	Patrik Persson	SWE	1	N/A	Conformal Software	Rectangular & circular waveguide apertures	N/A	N/A	UTD/MoM Hybrid	RP, S-para
5	KTH	Hybrid UTD-MoM for Conformal Arrays	Software	Patrik Persson	SWE	1	N/A	Conformal Software	Rectangular & circular waveguide apertures	N/A	N/A	UTD/MoM Hybrid	RP, S-para
6	Ericsson Microwave Systems		Cylindrical conformal array testbed	Maria Lanne	SWE	4	C	Cylindrical aperture testbed	Rectangular waveguide apertures	3 rows (18 el each)	No	I/H	RL, S-para, EP, G
7	Ericsson Microwave Systems		Doubly curved conformal array testbed	Maria Lanne	SWE	3	X	Paraboloid aperture testbed	Circular waveguide apertures	48 (one cross and one quarter arc)	No	I/H	RL, S-para, EP, G
8	Ericsson Microwave Systems	ERIEYE	Airborne early warning radar	Joakim Johansson	SWE	9	S	Active phased (azimuth-scan)	Slotted waveguides	192 columns	Active, CM, all 192 cols	HP HFSS, Momentum, MDS, I/H, Matlab	NF->EIRP & G/T
9	Ericsson Microwave Systems	ARTHUR	Artillery location radar	Joakim Johansson	SWE	9	C	Phased	Slotted waveguides	48 columns (64 el each)	RM char	Pagoda, I/H, Matlab	FF->RP,G, pointing
10	Ericsson Microwave Systems	GIRAFFE AMB	Air surveillance radar	Joakim Johansson	SWE	9	C	TX phased / RX DBF	Rectangular waveguide apertures	18 rows (48 el each)	Active, CM, all 18 rows, BIT	I/H MoM, HP HFSS, Matlab	
11	Thales Airborne Systems	ERASP	Space radar	Christian Renard	FRA	2 to 5	X	Phased reflectarray	Open waveguide	>20000	PPP @ 0 deg	I/H "AD" FEM, I/H "ADR2" FEM/Floquet, I/H	RP
12	Thales Airborne Systems	ALABAMA	Multifunction antenna	Joël Herault	FRA	4	C, X, Ku	Subarray for active array	Planar	100	No	I/H "AD" FEM, I/H "ADR2" FEM/Floquet	RP, RL
13	Alcatel Space	Conical Conformal Array	Satellite array	Gerard Caille	FRA	6	X	Scanning "semi-active"	Circular-pol dual patches	24 x 6	PPP char, BIT in flight	HFSS, ADS	RP
14	Alcatel Space	STENTOR Tx-DRA	Satellite array	Gerard Caille	FRA	8	Ku	Tx-only, Active phased	Cavity-backed dual patches	48 x 32	Active, CM	HFSS, ADS, Libra, Omnisys	NF->EIRP, IP
15	Alcatel Space	FAFR with DBF	Focal plane array	Roland Baudin	FRA	3	Ka	Rx-only, DBF active	Horns	119	CM PPP char, RM in flight	GRASP, I/H Simulated Annealing, Matlab/Simulink	RP, D, Lin, G/T, BER
16	Saab Ericsson Space	Patch Excited Cup (PEC)	Satellite array	Hans Ekström	SWE	9	L, S	R.E. for fixed multibeam active arrays	Patch excited cup element	5 - 200	N/A	HFSS, ROT2, Momentum/MMS	RP, PIM
17	Saab Ericsson Space	Remote sensing	Satellite array	Hans Ekström	SWE	9	C	Fixed, passive, dual-freq	Slotted waveguides	400 -5000	N/A	I/H	RP, XPD, RL
18	Saab Ericsson Space	GPS occultation	Satellite array	Hans Ekström	SWE	8	L1 + L2	Fixed beam, passive	Ring elements	18	N/A	Momentum	RP, G, XPD, RL, GpDel
19	Saab Ericsson Space	Dual-pol SAR	Satellite array	Hans Ekström	SWE	4	L, C, X	Subarray	Microstrip	N/A	N/A	I/H	RP, XPD, RL
20	Saab Ericsson Space	MultiKaRa	Satellite focal array	Hans Ekström	SWE	4	Ka	Active fixed multibeam	Horns	29 (7 active)	RM char?	QW3D, MDS, Momentum, HFSS	RP, G, Nfig
21	FOI	DIGANT	Radar testbed	Lars Pettersson	SWE	4 to 6	S	DBF active	Stripline dipoles	12 columns (4 el each)	RM & CM PPP	I/H MoM, NEC, Eesof	RP, EP, DOA, IP, etc
22	FOI	ELSA	Communication testbed	Lars Pettersson	SWE	4	UHF	Passive, circular	Mono-cones	16	No	I/H FDTD (cylindrical)	EP, S-para
23	FOI	AMALIA	Radar testbed	Aziz Ouacha	SWE	4	X	DBF active	Stacked patches	4 x 4	RM PPP	Ensemble, HFSS, Momentum, ADS, Libra	RP, EP, DOA
24	FOI	TSA array	EW testbed	Aziz Ouacha	SWE	4	2-6 & 6-18	Active, fixed beam TBC	Tapered slot antennas	7 x 8 (x 2 pol)	No	HFSS, I/H FDTD (Ph/Time shift boundaries), Eesof	S-para, EP, G
25	DLR	NRN	Near range radar (NRN) antenna	Michael Thiel	DEU	7	X	Passive, fixed beam	Aperture coupled elements	8 x 16	No	Ensemble, Linmic, Linplan, I/H coupling in large arrays	RP, G, Z
26	DLR	E-SAR		Michael Thiel	DEU	9	P, L, S, C, X	Passive, fixed beam	Aperture coupled, dual pol. el.	4 x 8	No	MDS, I/H coupling in large arrays	RP, G, Z
27	DLR	SATNAV	Satellite navigation	Michael Thiel	DEU	4	C	Active DBF	Aperture coupled, circular pol. el.	5 x 5	PPP	Ensemble, IE3D	RP, Z
28	Uni Karlsruhe	TerraSAR-X	Ground based satellite calibrator	Sergey Sevskiy	DEU	4	X	Fixed beam, active transponde	Corporate-fed microstrip patches	6 x 6	No	Ansoft Designer	RL, G, RP
29	Uni Karlsruhe	ARDS	Airborne communication antenna	Sergey Sevskiy	DEU	4	Ku	Passive, mechanically steered	Printed microstrip patch antennas	2 x 8	No	Ansoft Designer	RL, G, RP
30	Uni Karlsruhe	SIREV	Digital beamforming	Sergey Sevskiy	DEU	4	X	Active, digital beamforming	Printed patch subarrays	4 x 56	Using scatterers	ADS, MPATCH	RP
30a	Uni Karlsruhe	Inmarsat-Ant	Conformal patch array	Sergey Sevskiy	DEU	4	L	Phased array	Printed patch	4 x 64	N/A	MPATCH, Ansoft Ensemble	RL, RP
31	TU Darmstadt	X-band Rx-DBF	Small array testbed	Jens Freese	DEU	1 to 4	X	DBF active tesbed	E.g. Semi-circular patches	< 16	RM	CST-Microwave Studio, Ensemble, Matlab	EP
32	KU Leuven		Conformal array software	Gerald Moernaut	BEL	N/A	N/A	Conformal Software		N/A	N/A	Magmas	N/A
33	Politecnico di Torino	Reflectarray		Mario Orefice	ITA	4	Ku	Passive reflectarray	Microstrip	441 & 337	No	I/H "Simple tools", GA	RL, RP, G
34	Politecnico di Torino		Base station antenna prototype	Mario Orefice	ITA	5 to 6	UMTS	DBF active TBC	Dipoles + PIFA	8 columns (4 el each) x 2 pol	No	NEC, IE3D, I/H, Ensemble, Momentum	EP, RP, G, S-para
35	Univ Siena	GIFFT	Finite array software	Filippo Capolino	ITA	N/A	N/A	Software (planar large finite array)	Patches, slots, cavities in multilayered environment	N/A	N/A	I/H "Fast solver"	N/A
36	Univ Siena	Contoured array	Contoured array software	Enrica Martini	ITA	N/A	N/A	Software (planar large finite with any contour)	Dipoles	N/A	N/A	I/H	N/A
37	Univ Siena	T(FW)² - MoM	Open waveguide array software	Alessio Cucini	ITA	N/A	N/A	Software (planar large finite)	Rectangular waveguide apertures	N/A	N/A	I/H Mom	N/A
38	Univ Politécnica de Madrid	Reflectarray	DBS/ base station	José A. Encinar	ESP	4	Ku, Ka	Fixed contoured beam	Stacked patches	> 1000	No	I/H SD MoM	RP, G
39	Univ Politécnica de Madrid	Block elements for base station	Base station antenna prototype	José A. Encinar	ESP	4	GSM, UMTS	Switchable multi beam	Aperture coupled stacked patches	4 x 8	No	I/H pattern synthesis, RF Sim 99, ADS, Momentum	S-para, RP, RL, G
40	Univ Politécnica de Madrid	MoMiA	IFF antenna array	Manuel Sierra Pérez	ESP	5	Ka	Fixed beam S/D	Double orthogonal slots	(20 x 18) x 2	No	CST, I/H	RP, G, Eff
41	Univ Politécnica de Madrid	TaCoA	Tactical communication horn array	Belén Galocha	ESP	9	L	pasive	Horns	5 x 5	No	TICRA BEAM/FEED, I/H	RP
42	Univ Politécnica de Madrid	RaLiSA	Radial Line Slot Antenna	Manuel Sierra Pérez	ESP	9	Ku, K	Fixed beam	Radial line coupled slots	N/A	N/A	Ensemble, I/H coupling slot/WG	RP
43	Univ Politécnica de Madrid	LPRAA	Primary radar antenna array	Manuel Sierra Pérez	ESP	5	L	Active phased S/D	Printed dipole antennas	28	N/A	CST, Ensemble	near field
44	Univ Politécnica de Madrid	ADAM	Mobile phone basestation antenna	Manuel Sierra Pérez	ESP	9	UMTS	analog active, adaptive	Patches	4 x 8	N/A	Ensemble, MWO	S-para, RP
45	Univ Politécnica de Valencia		Basestation for broadband access	Juan L. Corral	ESP	4	Ka	Photonic active	Patches	4	CM & RM TD	Matlab, IE3D	RP, SNR
46	TNO	COWA	Multi-feeds reflector antenna (radar, satellite)	Roland Bolt	NLD	4	C, X	Software + Demo	Open waveguides + radome	100	N/A	I/H "MEN", I/H UTD, HFSS, Designer, Momentum	S-para, EP
47	TNO	APAR	Naval defence radar (4 planar arrays)	Lucas Van Ewijk	NLD	9	I	Active phased	Open waveguide	3424 (x 4 faces)	Confidential	I/H "MEN", I/H "PHASIM", HFSS, Designer, Momentum	S-para, EP
48	TNO	CYLAR	Software and demonstrators	Thomas Bertuch	NLD	3	X, C	Conformal Software + Demo	Open waveguide, patches	7 x 9	N/A	I/H "MEN", I/H GSM MM, I/H BEM, I/H MoM, HFSS	RL, S-para, EP
49	TNO	MiniSAR	Active X-band small array	Lucas Van Ewijk	NLD	4	X	Active phased	Stacked patches	3 x 8 (x 3)	No	Ensemble, HFSS, Momentum, ADS	S-para, G
50	Univ of Birmingham	Active integrated	Demo of self-locked active patches	Peter Hall	GBR	1 to 4	S	Power combining	Patches	1 x 4	No	I/H "Low level"	RP, EICL, RP @ harmonics
51	Univ of Birmingham	Corporate patch arrays		Peter Hall	GBR	1 to 4	X	Fixed beam	Patches	4 x 4	No	I/H MoM, etc	RP, G, RL
52	Univ of Birmingham	Multibeam patch arrays	Demo/Blass-like planar beam-former	Peter Hall	GBR	1 to 4	X	Fixed multiple beam	Patches		No	I/H	RP, G, RL
53	Univ of Birmingham	Seq rotated patch arrays	Demo/improves BW +XPD	Peter Hall	GBR	1 to 4	L	Fixed beam	Patches		No	I/H	RP, G, RL

European Commission - 6th Framework Programme	**ACE (Antenna Centre of Excellence)**	

REVIEW OF ARRAY ARCHITECTURES USED IN BASE-STATIONS

Institution	Authors
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Document Evolution		
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Rev. 2	03/04/2004	Second public issue
Rev. 2 T	08/12/2004	Integration within ACE_2.4_Doc-template, to be annexed to A2.4- D1

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Patch array technology has been applied for many years to base station antennas in mobile communications systems, due to their well known characteristics of low-profile, low cost, reliability and flexibility to achieve contoured beams. The pattern requirements for a base station antenna are normally a sector pattern in azimuth and a cosecant squared shape in elevation, which are easily obtained with a passive linear array appropriated excited by a corporated feeding network [1]. More recently, different array architectures have been proposed for Base Station antennas in order to improve the system performances by increasing channel capacity, extending range coverage, reducing multipath fading and cochannel interferences [2][3][4]. Research on antenna design has focused in developing new radiating elements and array architectures in order to fulfil the each time more stringent requirements of the system. Radiating elements must provide enough bandwidth, low levels of cross-polarisation and back radiation, high efficiency and power handling. The array architecture can be designed to provide beam shaping, space diversity, polarization diversity, multiple beams in azimuth in order to subdivide a sector and increase the channel capacity, or adaptive radiation patterns in order to eliminate cochannel interferences.

Some of more representative works on array antennas for Base Stations carried out outside of ACE are briefly described below.

1 IMPROVEMENT OF ELECTRICAL PERFORMANCES

A dual polarisation base station antenna with high polarisation isolation, better than 30 dB, was demonstrated in China [5]. The antenna is designed for dual linear polarisation in +/- 45º and exhibits a VSWR better than 1.4 in the 870MHz-960MHz band. The cross-polar isolation is improved by an appropriate design of the feeding network, which introduces a phase difference of 180º in cross-polar coupling from one element to the next.

Wide-band radiating elements have been proposed for base station antennas. A travelling wave subarray shown in Figure 1-A was demonstrated at Queens University of Belfast [6], which generate wide-band dual slant 45º polarisation. A good matching is obtained in the band from 1 to 3 GHz with a VSWR less than 1.5. The antenna exhibits well defined radiation patterns over the bandwidth of 1.7 to 2.2 GHz with, polarisation isolation better than 28 dB and 23 dB front-to-back ratio.

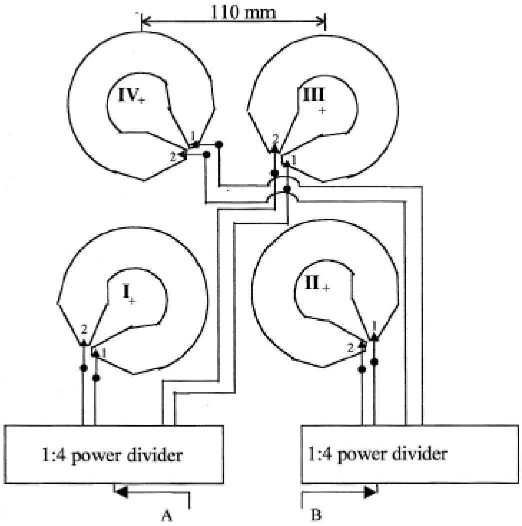

Figure 1-A : Dualslant 45º subarray.

Aperture-stacked patches (ASPs) are used as radiating elements in base station antennas due to their large bandwidth capabilities. However this radiating elements exhibits a front-to-back (F/B) ratio low as the aperture is relatively large to provide the required bandwidth. The F/B ratio can be substantially reduced by adding a microstrip patch element behind the aperture and feedline, which acts as a reflector [7]. The reflector patch is operated out of resonance and should radiate a filed 180º out of phase with the radiated field from the aperture, to produce cancellation. The same technique has been applied in University of Melbourne (Australia) for broad band antennas at Ka-band with applications in LMDS and picocellular base stations [8]. The antenna consists of an eight-element linear array of ASPs and eight corresponding back patches. The F/B ratio is better than 30 dB and the gain is increased in 2 dB by using the reflecting patches.

A VH-polarisation diversity antenna has been developed by NTT [9]. The radiating element is a circular disc microstrip antenna with two feeding ports for diversity reception which are orthogonal to each other. A stacked parasitic element is included to improve bandwidth. The advantage of this configuration is its reduced volume.

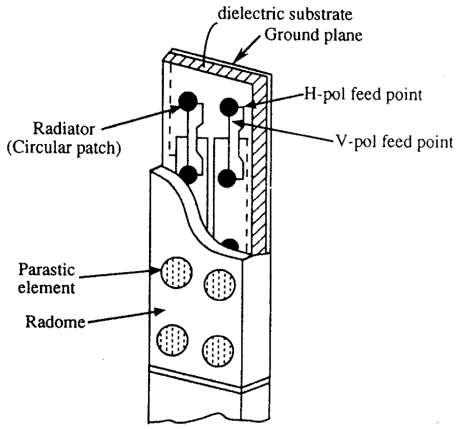

Figure 1-B : Configuration of polarisation diversity antenna.

Another configuration for VH-polarisation has been proposed for a base station of CDMA mobile communications in Japan [10]. The radiating elements for V and H polarisation are shown in Figure 1-C and they are combined in the array as shown in Figure 1-D. A continuous narrow ground plane is used with T-shape extensions under the aperture coupled patch to improve bandwidth up to 20%. This is also the ground plane for the array feeding circuits. A mounting plate (MP) is placed under the substrate to reduce the back radiation. A very low inter-polarisation coupling is achieved (less than –37 dB).

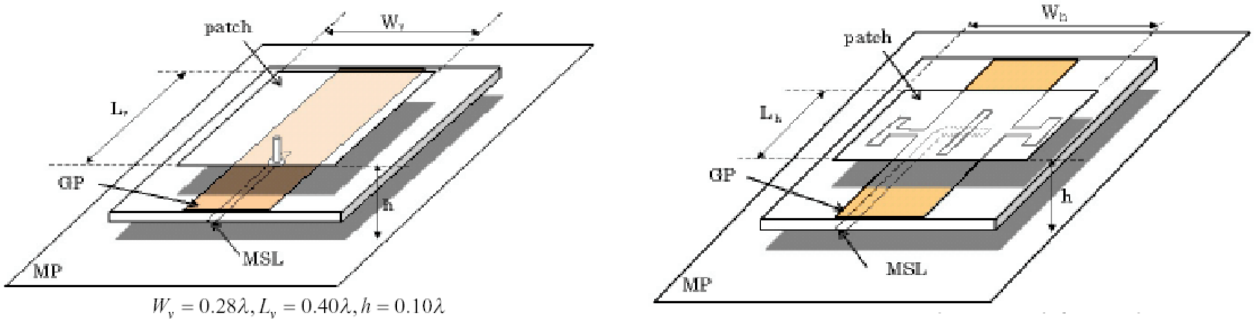

Figure 1-C : Radiating elements for V and H polarisation.

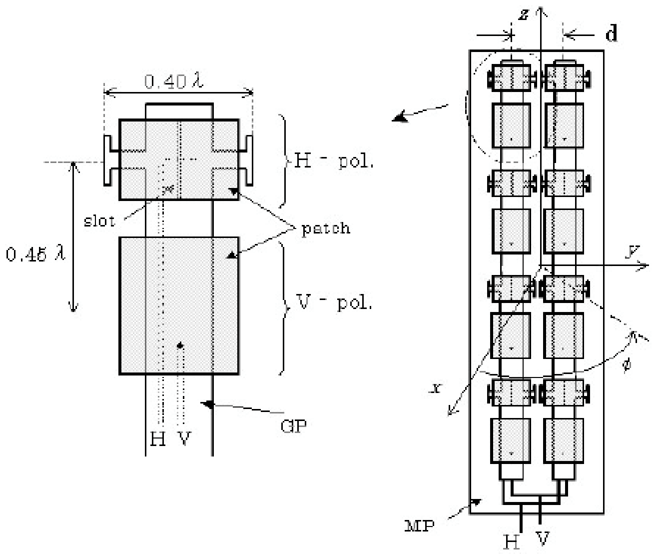

Figure 1-D : Array configuration.

A low-cost patch antenna array demonstrator has been designed, manufactured and tested for a base station to cover a rectangular street cell (100x400m) [11], operating in the two frequency sub-bands 1910-2000 MHz (up link) and 2110-2200 MHz (down link). The objective of this work was focused on providing an optimum balance among high performance, reliability, miniaturization and low-cost. Two stacked patch configuration was used to achieve the required band. The patches are directly fed by microstrip lines on the same substrate to reduce the number of substrate layers.

Dual band antennas have been investigated in order to have a single antenna for the different frequency bands in mobile telephone systems. An equally space array was proposed in Japan to achieve low sidelobe characteristics and electrical beam tilt in 800 MHz to 2000 MHz [12]. However, grating lobes appeared in the 1500 MHz and 2000 MHz band in the case of electrical tilt. The suppression of these grating lobes was achieved by unequally spaced arrays [13].

2 CONFORMAL ANTENNAS

In order to reduce the visual impact of base station antennas, conformal and flat panel configurations have been investigated. Patch antenna elements made of honeycomb composites are designed, developed and tested in the band of GSM 900 for possible use in dual-polarised flat panel base station antennas [14]. The benefits of using honeycomb sandwich technology as substrates and radomes in base station antennas are low-weight, high resistance to vibrations and stable dielectric properties in a large range of temperature variations. Also the elements of beamforming network, power dividers, directional couplers and phase shifters have been demonstrated in laminated materials compatible with honeycomb technology [15] (Poland). Figure 2-A shows the multi-layer configuration including radiating elements and feeding network.

Conformal antenna arrays, mostly cylindrical, have been studied [15][16][17]. A cylindrical antenna was proposed in [15] including polarisation diversity in the band 1850-2200 MHz. A 60º sector pattern in azimuth is achieved by a four-element cylindrical shaped panel, see Figure 2-B. The antenna was manufactured combining honeycomb composite materials and printed circuits.

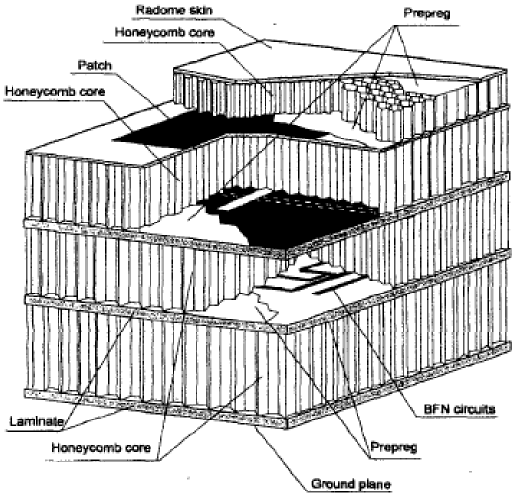

Figure 2-A : Printed antenna in honeycomb sandwich technology.

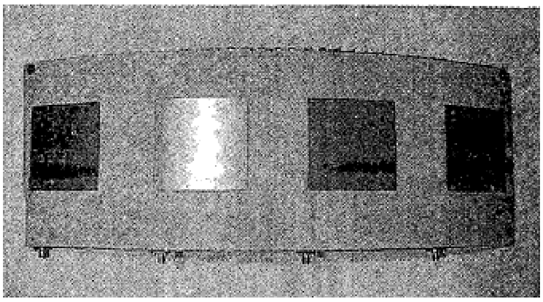

Figure 2-B : Four element cylindrical subarray

A slot array on a cylinder has been studied as base station antenna in Japan [16]. The antenna consists of wide bandwidth slots which are arrayed axially on a metallic cylinder. A bandwidth of 22% was achieved for VSWR less than 1.5. The radiation pattern is near omnidirectional in azimuth (beam width is about 155º) and it was synthesised in elevation to achieve a cosecant shape

A cylindrical array was proposed for communications base station antennas in [17] (Canada). The scanning antenna is achieved by arraying a number of travelling wave patch antennas in a cylindrical array configuration. Using a switching matrix, different subsets of the antenna elements in the array can be excited producing a narrow steerable beam. The topology of the antenna array is shown in Figure 2-C. The radiating elements are rectangular microstrip patches and the vertical arrays are a travelling wave antenna, which achieves the desired current distribution by varying width and spacing of patches spaced along the microstrip feed line. This cylindrical configuration keeps the high gain characteristics of directional antennas as well as the multi-directional characteristics of omnidirectional antennas, and allow to reduce transmit power, co-channel interference and increase system capacity. A cylindrical array configuration has been proposed for adaptive antennas in Japan [18]. This configuration makes it possible to create appropriate sector beams and user dedicated beams.

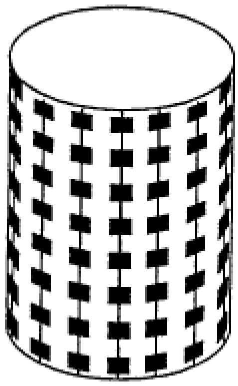

Figure 2-C : Cylindrical array of travelling wave patch antennas

3 MULTIPLE BEAM ANTENNAS

In general six sectors 60º wide are used in mobile communications. Instead of using two separated antennas, a double beam antenna with two beams in azimuth of 60º beam-width have been proposed by NTT in Japan [23][24]. The architecture to generate the two independent is sown in Fig. 8, and basically consists of using a 90º hybrid circuit to generate the two independent beams. The main advantage of this configuration is its simplicity and reduction in cost and mounting space.

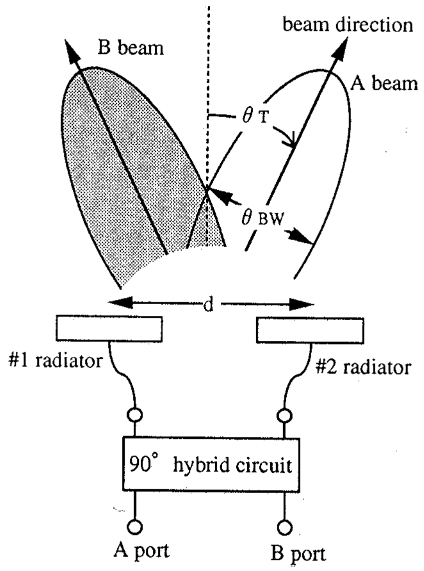

Figure 3-A : Configuration for two beams

To improve the performance capabilities of a base station antenna, i.e. to reduce co-channel interference and fading, to decrease radiated power and to increase capacity, the sector in cell can be covered with several narrow beams. The gain improvement of a low-complexity multibeam antenna system is investigated in [19][20] (USA). The multibeam antenna uses 12 or 24 beams (with beamwidth 30º and 15º, respectively), each with fix pointing directions. Selection combining is used to switch from beam to beam, avoiding the complexity of adaptive scanning. Switching approach allows the multibeam antenna and switch matrix to be easily integrated. The results showed that 5 dB gain enhancement can be achieved with 24-beam base station antenna in a cellular mobile radio environment.

A microstrip beamforming network based on 8x8 Butler Matrix was proposed by the University of Quebec at Rimouski [21] to form 8 beams in different directions, in order to provide an electronic scanning of the antenna pattern for Personal Communications System at 1.9 GHz. The antenna array and the beamforming network can be implemented in the same substrate for a better compactness.

A multi-beam prototype with eight narrow beams and a wide beam in a 120º sector was demonstrated for GSM in the 890-960 MHz band [22] (Russia). Each beam works in linear polarisation, being adjacent beams on orthogonal polarisation (+/- 45º). The antenna is made of five identical arrays, four of then to generate the eight narrow beams by using two 4x4 Butler matrices, one for each polarisation, and the fifth for the wide beam. The prototype was tested and the multi-beam performance demonstrated.

4 MISO ANTENNAS (SWITCHED BEAM ANTENNAS AND ADAPTIVE BEAMFORMING ARRAYS)

Smart antennas are the promise to improve the capacity of 3rd generation mobile systems. A large number of papers ([25], [26], [27], [28] and [29]) showing smart antennas advantages, the different architectures, and implementation techniques are presented by the several authors.

The first group of MISO architectures are based usually on a hardware solution by means of butler matrices in case of switched beam antenna [38]; or a set of smoothing filter (S), average amplifiers (Ave AMP), phase differentiators (D) as can be seen in the original architecture proposed to get profit just from polarization diversity [37].

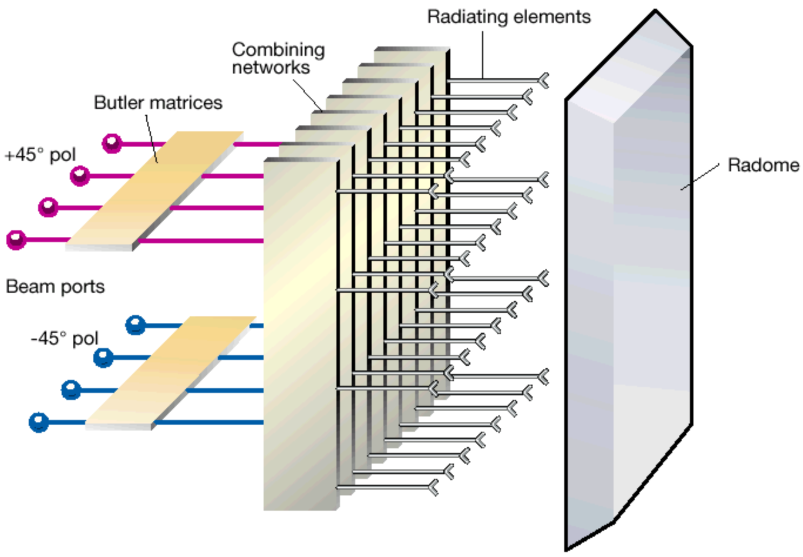

Figure 4-A : Block Diagram of the switched beam antenna ([38]).

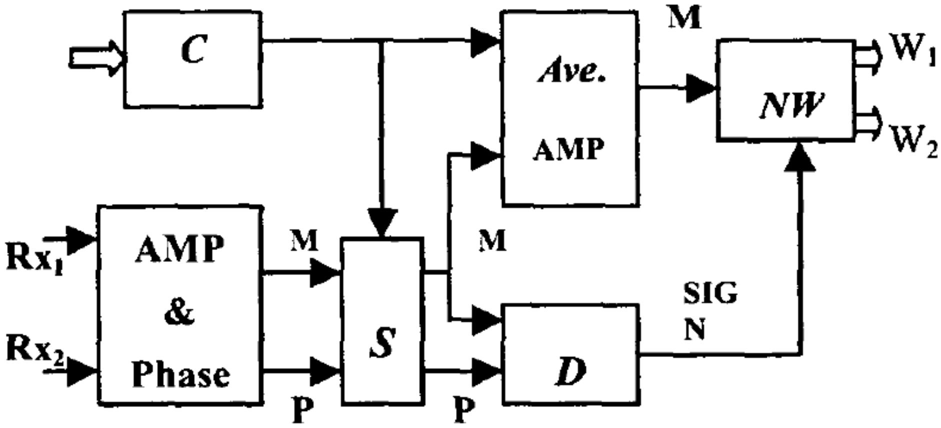

Figure 4-B : Block Diagram of the polarization MISO antenna ([37]).

The second group of MISO antennas are based usually on the implementation with SDR the adaptive beam forming algorithms. The probably most famous prototype is the one developed in TSUNAMI II project [35] as well as the test performed. Other prototypes can be found in the literature too. Some of them are a SDMA prototype of SDMA developed by Takatory et al.[41] in NTT laboratories, a prototype for CDMA2000 developed by Im et al ([39] and [40]); and a prototype for W-CDMA developed by Sierra et al. [43].

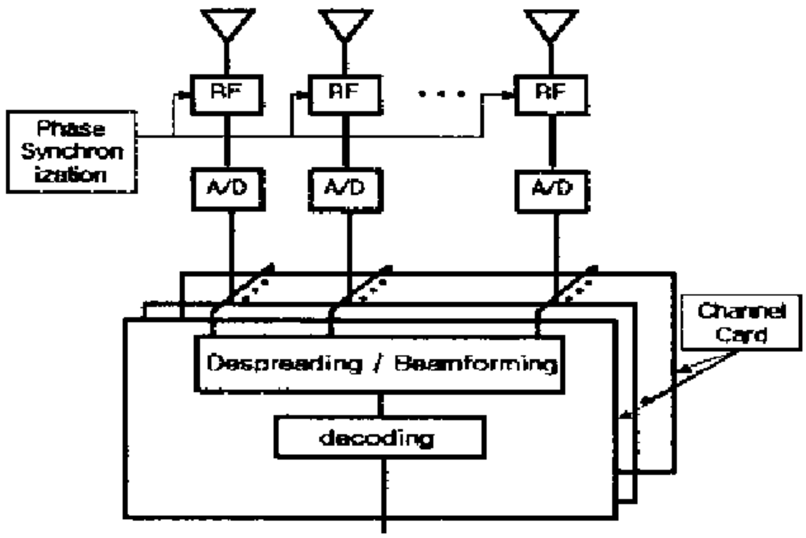

Figure 4-C : Block Diagram of CDMA2000 adaptive MISO antenna [41].

The core of the MISO antenna is the selection of the adaptive algorithms. Using each algorithm the weights may be adjusted to beam-form -in order to track desired users. Besides, the algorithms also determine the transient response of the antenna and the complexity of the beam-former. Generally, there are two categories time referenced or space referenced algorithms. The time-referenced algorithms maximize signal-interference ratio while space referenced ones tries to compute first the DOA to obtain the array factor. Moreover, algorithms can be classified as blind or non-blind depending on none or a reference signal is used to adjust the weights gradually, respectively. Non-blind algorithms include LMS, RLS, SMI, LCMV and so on, and blind algorithms includes CMA, MUSIC. Combined blind-non blind algorithms (e.g. SMI+CMA) may also be applied.

Several papers propose and compare the previously mentioned algorithms, and some of them ([30], [31], [32] and [33]) are included in the references.

This topic also has been developed in several of EC projects: TSUNAMI [34], TSUNAMI II [35], SUNBEAM. [36] from 1992 to 1999 covering the application of adaptive beam forming algorithms to GSM with SDMA up to W-CDMA and a simultaneous multiuser detection techniques.

	2G (GSM, IS-95, PHS)		3G (WCDMA, CDMA2000)	
	Switched beams	Adaptive Array	Switched beams	Adaptive Array
Nortel Networks [44]	🚗		🚗	
Lucent Technologies [45]	✯	✉	✯	
Ericsson [46]	✯			
Siemens [47]	✯	✉		✯
Huawei Tecnologies [48]			🚗	✉
Motorola [49]			✉	✉
Nokia [50]				
ArrayComm [51]		✯	🚗	
Metawave [52]	✯			
	✉: On design	🚗: Prototype	✯:Commercialisation	

Table 4-A : State of art in MISO antennas

Unfortunately in spite of all of these prototypes, few companies have available prototypes and even less commercially available products. The architecture of MISO antenna prototypes can be reached following two architectures: a) switched beam antennas and b) adaptive beam-forming antennas. The Table 4-A shows the results of research activities done by private companies.

5 MIMO ANTENNAS

Several algorithms has been proposed ([53], [54], [55] and [56]) which provide large increments of capacity as can be found in [57]. Usually these algorithms are based on a simultaneous time-space coding in order to get profit for a simultaneous usage of space and time diversity.

Due to the newness of this technology, few prototypes has been tested. BLAST ([58]) was the first MIMO prototype antenna has demonstrated the feasibility and capacity increment of obtained with the MIMO concept. It extends the third-generation (3G) wireless system over the existing UMTS standard using an associated space-time RAKE receiver. The BLAST prototype consists on a MIMO transmitter and receiver architecture, both realized on digital signal processors (DSPs) and FPGAs within a precommercial OneBTS base station. It uses four transmit and four receive antennas to achieve downlink data rates up to 1 Mb/s per user with a spreading factor of 32 and the UMTS chip rate of 3.84 MHz.

Within IST METRA a MIMO channel sounder was developed that provided realistic multi-antenna channel measurements. Using these measured data, stochastic channel models were developed and properly validated In conclusion a performance evaluation of multi-antenna terminals in combination with adaptive antennas at the base station in UMTS communication systems was done. Fig. 10 shows a comparison between both architectures which is mainly the inclusion of beam-former which allows in the uplink the base station receiver knows everything about the intra-cell users, whereas in the downlink the mobile unit receiver does not usually have access to that information.

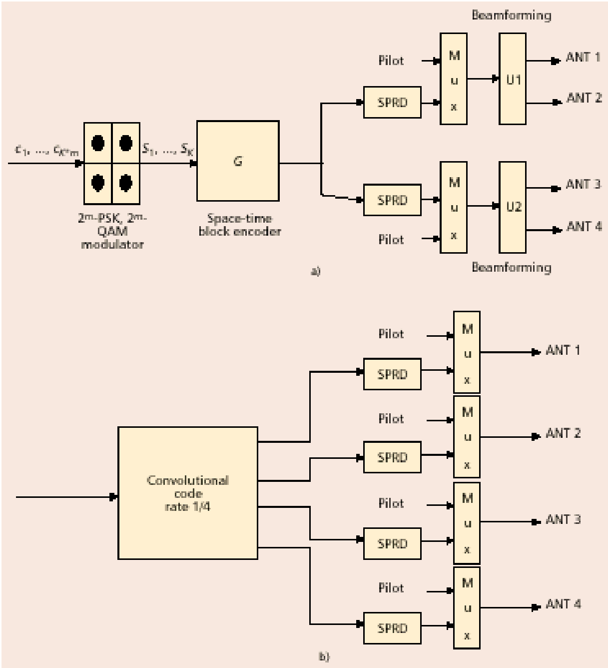

Figure 5-A : Comparison between METRA (a) and BLAST (b) architectures [59].

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European Commission - 6th Framework Programme	***ACE (Antenna Centre of Excellence)***	Information Society Technologies

REVIEW ON ANTENNA TECHNOLOGIES FOR COMMERCIAL AND CIVIL RADAR APPLICATIONS

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1 INTRODUCTION

Within the last two to three decades military technologies have been brought to the daily life of the average consumer in many ways. An overview of the most popular commercial and civil radar application fields are given in the following list [1][2][3]:

- Airport, air and sea traffic control
- Automotive & vehicular sensors
- Industrial sensors
- Meteorology applications
- Motion sensing
- Radar imagery applications
- RF – identification
- Traffic supervision

The focus of this study is on the antenna technology used in these radar systems. As far as possible other aspects like market potential and frequency allocation issues are addressed as well. The following part is subdivided into the major areas automotive sensors, air and sea traffic control, remote sensing, meteorological observation, RFID, and industrial and automation sensors.Automotive Radar Sensors

Introduction

The use of radar for automotive collision avoidance or Adaptive or Intelligent Cruise Control (ACC or ICC) has been investigated since the early 1970s [3]. Today radar technology has gained strong support from leading members of the automotive industry and automotive radar sensors have been developed world-wide by numerous companies. Especially the Forward-Looking Radar (FLR) type has been intensively developed and many car manufacturers and suppliers like Mercedes and Nissan with A.D.C., Jaguar with Delphi, BMW and Audi with Bosch, or Volkswagen with TRW-Autocruise offer ACC for highway operation as an option [4]. Besides the forward looking radar, increasing interest is being expressed in short-distance sensor functions, shown in Figure 1-A, which includes lane-change aid, blind-spot detection, park distance control, precrash detection, occupant sensing and a stop-and-go option for future enhanced ACC systems.

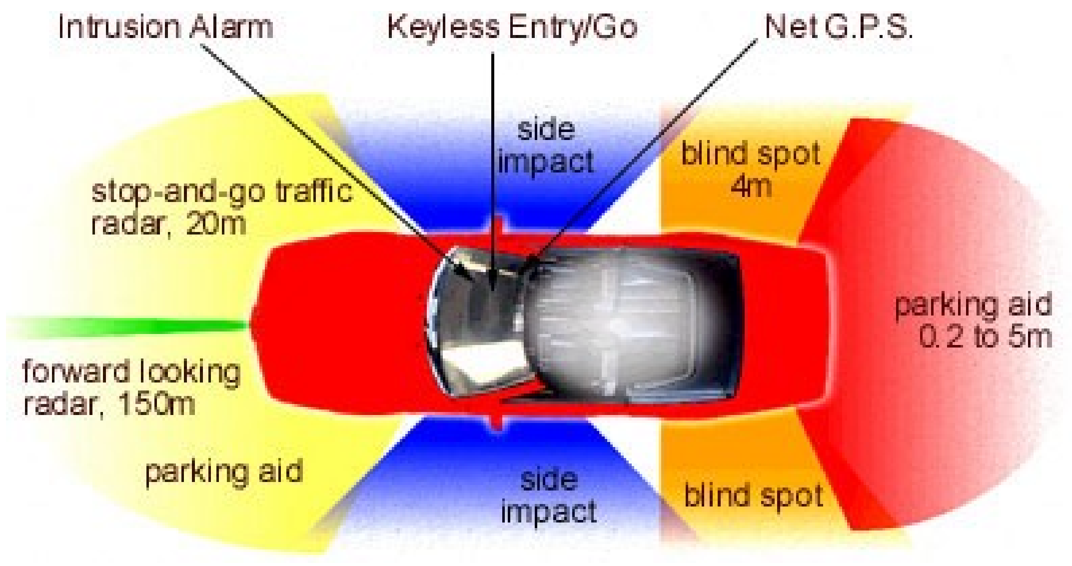


Figure 1-A : Automotive radar applications for short and long range radar systems [5].

A large number of competitors have already brought automotive radar sensors to market or they are planning to do this in the near future. The joint venture company Valeo Raytheon Systems, Inc. introduced 2003 a 24 GHz radar-based system in September that monitors the driver's blind spot on both sides of the vehicle. The Blind Spot Detection (BSD) system consists of two radar sensors joined to a control box and two LED warning indicators mounted in the side rear-view mirrors [6]. Delphi offers the product family “Forewarn” including back-up warning radar at 24 GHz/17 GHz and ACC radar systems. A dual beam radar sensor to assist the driver in detecting objects when backing shall be available May 2006 [7]. Some important automotive radar market players are:

- A.D.C. – Continental TEMIC
- Autocruise – TRW
- Bosch
- Delphi
- DENSO
- Eaton VORAD
- E2V Technologies
- Fujitsu-Ten
- Hitachi
- M/A-Com
- Mitsubishi Electric
- Roadeye - Groeneveld
- Siemens VDO
- United Monolithic Semiconductors (UMS)
- Valeo Raytheon Systems (VRS)

According to a recently published study performed by Strategy Analytics short and long-range distance warning systems will become increasingly common features on passenger vehicles. Ultrasonic, camera and radar technologies will be used extensively, but only radar systems will find significant application in both short and long-range systems. Strategy Analytics expects market development of automotive radars to accelerate now since more safety-oriented features are reaching the market, along with lower-cost short range 17/24 GHz devices. For long range systems, a market of approximately 2.5 million system units is expected by 2007. Short range system sales will reach around 11 million units/year by the same time, with over 43 million individual sensors fitted [8].

Long range radar sensors typically operate at 77 GHz and require a minimum range of about 50 m and a range resolution of around 5 m. These requirements are very different from that of short range sensors which operate at 17 GHz and 24 GHz. In these systems a range resolution of down to some centimetres and therefore a bandwidth of up to 4 GHz is desired, which lies outside the respective ISM-Bands and leads to an Ultra-Wide Band (UWB) system. For the US the Federal Communications Commission (FCC) issued an UWB ruling in February 2002 that opens the door for UWB communications and automotive radar. To protect other applications in remote sensing and radio astronomy the regulations are complex and limit emission levels in several ways. Besides some spectral properties the radiated power levels 30° above the horizon must be reduced from –25 dB in 2005 to –35 dB in 2014. This stringent requirement seems to be difficult to be fulfilled with a mass producible planar antenna and hence other concepts have to be investigated [9].

To seek for the global harmonization of automotive UWB Short Range Radar (SRR) the consortium SARA (Short range Automotive Radar frequency Application consortium) has been established. The consortium incorporates nearly all major automotive and supplier companies that are working in the field of safety electronics. In this activity a 2-phase plan is proposed. During the first phase 24 GHz UWB systems may be deployed and used until 2014. After this time new vehicles are equipped with 79 GHz SRR systems which will be developed until then. Existing systems may stay in service after 2014 [10].

Long Range Radar

An early publication by Steven Zelubowski deals with low-cost antennas for Long Range Radar (LRR) applications [11]. There it is stated that scanning or multiple beam antennas are needed to minimize the number of cases where cut-ins are missed or the track of targets is lost in curves. The application of frequency scanning antennas would have the potential of low cost but bandwidth restrictions due to frequency allocation preclude this approach. Electronic scanning with phase shifters and digital beamforming techniques are identified to offer great promise but they are assumed to be too costly. Hence, the sensor proposed in [11] is based on a three beam antenna that produces a 3° beam in the horizontal plane and approximately 5° beam in the vertical plane. Today several radar sensors in the market are using this multibeam antenna concept.

The design and measured results of a single-substrate tranceiver module suitable for 76-77 GHz pulsed-Doppler radar applications are presented in [12]. Three switched 3° beams are used in 3° separation and the sidelobe level is about 15 dB below the main beam. To maintain a compact, easy-to-manufacture, low-cost package for this module, the MMIC-compatible microstrip-to-waveguide transition in Figure 1-Ba is used.

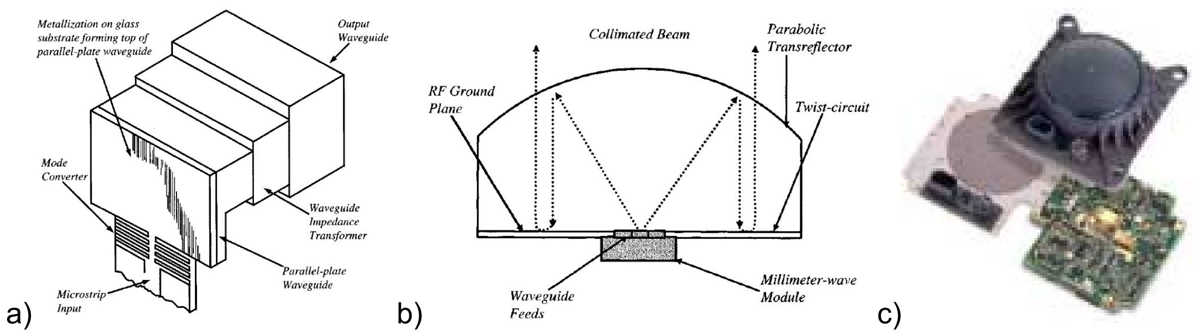


Figure 1-B : a) Microstrip-to-waveguide transition and b) antenna design utilizing folded optics [12], c) photograph of the M/A-COM LRR sensor [5].

The RF-module is mounted directly on the reverse side of the antenna ground plane and radiates directly into the input ports of the antenna. The antenna used in this front-end is a quasi-optical lens-based design [13], [14]. The proposed antenna design utilizes folding optics to minimize the total length of the antenna. The module waveguide ports illuminate a parabolic transreflector on the inner surface of the lens that either reflects or transmits the millimetre-wave signal depending upon the specific polarization. The reflected energy is repolarized by a microstrip “twist-circuit” on the antenna ground plane to form a collimated beam, that is then transmitted. The operation principle is shown schematically in Figure 1-Bb. The photograph of a likewise commercially available radar sensor in Figure 1-Bc can be found on the website of M/A-COM [5].

A 77 GHz radar sensor that uses a similar polarization dependent parabolic subreflector and a mechanically scanned polarisation-twisting planar main reflector is presented in [15], [16] and shown in Figure 1-C.

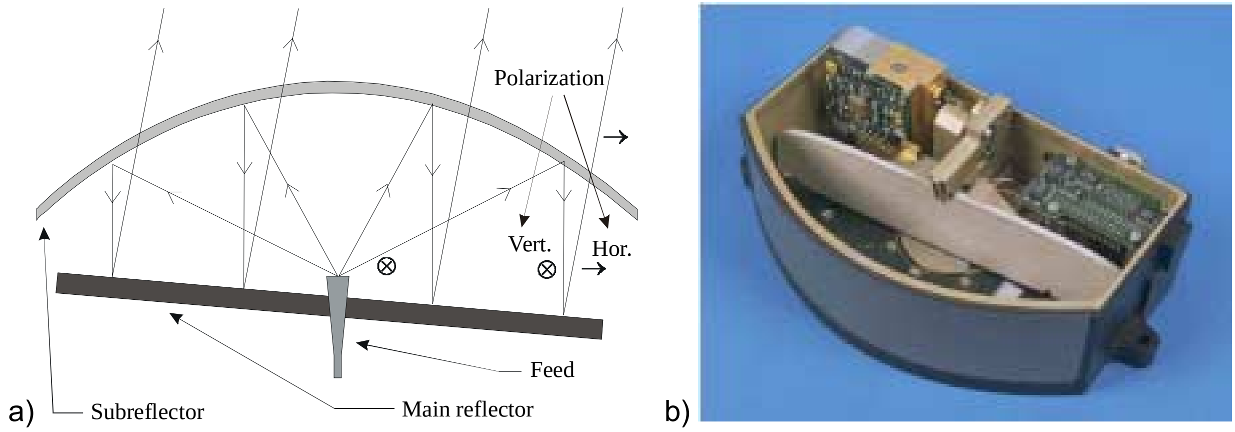


Figure 1-C : a) Schematically view of the Cassegrain type antenna from [15] and b) the photograph of the antenna and RF unit from [16].

The weight of the antenna-RF unit in Figure 1-Cb is 1.8 kg and the dimensions are 200 mm in width, 71 mm in height, and 125 mm in depth. The scan rate is about 10 Hz, the antenna beamwidth in the scanned direction is 1.5° and the angular coverage is about ±10°. The beamwidth in the fixed vertical direction is 6° and the sidelobe level is demonstrated to be below –25 dB for some scan directions.

Another approach that deploys the folded optics but a planar reflectarray instead of a parabolic reflector or transreflector is proposed in [17] and [18]. The basic cross section of this planar folded reflector antenna is sketched in Figure 1-Da.

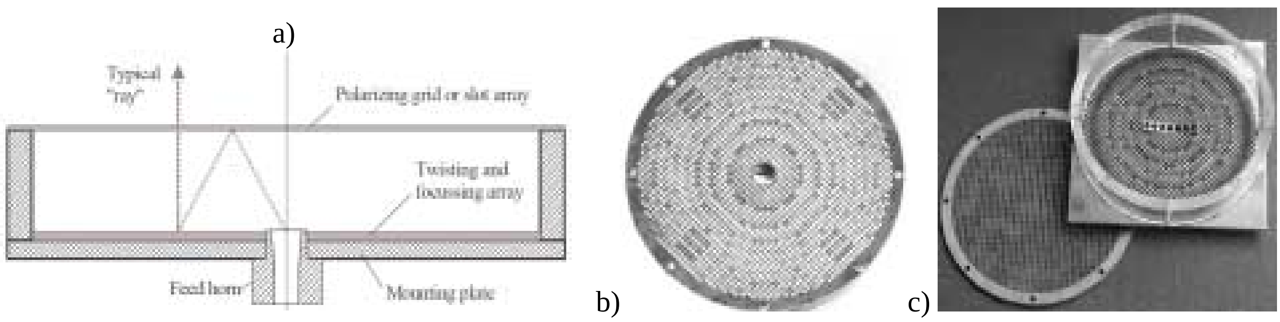


Figure 1-D : a) Basic principle of the folded reflector antenna and photographs of b) the reflector substrate of a folded reflector antenna and c) a folded bifocal reflector antenna [18].

The radiation from the feed is reflected by a printed grid or slot array at the front of the antenna and the wave is incident on the reflectarray with printed patches. The patches are used to twist the polarization and to transform the incident spherical wave into an outgoing plane wave which can pass the polarizing structure in front of the antenna.

Based on this principle, various antennas have been realized. Figure 1-Db shows a photograph of the reflectarray substrate of a 61 GHz folded reflectarray antenna with a diameter of 100 mm and a depth of 25 mm. The achieved beamwidths are 3.2° and 3.4° in E- and H-plane, respectively, and the sidelobe level is less than –24 dB. The achieved gain is about 31 dBi within a 7.2 GHz bandwidth. At 77 GHz beam scanning has been demonstrated by tilting the reflectarray, and an antenna with three beams for automotive applications is presented in [17]. The achieved beamwidths are 2.9° for the center beam and 3° for the tilted beams. To allow beam scanning or multibeam operation in a wide angular range, the extension to a bifocal type of reflector antenna which exhibits a focal ring instead of a focal point is proposed in [18]. Figure 1-Dc shows the photograph of such an antenna with an operation bandwidth of at least 76.5 ± 1 GHz. The antenna diameter is 90 mm and seven feeds are used. The presented beamwidths are between 3° and 3.3° and the scan range is ±13.5°. The sidelobe level is better than –18 dB for most of the scan directions.

The goal of the European project DenseTraffic is to develop a Forward-Looking Radar Sensor (FLRS) for second-generation Adaptive Cruise Control (ACC) systems with stop-and-go and cut-in situation capabilities. The desired beam pattern in azimuth for these functions and a prototype of the sensor are shown in Figure 1-E.

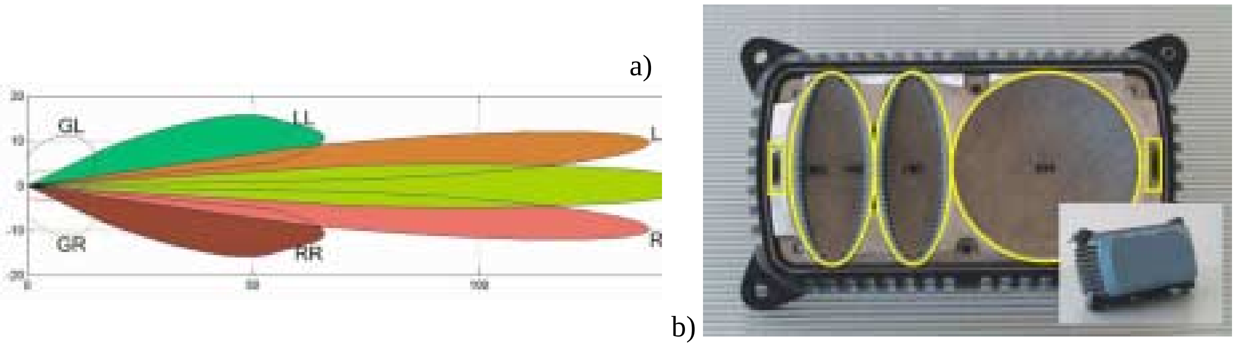
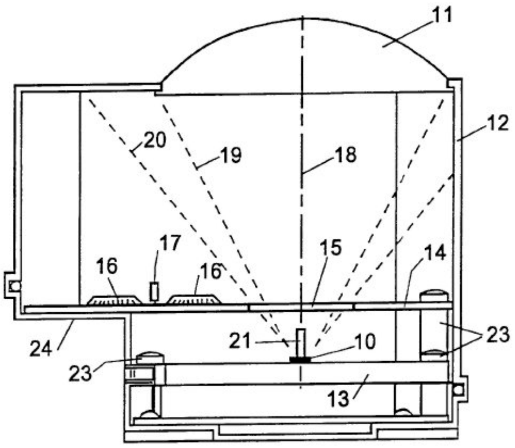


Figure 1-E : a) Desired beam pattern in azimuth for the ACC system with stop-and-go and cut-in situation capabilities, b) prototype of the sensor with multiple apertures [19].

The antenna consists of several apertures. The single illuminator beam (12° × 4°) is implemented in the oval aperture at the center of the antenna. The Left, Center and Right beams (L, C and R, each 4° × 4°) are implemented in the circular aperture to the right of the illuminator. The Left-Left and Right-Right beams (LL and RR, each 12° × 4°) for wide angle coverage are located in the oval aperture to the left of the Illuminator. Finally, the Guard-Right (GR) and Guard-Left (GL) beams are produced by the small apertures at the extremes of the antenna. Again the folding optics principal is applied in this antenna to allow the design of a very shallow antenna. Therefore, the radome has horizontal metallic lines printed on it to reflect incident waves from the feeds towards the parabolic reflectors. The reflectors have corrugations at 45° which twist the polarization of the wave. For the fabrication of the antenna housing thyxo-molded magnesium is used. The magnesium is both thermal and electrically conductive and thyxo-molded magnesium can reach very high mechanical precision, of the order or better than plastic which is required to be able to reproduce the small details and accuracies required by the 76 GHz RF frequency [19].

The cross section of a Bosch patented motor-vehicle radar system is found in [20] and shown in Figure 1-Fa. The photograph of Bosch's first generation LRR sensor system in Figure 1-Fb is found e.g. in [21]. The field of view is ±4° and the detection range is about 120 m to 160 m. The following LRR Sensor generation will show a significant size reduction and may have a larger field of view of about ±8°.

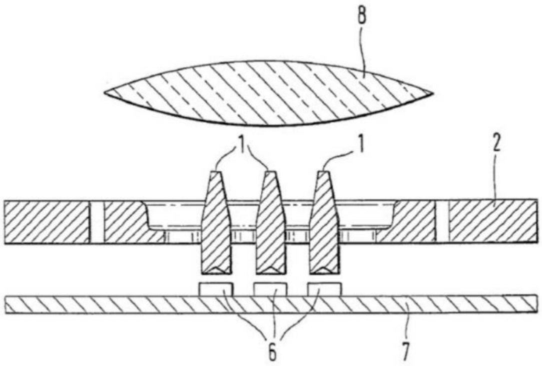


a)

b)

Figure 1-F : Cross section of a Bosch patented motor-vehicle radar system [20] and b) photograph of Bosch's first generation LRR sensor.

The antenna arrangement in Figure 1-Fa is made up of one or multiple feeder elements (10) and one antenna lens (11). The feeder elements are preferably patch elements. To overcome the problem of the usually low directivity of the feeder elements it is proposed to use dielectric rod antennas (polyrods) (21) in front of the elements. A second approach to optimize the portion of emitted microwave power that passes through the antenna lens (11) is to use a sub-lens instead of the window (15). When polyrods are used to focus the beam of the feeder element, their exact mounting is very important. A multi-beam radar sensor with a fixing device for such polyrods is described in [22] and shown in a three-beam configuration in Figure 1-Ga and Figure 1-Gb.



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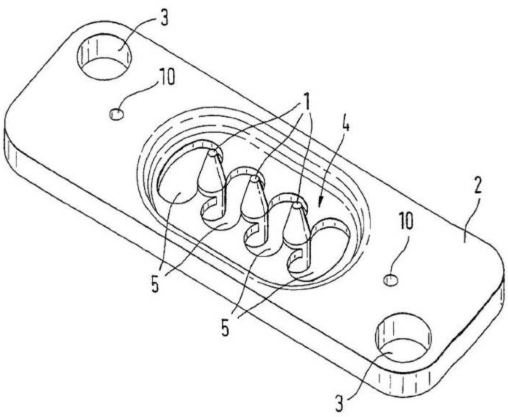
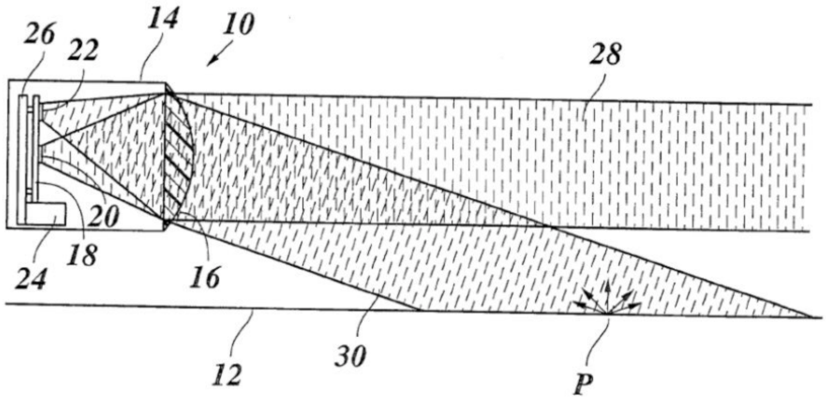


b)

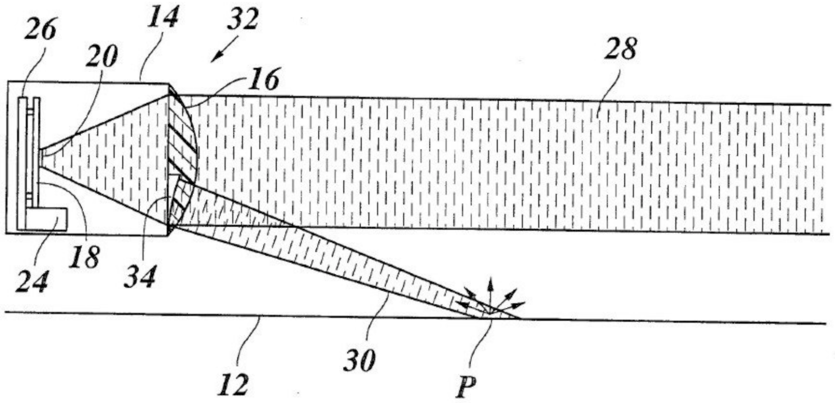
Figure 1-G : a) Cross section of a three-beam radar sensor and b) a proposed fixing device for polyrods as focusing elements as described in [22].

In this arrangement the dielectric plate (2) is used to mechanically secure the polyrods as focusing element (1) above the transmitting and receiving elements (6). In the region around these elements a larger opening is provided in the dielectric plate. The mounting area (4) has recesses (5), since coupling is the least across the air path between the polyrods.

An additional radar beam that points on the surface of the road in front of the vehicle may be produced by using an additional feeder element or by modifying the focusing lens of the sensor as shown in Figure 1-Ha Figure 1-Hb, respectively [23].



a)



b)

Figure 1-H : Additional radar beam produced a) by an additional feeder element or b) by modifying the focusing lens of the sensor to increase the sensor functionality [23].

The added beam may be used to measure the vehicle's speed over ground, to control the angular adjustment of the sensor in elevation during operation or to implement a control function that checks if the sensor works correct or not - the so called sensor or system blindness detection.

A millimeter-wave radar sensor with digital beam-forming capability for pre-crash detection is presented in [24] and some details can be found on the website of the automotive supplier DENSO [25]. The sensor in Figure 1-Ia enables a broad operating range of about 20° with a detection accuracy of 0.5°. The specified detection range is 2m – 150m. To decrease the complexity of the RF-hardware, only one receiver branch, including LNA, mixer and A/D-converter, is used in the architecture, as shown in Figure 1-Ib. Four SP3T-switches are applied to connect the nine receive antennas with the receiver branch, while a separate antenna is used to illuminate the scenario. The antenna is a triplate-type, which enables a compact construction and high gain. A wave-guide coupling with low-line loss is used for connection between the antenna and the millimetre-wave circuit. An efficient signal processing procedure has been developed to detect objects in front of the vehicle with an update rate of 10Hz.

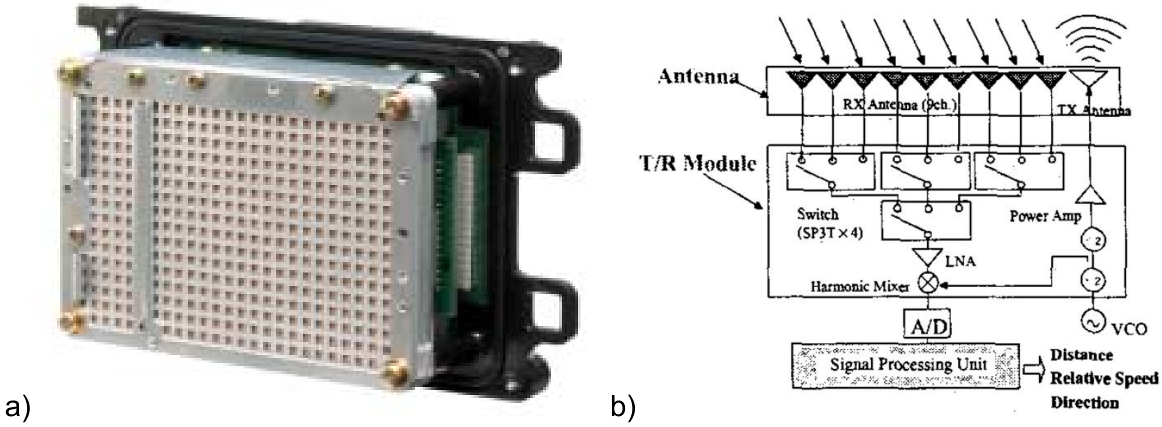


Figure 1-I : a) DENSO's millimetre-wave radar from [25], b) Configuration of the digital beamforming millimetre-wave radar described in [24].

A millimetre wave holographic radar with a simple structure is proposed in [26]. The simplicity can be realized by switching both transmitting and receiving antennas. High resolution, e.g. less than 2° beamwidth, is aimed for but difficult to realize. Therefore the use of superresolution algorithms is proposed. In this case it is assumed, that the array consist of elements with a beamwidth of 26° and the element spacing is 1.5 wavelengths. Nine receiving antennas are needed to achieve a resolution of 2°, when ESPRIT is used as the DOA-estimation method in the case of the fundamental holographic radar shown in Figure 1-Ja.

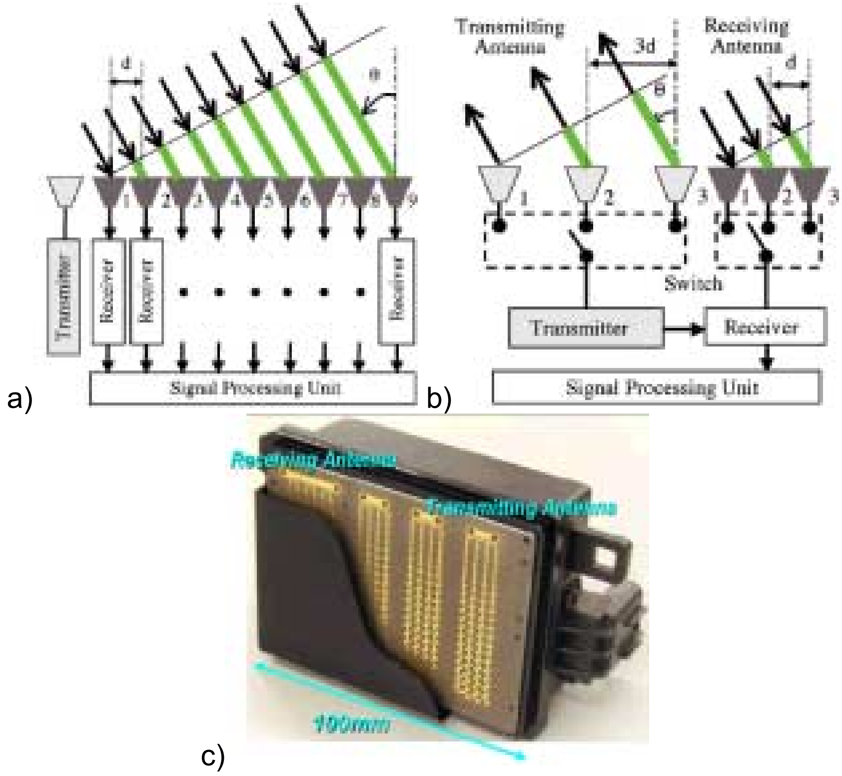


Figure 1-J : Configuration of a) fundamental and b) novel holographic radar [26] and c) photograph of a fabricated radar sensor [27].

The switching of the transmitting and receiving antenna elements in the configuration of the proposed novel holographic radar shown in Figure 1-Jb enables the decrease of the number of antennas. This arrangement is essentially equivalent in detecting the target direction compared to the fundamental approach, although the received signal corresponding to each receiving antenna is obtained in the time division manner. A radar sensor that uses this operating principle has been presented in [27] and is shown in Figure 1-Jc. The beamwidth of the transmitting and receiving antenna is 4° in elevation and about 30° in azimuth. The spacing of the transmitting and receiving antenna is 4.5 and 1.5 wavelengths, respectively. The frequency range is 60 GHz – 61 GHz and the antennas are 45° linear polarized.

An automotive radar sensor that provides an angular coverage of 16° in azimuth and uses the monopulse principle is presented in [28]. The system uses one transmitting and two receiving planar antennas as shown in Figure 1-Ka and fully monolithic integrated T/R-modules with two receive channels. The interconnection between the antenna and the RF-modules is DC-shorted as shown in Figure 1-Kb to protect the integrated circuits from ESD-damage.

a) 

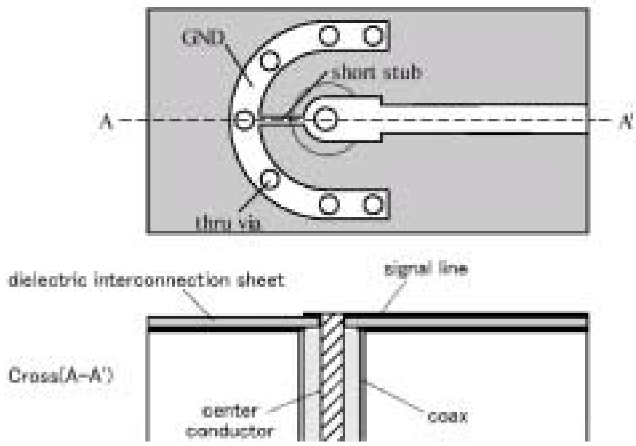
b) 

Figure 1-K : a) Automotive radar sensor from [28] that uses the monopulse principle and b) the employed interconnection between antenna RF-modules for ESD-protection

A multi-beam antenna concept based on a Rotman lens feed for use in a 76-77 GHz automotive Intelligent Cruise Control (ICC) radar is presented [29]. The Rotman lens is formed as a printed circuit on a 5 mil thick soft flexible substrate and the antenna elements are columns of series-fed patch elements on the same substrate. The antenna produces several overlapping beams to cover the field of view and employs sequential lobing techniques in order to locate targets in azimuth. With this approach antennas that provide an azimuth coverage of 8.8° using four beams and 15.4° using seven beams, each with an individual beam width of 2° have been built. The antenna's ideal area gain is 37.5 dBi and the losses, including the Rotman–Turner lens, are approximately 10 dB.

This antenna concept is used in [31] and [30], too. As shown in the Figure 1-La the antenna system possesses five narrow beams of 2.7° beamwidth for ACC functions and two broad beams of 16.8° beamwidth for near range functions like cut-in detection.

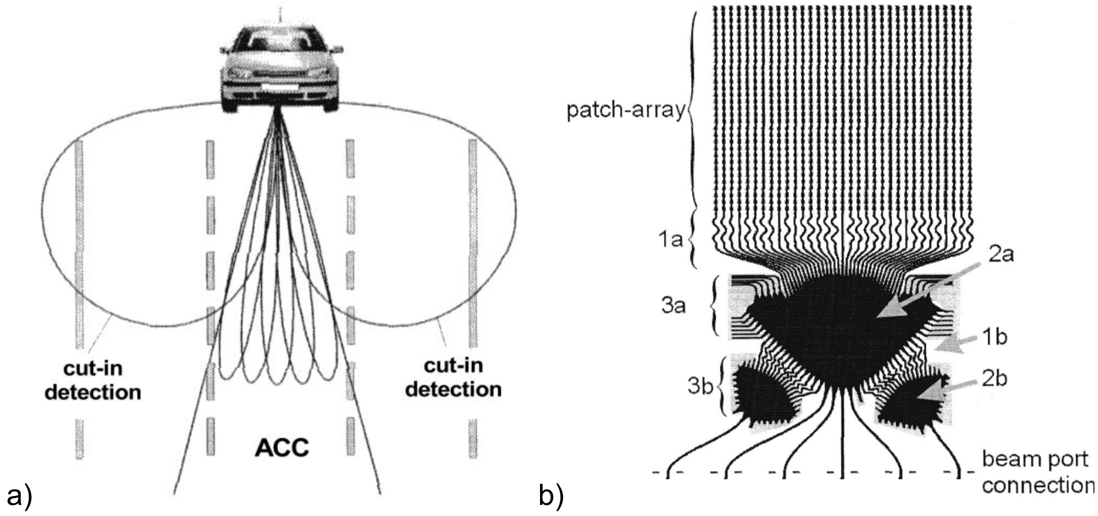


Figure 1-L : a) Desired angular coverage and b) 77 GHz multiresolutional microstrip antenna for ACC and cut-in detection [30].

The elevation characteristic is determined by 33 series-fed patch rows, each of 30 patches, which should result in a beamwidth below 3° in this plane. The excitation of the array is performed in two stages. A primary Rotman lens (Figure 1-La) sets the phase and amplitude distribution to the 33 columns of the array as shown in Figure 1-Lb. By distributed feeding at the lens sidewalls the high resolution ACC antenna can be used for broad beam generation as well. For this purpose, secondary lenses (Figure 1-Lb) are added to the feeding network and the achieved gain is about 13.7 dBi for these broad beams. The high resolution beams exhibit an average gain of 26.6 dBi gain which corresponds to an average loss of 9.6 dB.

An innovative scanning antenna concept proposed by Waveband Corporation (USA) is the spinning grating antenna shown in Figure 1-M [32].

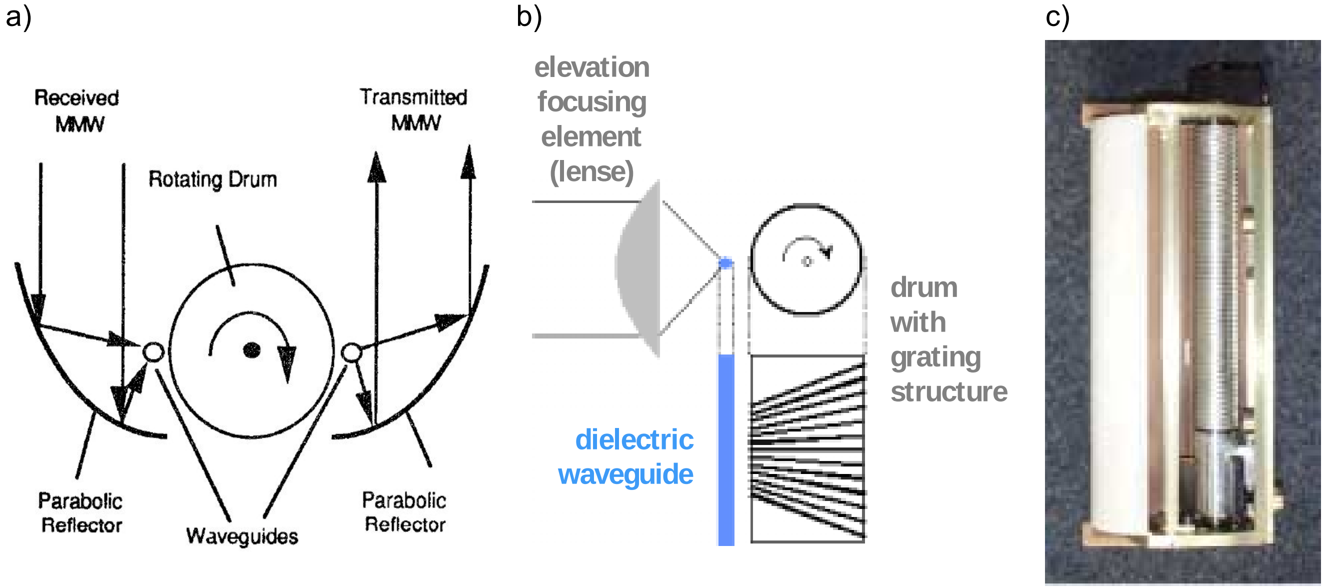


Figure 1-M : Spinning grating antenna consisting of dielectric waveguides, a spinning drum with the grating structure and a) a parabolic reflector or b) a dielectric lens as focusing element;.c) Prototypic implementation designed and manufactured by WaveBand Corp, USA:. Fig. from [32] and [33].

The antenna consists of a spinning metal grating that perturbs the propagation of an evanescent wave along dielectric waveguide. The period of the grating close to the waveguide controls the diffraction of the wave out of the waveguide and is a function of the angular position of the drum. Therefore, the rotation of the drum steers the beam. For beam forming in the second plane either a cylindrical parabolic reflector or dielectric lens can be used.

A prototypic implementation of this type of antenna, that was applied for the investigation of a high resolutional radar system in [33] is shown in Figure 1-Mc. The dimensions of the antenna are 24 cm in width, 6 cm in height, and 10 cm depth. A rigid quartz rod of about 1mm diameter forms the dielectric wave-guide and a mode launcher allows the antenna to be connected via a standard WR-12 wave-guide flange. The drum driving is performed by a small DC gear motor, an angular encoder serves for rotation speed control and exact reference for the beam pointing direction. The azimuth beam width is 1.5°, the elevation beam width is 4.2°, and the angular field of view is about ±11.5°. The antenna gain is above 35.5 dBi and the sidelobe level is below -15dB. The maximum scan rate for the continuous azimuth scan is 20 Hz.

The concept of a polarimetric 76 GHz imaging radar, delivering an image-like representation of the traffic scenario ahead is mentioned in [34]. The photographs in Figure 1-N show a polarimetric planar focal plane array with 16 transceiver modules mounted on a carrier and the radar front-end using a Rexolite lens and a mirror. The resulting beamwidths of the antenna are 0.75° in azimuth and 3° in elevation. The primary feed array in the focal plane consists of microstrip patch rows with a spacing of 3.75 mm between the rows. The microstrip antennas have been realized either on RT-duroid and on GaAs. The patches on GaAs have been realized by using a technology step which is compatible to standard GaAs processing techniques. The antenna patches are suspended on thin freestanding SiN_X membranes on GaAs substrates and aperture coupled to the feeding microstrip circuit [35].

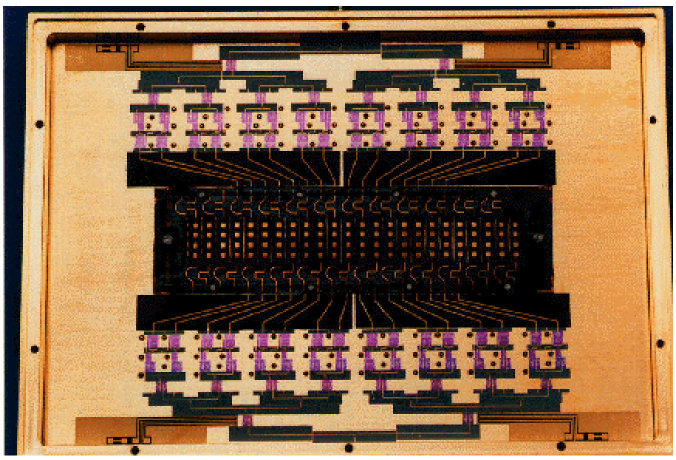
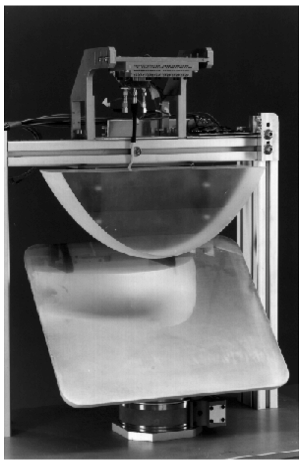
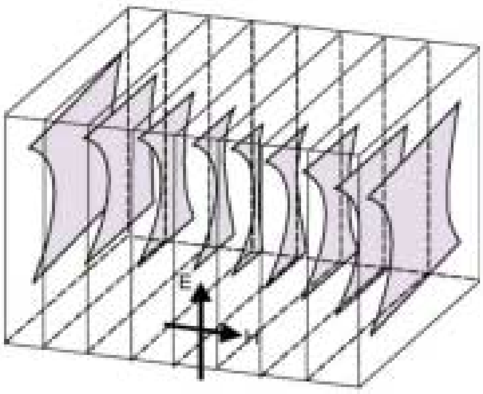
a)  b) 

Figure 1-N : a) Polarimetric planar focal plane array with 16 transceiver modules and b) the radar front-end using a Rexolite lens and a mirror.

In [36] a ceramic antenna array is presented. The array is manufactured using low temperature co-firing glass ceramics, in which cooper can be used as metallized material. The dielectric constant and loss of the ceramic is 4.8 and $8*10^{-4}$, respectively. The array consists of 256 so called Laminated Resonator Antenna (LRA) elements which are connected by a three layer Laminated Waveguide (LWG) feeding network. The width of the single beam is about 3.5°, the essential gain of the antenna is 28.1 dBi at 76.5 GHz and the efficiency is about 23%.

A focussing system based on foam printed technology is presented in [37]. A sketch of the internal view of the proposed double focused lens and a photograph of the lens with a horn as primary source is shown in Figure 1-O.

a) 

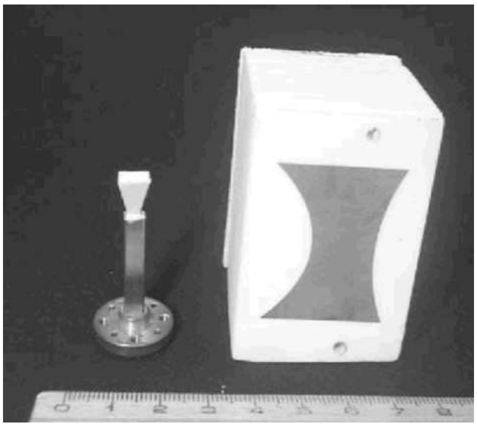
b) 

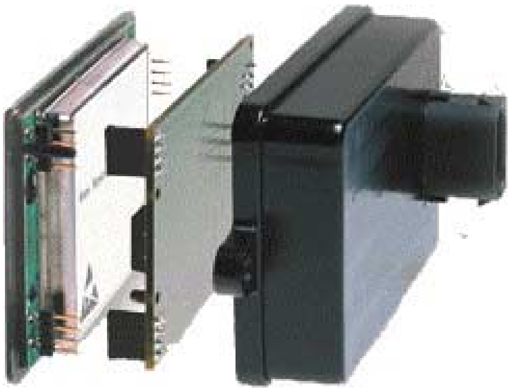
Figure 1-O : a) Sketch of the internal view of the proposed double focused lens and b) the photograph of the lens in metalized foam technology and a horn as primary source.

The design is based on artificial lenses consisting of stacked parallel-plate waveguides of various lengths. The proposed technology may provide a low-cost solution for future radar systems. A 5° beamwidth was obtained with 19.3 dBi gain using a pyramidal horn at 76 GHz. As the main beam is steered off broadside, measurements showed that sidelobe levels varied from -15 dB to -20 dB.

For automotive radar mass-producible compact (flat) antennas with narrow azimuth beamwidth, low side-lobes and a large field of view as well as low-cost packaging and testing of radar sensors are a pre-requirement for market penetration [38]. Numerous antenna types that meet the functional requirements of today's forward looking radar sensors have been built, but there is no specific antenna type which fulfils the demands for future systems.

Multi-Sensor and Multi-Frequency Systems

For Short Range Radar (SRR) functions a network of radar sensors is used to detect obstacles in the vehicle environment. The multi-sensor near range radar system offered by M/A-Com is shown in Figure 1-P.

a) 

b) 

Figure 1-P : Photograph of a) a 24 GHz short distance radar sensor and b) a multi sensor system mounted invisibly behind the bumper [5].

The system operates at 24 GHz with multiple sensors, that are connected to a central processor. It works within a distance of up to 20 m and has an angular resolution of 5° [5].

The goal of the European project “RadarNet” is to develop a new type of low cost radar network for automotive applications. Within RadarNet both, near and far distance sensors, will be realised using one integrated 77 GHz MMIC technology [39]. The description of the radar module with the four element series fed patch rows in Figure 1-Qa is given in [40]. Test vehicles with 77 GHz RadarNet sensors distributed over the vehicle's front for urban collision avoidance applications are shown in Figure 1-Qb [42] and Figure 1-Qc [41].

Figure 1-Q : a) photo of the 77 GHz RF module of the near distance RadarNet sensor [41], b) test vehicle with four 77 GHz RadarNet sensors [42], and c) example of radar network vehicle installation for the urban collision avoidance application [41]

Two versions of a multi-beam dual frequency antenna for 24 and 77 GHz automotive applications are presented in [43]. The antenna consists of a spherical Teflon lens with a frequency selective surface (FSS), which is fed by two sets of endfire tapered slot antennas (TSAs). The FSS is built on a 127 μm-thick Duroid™ substrate and is placed between two Teflon hemispheres, and is reflective at 24 GHz and transparent at 77 GHz in the first design, and is transparent at 24 GHz and reflective at 77 GHz in the second design which is shown in Figure 1-Rb. The TSAs for the 24 GHz and 77 GHz systems are built on a single piece of 254 μm thick Duroid™ substrate. The measured patterns result in E and H-plane patterns with a −3-dB beamwidth of 19° at 24 GHz and 5.5° at 77 GHz. The sidelobe level is below −17 dB when the FSS is transparent and is below −14 dB when the FSS is reflective. The calculated efficiency of this antenna system is around 50%. The presented designs provide 33° coverage at 24 GHz (3 beams) and 55° coverage at 77 GHz (11 beams) in the first design, and 99° coverage at 24 GHz (7 beams) and 33° coverage at 77 GHz (7 beams) in the second design.

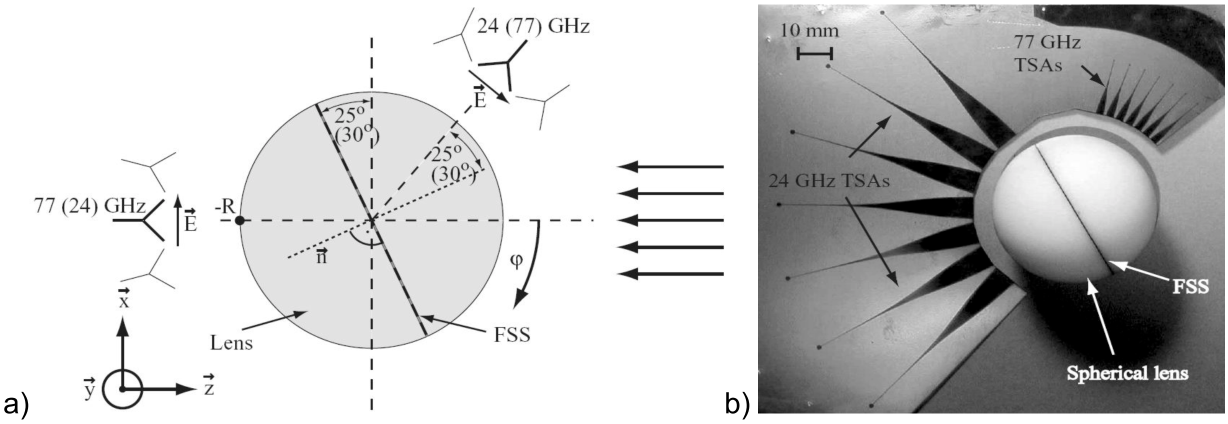


Figure 1-R : a) Schematic of the dual-frequency antenna with 24 GHz in reflective mode and 77 GHz in transmission mode (and with 24 GHz in transmission mode and 77 GHz in reflective mode) and b) the photograph of a fabricated antenna system.

2 AIR AND SEA TRAFFIC CONTROL

Air Traffic Control

Air Traffic Control (ATC) radar has evolved into three distinct types [44]:

- long range Air Route Surveillance Radars (ARSR) to monitor flights (en-route traffic) between airports,
- medium range airport surveillance radars (ASR) to align and sequence aircraft operations into and out of airports,
- airport surface detection equipment (ASDE) radars for controlling traffic on airport taxiways during congestion or under conditions of low visibility.

The air route surveillance radar (ARSR) separates traffic at high altitudes out to a range of 250 nautical miles. To achieve the long range ARSR antennas rotate more slowly and transmit at higher power. They can detect a one square meter target at 110 miles (approximate head-on cross section of a fighter aircraft), and their secondary radar range extends beyond 200 nautical miles. En-route controllers use long range radar data to coordinate traffic with adjacent centers as well as interface with terminal areas which control climbing and descending traffic.

Airport surveillance radar (ASR) monitors traffic from about 60 miles as is transitions into and out of terminal airspace. It is used to line up aircraft for landing and vectoring them to high altitude after departure. Terminal radar controllers accept radar handoffs from the en-route centers for incoming traffic and then turn these aircraft over to tower controllers. The procedure is reversed for traffic departing the area.

Examples for modern airport surveillance radar systems are Raytheon's ASR-10SS and the digital ASR-11, that operate in the frequency range 2.7 GHz – 2.9 GHz. The antenna gain is about 35 dBi and the azimuth beamwidth is 1.4°. The ASR-11 antenna in Figure 2-A operates with linear and circular polarization and has two feed horns for switchable beam patterns [45].

Figure 2-A : Air traffic control radar antenna for ASR-10SS system from Raytheon [46].

For larger airports where surface visibility may be restricted, a special short range airport surface detection radar (ASDE) displays aircraft and vehicles on the ground. A map of the airport is overlaid on the controller display. The system operates at the Ku band with a range to 12000 feet. The antenna is located in a radome on the roof of the tower cab [44].

Airport Surface Detection Equipment (ASDE) systems operate in two bands – X- and Ku-Band – and are available primarily from Raytheon, Northrop-Grumman, TERMA, and Thales (Thomson CSF). Typical ASDE antennas use slotted waveguide antennas e.g. with lengths at X-Band of 6m to achieve better than 0.4 degree beam width in azimuth. The elevation beams can be narrow and can be shaped for improved performance in rain [1]. The antenna requirements for the ASDE-3 system are described in detail in [47].

A Near-Range Radar Network NRN is described in [48] as a noncooperative sensor component for the multisensor fusion of a Surface Movement Guidance and Control System (SMGCS) on airports. Fixed, nonrotating antennas having broad sector characteristics in the azimuth and low power transmitters are applied. Sophisticated processing of echo signals of expanded pulses allows the detection of targets with a backscattering cross section of 1m^2 at a distance of 1 km. From the echo profiles, measured at four stations of an NRN module, the so-called rolling status for a plurality of targets including target classification is derived. Because of its modular structure and its high flexibility an NRN can minimize shadowing effects by buildings and due to its noncooperative concept it can detect all vehicles. Each NRN module, controlling an area of about 1 km^2, consists of four radars operating at 9.06 GHz. The radar stations are equipped with non-rotating patch arrays with a broad beam in the azimuth. The required network to form the sector characteristic is built up in microstrip technology (Figure 2-Ba and Figure 2-Bb). There are three antennas, one for the transmitter and two for the receiver in order to split the beam (Figure 2-Bc).

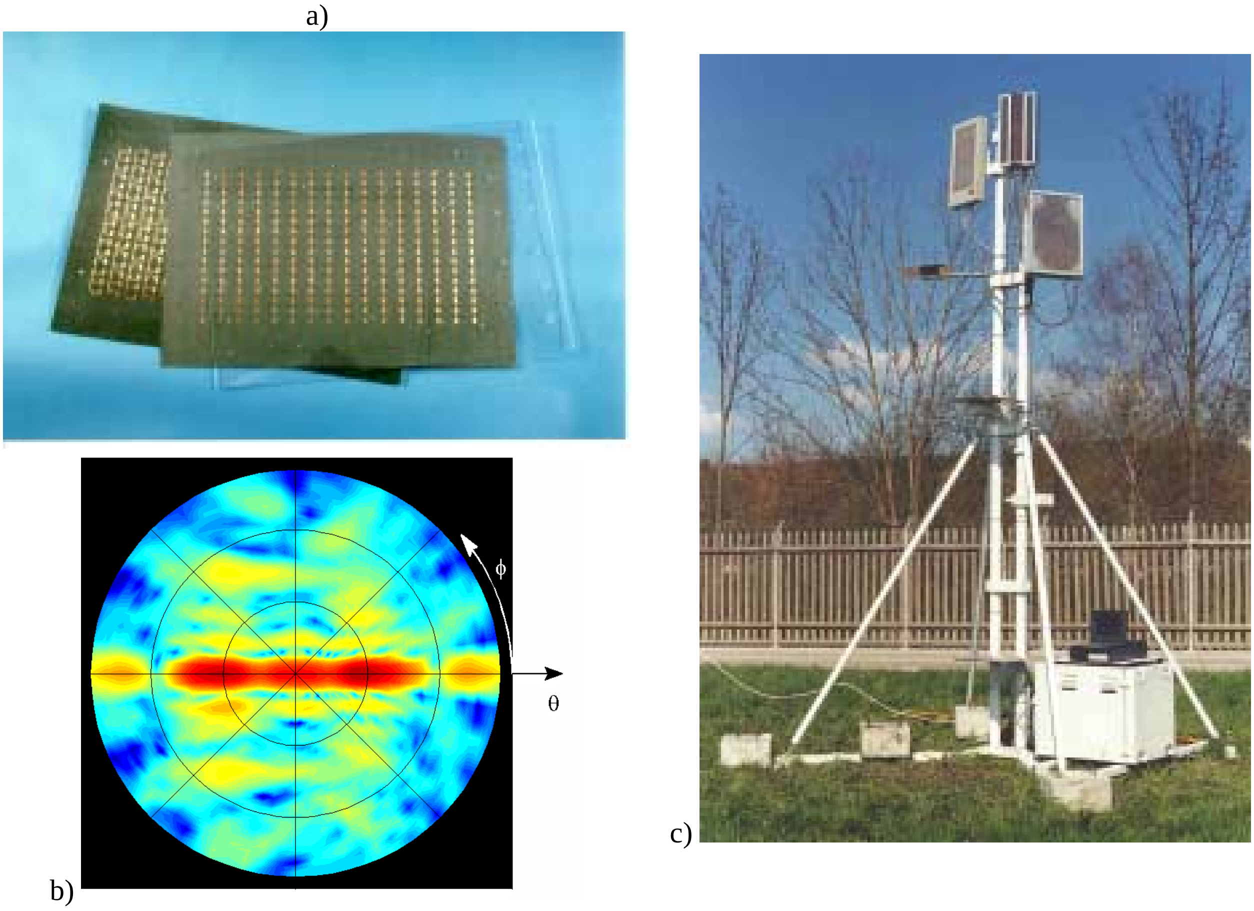


Figure 2-B : NRN equipment: a) Antenna array with beamforming network, b) sector radiation characteristic (90°), and c) module with receive and transmit antenna.

In [49] system tradeoffs and potential architectures of active array radar technology are described for civil air traffic control applications.

Observation of weather is another important function of ATC and airborne radars. Two special purpose ground-based Doppler radars are in place to detect microbursts and other hazardous weather conditions. First, a C-band Terminal Doppler Weather Radar (TDWR) detects and reports hazardous weather in and near the approach and departure zones of larger airports. TDWR can also detect wake vortices from heavy aircraft that could upset lighter aircraft. Second, the National Weather Service (NWS) Doppler radars (NEXRAD) detect storms and provide meteorological information to the FAA. They transmit storm activity data to en-route traffic-control centers, where FAA controllers relay this information to highflying aircraft. The airborne nose-mounted weather radar that operates in the X-band was the first pilots aid for avoiding bad weather. It presented an image of water vapour ahead of the aircraft that delineates a storm. Modern airborne weather radars display water droplet speeds in several colors, thus indicating storm intensity. In newer aircraft the weather display is often superimposed on the horizontal situation display (HSD) thus allowing the crew to be aware of all information in the horizontal plane [44]. Moreover, windshear and turbulence detection is being integrated into on-board radar systems, as are terrain and traffic warning systems. Pilots now can be presented different warnings of the three major hazards—traffic, weather and terrain—and even have indicated the hazard that needs priority attention. Two U.S. companies dominate the airborne weather radar market: Honeywell, now encompassing AlliedSignal's product line, and Rockwell Collins. Little European competition exists in the commercial market, although Thomson-CSF and Marconi Electronic Systems are strong contenders in military and surveillance radars, as is Raytheon in the United States. Another company, Telephonics, has manufactured many radars for the military market and threatens to give Honeywell and Collins competition in the civil market [51].

Honeywell RDR-4B Forward Looking Windshear Detection/Weather Radar System uses a 30 inches or 24 inches flat plate X-band waveguide array with a gain of 35 dBi and 33dBi and beamwidths of 2.9° and 3.6°. The antenna assembly scans a 180° sector in azimuth with scan rates of about 40°/sec and has a tilt (elevation) coverage of ±15° [52]. The sensor portion of the Rockwell Collins TWR-850/WXR-840/WXR-800 system is a single unit comprising an integrated receiver, transmitter, antenna and processing circuitry. This entire unit weighs less than 24 pounds and mounts in the aircraft radome. The flat plate X-band antennas, one example is shown in Figure 2-Ca, produce beamwidths from 8° to 6° at diameters from 30.5cm to 45.7cm. The scan rate is 27° per second [53].

a)  b) 

Figure 2-C : Multimode airborne radar systems with weather avoidance and windshear detection capabilities: a) Rockwell Collins TWR-850 [53] and b) Telephonics RDR-1500B [54].

Telephonics developed the surveillance and weather avoidance radar systems RDR1400/1500/ 1600/1700. The Telephonics RDR-1500B radar system is a lightweight, X-band, 360-degree digital color radar system. The system is designed primarily for fixed or rotary wing aircraft engaged in maritime patrol, surveillance, search and rescue, precision terrain mapping, fisheries patrol and drug interdiction operations. The system also provides weather avoidance, beacon transponder location, and waypoint navigation display Various options are available to allow customization of the system to meet user airframe and operational requirements. As an alternative to the 360° scan one available option is a nose-mount 120-degree forward sector scan antenna and drive. The dimensions of the antenna in Figure 2-Cb are 39 inches x 9 inches that results in an antenna gain of 31 dBi and beamwidths of 2.6° in azimuth and 10.5° in elevation. Scan Rates of 45°/sec - 90°/sec for the 360° scan range option and 28°/sec for the 120° scan range option are achieved [54].

Sea-Traffic Control

Marine radars have been in the market for over 50 years. Leading suppliers are Raytheon, Furono, JRC and Litton. The market has evolved into areas, which are distinguished by the size of the ship for which the radar is intended. Standards for these radars are well defined and regulated by the International Maritime Organization (IMO). High seas radars typically use slotted waveguide antennas of lengths up to 3.5m. Azimuth beamwidths are typically 0.8 and 1.8 degrees at X- and S-Band, respectively. Elevation beamwidths are approximately 20 degrees to accommodate the ship's roll and pitch. Important design considerations are the turning power and mechanical strength needed to withstand 100-knot winds [1].

The purpose of a Vessel Traffic Service (VTS) is to provide active monitoring and navigational advice for vessels in particularly confined and busy waterways. There are two main types of VTS, surveilled and non-surveilled. Surveilled systems consist of one or more land-based sensors (i.e. radar, AIS and closed circuit television sites), which output their signals to a central location where operators monitor and manage vessel traffic movement. These systems typically use slotted waveguide arrays and operate in the X-Band. Suppliers are EADS, Norcontrol IT, Terma, Lokheed Martin.

3 REMOTE SENSING AND METEOROLOGICAL OBSERVATION

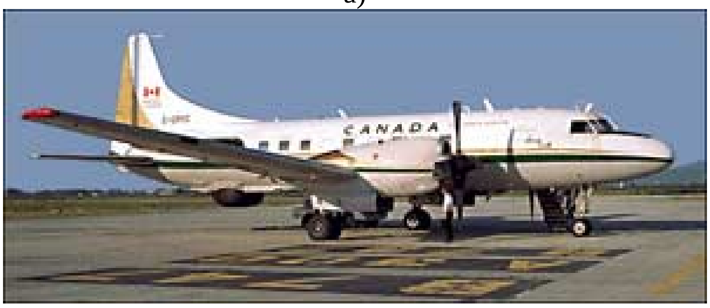
Remote sensing

Remote sensing is the science of acquiring information about the Earth's surface without actually being in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information. Applications of imaging radar for remote sensing include more accurate elevation mapping, natural hazards monitoring, soil moisture mapping and biomass estimation. Remote sensing systems which measure energy that is naturally available are called passive sensors. Active sensors, on the other hand, provide their own energy source for illumination. Synthetic aperture radar (SAR) is an examples for an active sensor. An imaging radar sensor may be carried on either an airborne or spaceborne platform. Depending on the use of the prospective imagery, there are trade-offs between the two types of platforms. Regardless of the platform used, a significant advantage of using a Synthetic Aperture Radar (SAR) is that the spatial resolution is independent of platform altitude. Thus, fine resolution can be achieved from both airborne and spaceborne platforms. [55].

Airborne Platforms

The Convair-580 C/X SAR system shown in Figure 3-Aa was developed and operated by the Canada Centre for Remote Sensing. The system was transferred to Environment Canada in 1996 for use in oil spill research and other environmental applications. This system operates at two radar bands, C- (5.66 cm) and X- (3.24 cm). Cross-polarization data can be recorded simultaneously for both the C- and X-band channels, and the C-band system can be operated as a fully polarimetric radar.

a)



b)

Figure 3-A : Airborne platforms carrying imaging radar sensors, a) the Convair-580 C/X SAR system [55] and b) the E-SAR system mounted on board a Dornier DO 228 aircraft [56].

The Sea Ice and Terrain Assessment (STAR) systems operated by Intera Technologies Limited of Calgary, Alberta, Canada, (later Intermap Technologies) were among the first SAR systems used commercially around the world. Both STAR-1 and STAR-2 operate at X-band (3.2 cm) with HH polarization in two different resolution modes. They were primarily designed for monitoring sea ice (one of the key applications for radar, in Canada) and for terrain analysis.

The Jet Propulsion Laboratory (JPL) in California has operated various advanced systems on contract for NASA. The AirSAR system is a C-, L-, and P-band advanced polarimetric SAR which can collect data for each of these bands at all possible combinations of horizontal and vertical transmit and receive polarizations (i.e. HH, HV, VH, and VV). Spatial resolution of the AirSAR system is on the order of 12 metres in both range and azimuth. Incidence angle ranges from zero degrees at nadir to about 70 degrees at the far range [55].

The E-SAR is a multi-frequency SAR system mounted on board a Dornier DO 228 aircraft, which is owned and operated by the German Aerospace Center DLR. The radar is operational in P-, L-, S-, C- and X-Bands with selectable vertical or horizontal antenna polarizations. The photo in Figure 3-Ab shows a DLR research aircraft of type Dornier DO 228 with the E-SAR radar installed onboard. Antenna installations are visible under the nose and in the back of the aircraft. The cigar-like pod under the nose contains the P-Band antenna. Beneath the cargo door in the back a radome covers both the C- and X-band antennas. The L-Band antenna, splited into two individual arrays, one for each polarization, is attached to the tail of the aircraft and carries the aircraft's ID [57].

Particularly, the C-band and X-band SAR antenna arrays operate at the frequency ranges from 5.05 GHz to 5.55 GHz and from 9.1 GHz to 10.1 GHz, respectively, working at the same time as transmitters and receivers. Both antennas are dual linearly polarized, having their main polarization components at the azimuth and elevation planes. A bandwidth of about 10%, reasonably good gain, well defined beam characteristics and very small cross polarization levels are the most significant requirements for these antennas.

The design of this antenna consists of a multilayer configuration that can be divided into two main parts: the antenna elements together with the azimuth feeder network and the elevation feeder network. Figure 3-Ba represents the exploded view of the structure of a single antenna element where the two stacked patches fed by electromagnetic coupling through a pair of crossed slots can be observed, as well as the feeding points (ports 1 and 2) for each polarization. The planar antenna arrays consist of 32 elements arranged in a matrix of 8×4. The elevation power-divider circuitry, which must handle the highest signals power (input power), consists of a module that is directly connected to the bottom of the antenna elements. The upper antenna array layers (elements and feeding network) can be seen in Figure 3-Bb.

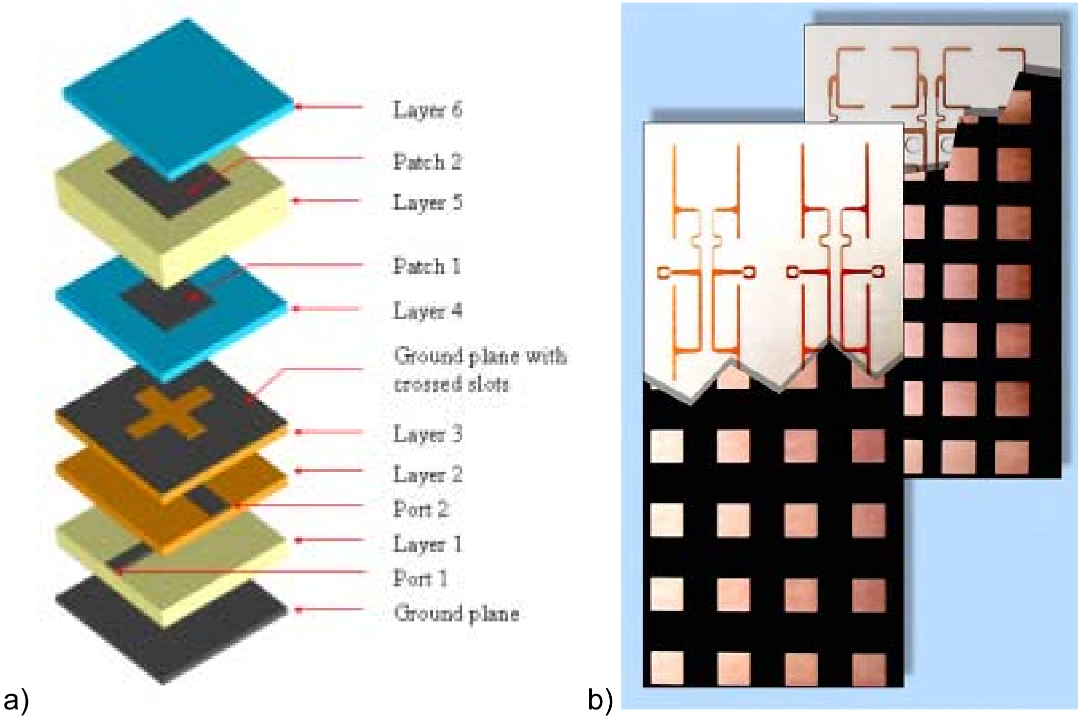


Figure 3-B : a) Cross section of the dual polarized element and b) antenna-array layers with feed single networks.

A system implementation of an active antenna for a forward looking airborne SAR with digital beamforming onreceive-only is presented in [58].

For transmit, a high power horn antenna for illumination with the radar pulse is mounted in the middle of the antenna system (see Figure 3-Ca). For receive the linear array in Figure 3-Cb with 56 horizontally polarised aperture coupled microstrip 2x2 subarrays is used. The centre frequency and bandwidth are 9.55 GHz and 400 MHz, respectively. A simplified hardware configuration is achieved by switching through the receiving array, thus sequentially recording return signals from each receiving antenna.

a)  b) 

Figure 3-C : a) The antenna system (pipe on bottom) fixed at the skids of the helicopter. b) Antenna system without the PVC pipe.

The dual-polarized microstrip antenna array for an X-band airborne SAR with an aperture size of 1.2 m by 0.3 m has been developed by the Commonwealth Scientific & Industrial Research Organization (CSIRO). The array that is shown in Figure 3-D has a bandwidth of approximately 600 MHz, is capable of high power operation and offers 30 dB of polarization isolation. It comprises three panels each having 64 elements, mounted in a lightweight frame suitable for use in the radome of an aircraft [59].

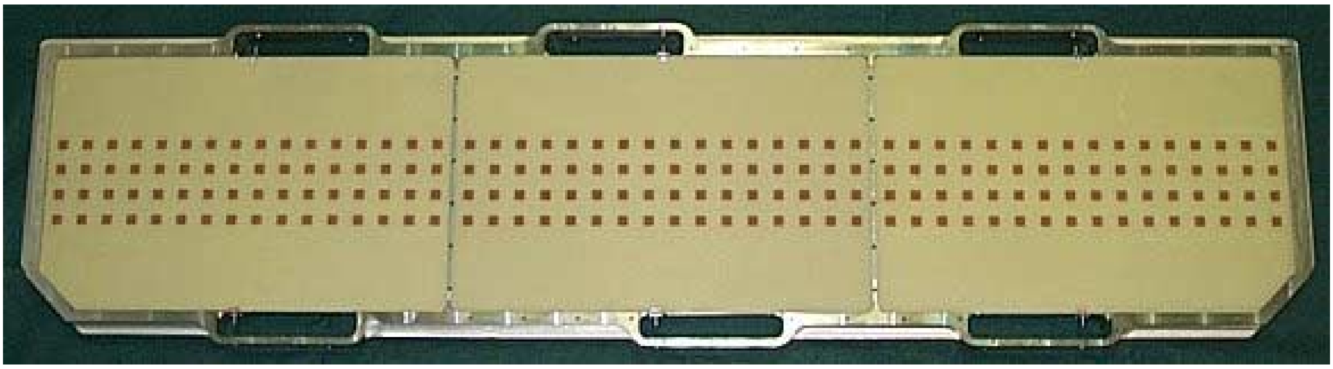


Figure 3-D : CSIRO's dual-polarized microstrip array for an X-band airborne SAR [59].

Spaceborne Platforms [60], [55]

With the advances and success of airborne imaging radar, spaceborne systems were the next logical step. Operational spaceborne systems of today are capable of generating global geological and topographic maps, using advanced SAR techniques

The first civilian space-borne SAR system to acquire high-resolution images of the Earth surface was flown aboard SEASAT, launched by NASA in 1978. The SEASAT SAR system, shown in Figure 3-Ea operated at L-band and utilized a 2.2x10.7 meter planar array antenna, with horizontal polarization. The system was designed primarily for observations of ocean and sea ice, but a great deal of imagery was also collected over land areas.

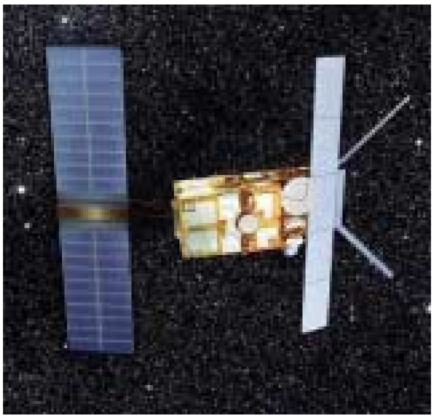
a)  b)  c) 

Figure 3-E : Spaceorne platforms carrying imaging radar sensors: a) SEASAT [61], b) ERS [62], and c) JERS [63].

The spare SEASAT radar components were subsequently modified and flown on two space shuttle flights as the Spaceborne Imaging Radar (SIR) experiments. The first, SIR-A in November 1981, had a reduced length antenna mounted at a fixed 50° look angle. The SIR-B system was then modified and flown in 1984, with the full length SEASAT SAR antenna mechanically steerable over a 20° to 60° look angle range.

The russian Almaz-T program was originally designed as a military reconnaissance craft. By early 1987, after the Ministry of Defense refused to further finance the project, the program was reoriented to civilian operations for remote sensing rather than military observations. Almaz-T was designed, manufactured, and operated by NPO Machinostroenye. The sensor was a 3 GHz (10 cm) S-band Synthetic Aperture Radar (SAR) that used two 1.5 m x 15 m slotted waveguide antennas. A first attempt was made in 1986, but the launch failed to reach orbit. A duplicate satellite was later flown during 1987-1989 as Kosmos 1870. Almaz 1 was launched on 31.03.1991. The Almaz-1 spacecraft reentered the Earth's atmosphere on 17.10.1992 after 18 months in orbit [64], [65].

The European Space Agency (ESA) launched a SAR aboard the European Remote-Sensing Satellite (ERS, Figure 3-Eb) in August 1991 (ERS-1) and another in April 1995 (ERS-2). Each ERS employs a C-band SAR operating at a fixed look angle of 23°. The antenna is a 10 m x 1 m planar waveguide array and utilizes a travelling wave tube for its transmitter. Of particular note to scientists are the arctic ice coverage products. Multiyear, time-sequenced data depict the polar ice pack motion, ice thickness and glacier motion.

The Japanese National Space Development Agency (NASDA) launched a SAR aboard the Japan Earth Resources Satellite (JERS-1, Figure 3-Ec) in February 1992. It operated at L-band with a look angle of 35° to provide global landcover mapping. A digital map database of the South American rainforests, which are often cloud-covered, was produced. Repeat pass interferometric data have been used to measure surface deformations on the order of mm.

After the launch of Canada's RADARSAT satellite on Nov. 4, 1995, RADARSAT has provided global SAR products for commercial and scientific customers, including sea ice mapping, coastal surveillance, land use, geology, environmental monitoring, hydrology, agriculture, and forestry. RADARSAT carries a planar slotted waveguide array antenna for the advanced C-band, horizontaly polarized SAR with a steerable radar beam allowing various imaging options over a 500 km range. Imaging swaths can be varied from 35 to 500 km in width, with resolutions from 10 to 100 metres. Viewing geometry is also flexible, with incidence angles ranging from less than 20 degrees to more than 50 degrees [55].

The Spaceborne Imaging Radar C/X band Synthetic Aperture Radar (SIR-C/X-SAR), shown in Figure 3-Fa, in 1994 was the first spaceborne multifrequency (L, C, and X bands), multi-polarization imaging radar. SIR-C and X-SAR were effectively five separate radars with regard to frequency and polarization. SIR-C operated at 1250 MHz (L band) and 5300 MHz (C band) while X-SAR operated at a single 9600 MHz (X band) frequency. The broad range of frequency and polarization discrimination greatly enhanced the remote sensing utility. The antenna aperture shared by the three antennas was 4.2 x 12 inches. The German/Italian X-SAR used a slotted waveguide antenna, mechanically steerable in elevation. The NASA SIR-C used an active phased array antenna, which allowed boresite steering and beamwidth adjustment in elevation.

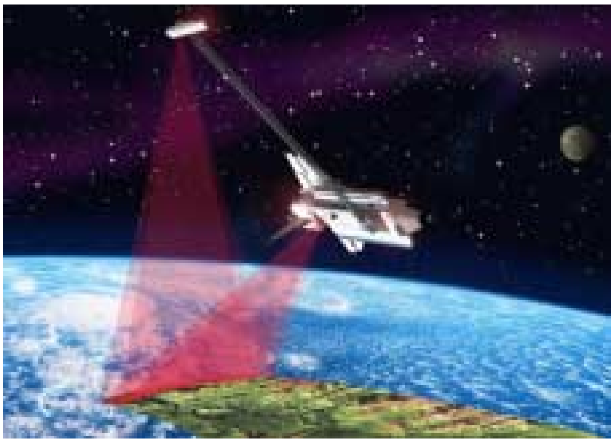
a)  b) 

Figure 3-F : a) SIR-C/X-SAR in the cargo bay of the Space Shuttle Endeavour [66]. b) SRTM to produce a globally consistent, high-resolution, elevation map of the Earth's land surface. [67].

The Shuttle Radar Topography Mission (SRTM) was a 10 day Space Shuttle flight in 2000. SRTM was built on SIR-C/X-SAR to allow production of a near-global map significantly sooner than with other systems. Augmentations included the addition of receive antennas at C and X bands that were extended to a length of 60 meters during flight as shown in Figure 3-Fb. These receive antennas, operating in concert with the antennas mounted in the shuttle bay, formed interferometric pairs. A star tracker and an inertial reference unit measure the baseline attitude. The relative motion of the outboard antenna is monitored by two other sensors, as is the distance between the inboard and outboard platforms.

Continuing the ERS-1/2 missions, the ENVISAT satellite has been launched by the ESA on March 1, 2002. The polar-orbiting Earth observation satellite with a lifetime of 5 years includes an advanced C-band SAR capable of beam pointing and shaping. [68]

Space-borne SAR systems for civilian applications are currently planned by a number of countries. NASDA in cooperation with the Japan Resources Observation System Organization plans to launch the phased array L-band SAR as one of three instruments aboard the Advanced Land Observing Satellite (ALOS). It is scheduled to be launched by the H-IIA launch vehicle from the Tanegashima Space Center (TNSC) in the Japanese fiscal year 2004 [69].

The Canadian Space Agency (CSA) in cooperation with MacDonald Dettwiler developed the RADARSAT-2 system. RADARSAT-2 is the first commercial radar satellite to offer multi-polarization capability that aids in identifying a wide variety of surface features and targets. The satellite is scheduled for launch in 2005 and has a design life of 7 years [70].

The German Aerospace Center and the EADS Astrium GmbH are developing the radar satellite TerraSAR-X. The launch of the 1-ton satellite, shown in Figure 3-G, into a 514 km orbit is planned on top of a Russian rocket for mid 2005 and the satellite is to be operated for a period of at least 5 years. The TerraSAR-X SAR instrument is an active phased array X-Band system with a centre frequency of 9.65 GHz. The antenna is capable of operation in two polarizations, H and V, and consists of 12 panels with 32 dual polarised slotted waveguide subarrays arranged in elevation each with a dedicated Transmit/Receive Module. The SAR antenna approximate dimensions are 4800 mm in length, 800 mm in width and 150 mm in depth [71], [72].

According to a recent analysis by Forecast International, “The Market for Civil and Commercial Remote Sensing Satellites,” approximately 170 remote sensing satellites will be manufactured between 2004 and 2013, 130 of which are slated for production within the next five years. Forecast International’s reported value of production for these systems is approximately $15.5 billion, with $10.1 billion of that amount being generated in the first half of the 10-year forecast period [74].

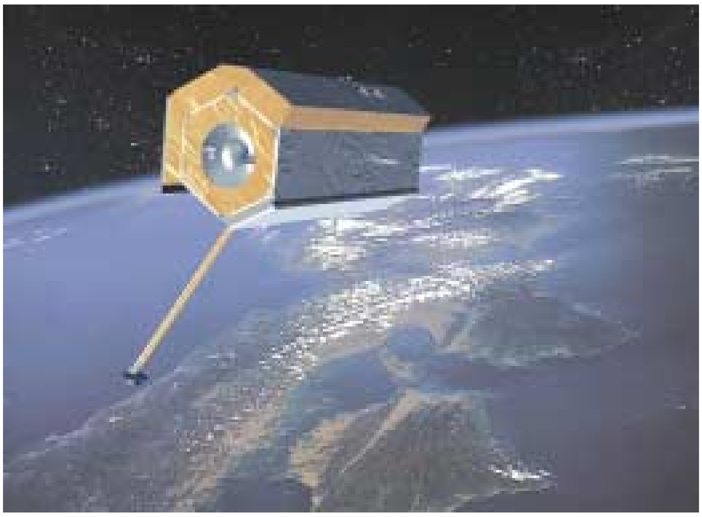


Figure 3-G : Artist view on TerraSAR-X [73].

Meteorological Observation [76]

Doppler Weather Radar

The use of radar for meteorological observation began by accident, when strange unexplained echoes were observed on the radar display during testing of microwave radar at MIT Radiation Laboratory during WWII. Dedicated weather radars were installed throughout the US and elsewhere in the early 1960s to observe rainfall. These were relatively simple C-band pulse radars. As military engineers began to employ the Doppler effect and develop the technology needed for its use, radar meteorologists began to explore how the Doppler frequency shift could add to the information available from the radar echo obtained from precipitation as well as the clear air. This led to the current Nexrad Doppler weather radar system (WSR-88D) deployed through the US. Nexrad is an S-band scanning pencil beam radar that provides the amplitude of the echo (from which the rainfall rate is estimated), the mean value of the echo signal Doppler frequency spectrum (that provides mean radial velocity), and the width of the Doppler spectrum (that provides a measure of the spread in radial wind speed). From these three radar measurements as a function of azimuth, elevation, range, and time, approximately 30 kinds of weather products can be produced to help the operator to interpret the weather and to warn of mesocy-clones, tornados, flooding, hail, high winds, and other severe weather effects.

The SPY-1 radar technology was originally developed by Lockheed Martin to support operations aboard U.S. Navy ships and is currently tested and enhanced by National Severe Storms Laboratory (NSSL) researchers with the vision of using this technology to potentially upgrade the WSR-88D Doppler weather radars. SPY-1 is a phased array radar and uses multiple beams and frequencies that allow it to scan the atmosphere six times faster than the WSR-88D. The dual-polarization radar uses two pulses instead of one, providing more information for forecasters to better predict flash floods, hail and winter weather. The testbed facility that is shown in Figure 3-Ha is installed in Norman, Oklahoma. An illustration of the various components of the phased array radar is shown in Figure 3-Hb [77].

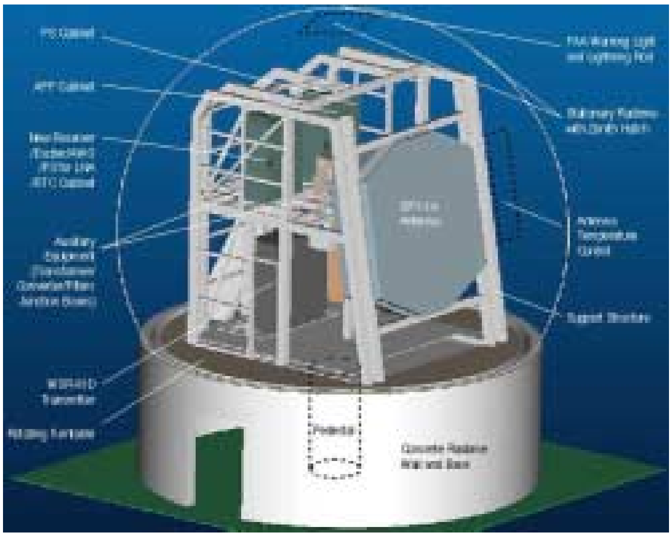
a)  b) 

Figure 3-H : a) Picture of NOAA phased array weather radar in Norman, Oklahoma. b) Illustration of the components of the phased array radar.

Within the Operational Programme for the Exchange of Weather Radar Information (OPERA) several European Meteorological Services are engaged to harmonise and improve the operational exchange of weather radar information between national meteorological services. One of the planed tasks is to agree on a common specification for radar sensor hardware and software [78].

Wind profiler

Wind-profiling radar systems are vertical looking radars, usually designed to operate at frequencies around 50, 400 and 1000 MHz. It obtains an echo from the wind as function of altitude. The echoes are obtained from the clear atmosphere since radar is able to reflect (although weakly) from atmospheric turbulence. The most common technique is known as Doppler Beam Swinging (DBS) which involves making observations in a cyclic sequence of vertical and near-vertical beam pointing directions. In order to derive the full three-dimensional wind vector, observations must therefore be made in a minimum of 3 non-coplanar beam pointing directions; a typical sequence includes observations made in the vertical direction and at an off-vertical angle of between 5° and 20° in two orthogonal azimuths. The maximum and minimum observable altitude decreases with increasing frequency. It is typically 2 km-20 km at 50 MHz, 0.5 km-10 km at 400 MHz, and 0.1 km-3 km at 1000 MHz. For this reasons, profilers operating around 50 and 400 MHz are called Stratosphere-Troposphere (ST) radars (or MST radars in the case of 50 MHz radars which are sufficiently powerful to detect the sporadic and weak returns from the Mesosphere), whereas those operating around 1000 MHz are called boundary-layer wind-profilers [79].

One of the simplest ways to perform the needed beam steering for UHF profilers, which have horizontal antenna dimensions of the order of a few metres, is to use a separate antenna for each beam direction. This is the case for the 1290 MHz UFAM boundary-layer wind-profiler operated by the Natural Environment Research Council (NERC-MST) Radar Facility at Aberystwyth, UK, that is shown in foreground of Figure 3-Ia. Each of the 3 antennas has dimensions of 2 × 2 m; the off-vertical angle is 17°.

a)


b)


Figure 3-I : NERC MST radar facilities: a) 1290 MHz mobile boundary-layer wind profiler, b) 46.5 MHz Mesosphere-Stratosphere-Troposphere Radar.

Since it is impractical to have more than one antenna, with horizontal dimensions of the order of 100 m, for a lower-VHF radar, beam steering is achieved through the use of a single phased-array antenna. The antenna array for the 46.5 MHz NERC MST Radar in can be seen in Figure 3-Ib. It is composed of a 10 × 10 array of 2 × 2 sub-groupings of 4-element Yagi aerials.

Other systems use the combination of radar wind profiler and radio acoustic sounding system (RASS) to measure wind profiles and virtual temperature profiles. These systems operate by transmitting electromagnetic energy into the atmosphere and measuring the strength and frequency of backscattered energy. Virtual temperatures are recovered by transmitting an acoustic signal vertically and measuring the electromagnetic energy scattered from the acoustic wavefront [80]. The rectangular antenna in the middle of the integrated wind profiler in Figure 3-J transmits and receives radio waves, while the four cylindrical loudspeakers surrounding it emit sound waves into the atmosphere.

Figure 3-J : Integrated wind profiler and radio acoustic sounding system [81].

Spaceborn weather radar

A properly designed radar in a satellite has the potential to detect, measure, and map rainfall worldwide. This might not be too important over land where there are adequate meteorological observations stations, but it is one of the few ways that precipitation can be observed over the oceans, especially in the tropics, where weather information is normally based on cooperative reporting from ships. The NASA/Japanese weather satellite of the Tropical Rainfall Measuring Mission (TRMM) was launched on November 27, 1997. The observatory for rainfall observations consists of a precipitation radar, a multi-frequency microwave radiometer and a visible and infrared (VIS/IR) radiometer. For related precipitation observations (i.e., lightning) and for additional important climate observations, a lightning imager and an Earth radiation budget sensor have been added. The Precipitation Radar (PR) measures the 3-D rainfall distribution over both land and ocean. It is an electronically scanning radar operating at 13.8 GHz with horizontal polarization using a 128-slotted waveguide antenna and solid state power amplifiers to develop an active phased array. The horizontal resolution is 4.3 km at nadir, the range resolution is 250 m and the scanning swath width is 220 km [82].

4 RF IDENTIFICATION

The concept of RFID systems have been around since WWII when the British Royal Air Force (RAF) used the technology to identify friend and foe aircraft (IFF). A related system is used today for air traffic control at civilian airports. Nowadays, new technology combined with today's demanding competitive environment have made RFID more attractive and thus increasingly tested for the real world. Now that companies are learning about the potential, and the technology has had time to mature, the demand is rising for extensive use worldwide [83] [84].

The top 100 suppliers to Wal-Mart and the Department of Defense will spend between $515 million and $3.8 billion in 2004 on technology and services to support RFID implementations based upon electronic product codes (ePC), according to Boston-based Yankee Group.

Vendors providing RFID tags, readers and networking equipment clearly would benefit as RFID adoption increased. In addition, the opportunity for vendors in the database, enterprise application, B2B communications, and systems integration markets is substantial. The Yankee Group estimates that during the next three years, manufacturers will spend approximately $2 billion on ePC RFID tags and $1 billion to $3 billion on infrastructure [85].

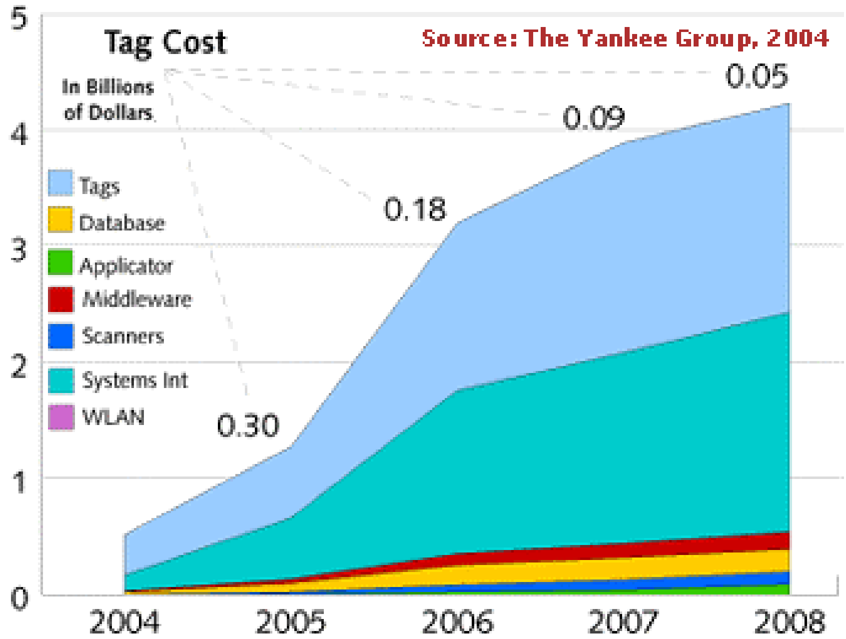


Figure 4-A : Predicted tag cost and ePC RFID development [85].

There is a huge variety of different operating principles for RFID systems. The two most common types of RFID technologies are divided in active and passive. Passive tags reply by backscatter, active tags incorporate low power radios to communicate with the reader. Therefore, passive systems maybe assigned to radar systems, whereas the active system may belong to communication systems. However, a strict assignment is not possible in every case.

There are different frequency bands which passive technology operates within. Low and High Frequency RFID operate on the inductive coupling principle. That is, the energy is transferred from the reader to the tag through shared magnetic field. UHF and microwave RFID tags reply to the reader using the backscatter principle and use a technique similar to radar. UHF RFID systems operate at 868 MHz in Europe and 916 MHz in North America. Microwave systems are used at 2.45 GHz and 5.8 GHz.

As schematically shown in Figure 4-B, the tag uses an antenna with a high reflection cross-section for incident electromagnetic waves. Thus a portion of the power radiated by the reader antenna is reflected off the tag's antenna and is then received by the reader. By switching on or off a load connected in parallel to the reader's antenna, it is possible to vary the amount of reflected power. By modulating the switching with data, information can be transferred from the tag to the reader. The reflected power is received at the reader and the data is decoded. [83] [84] [85]

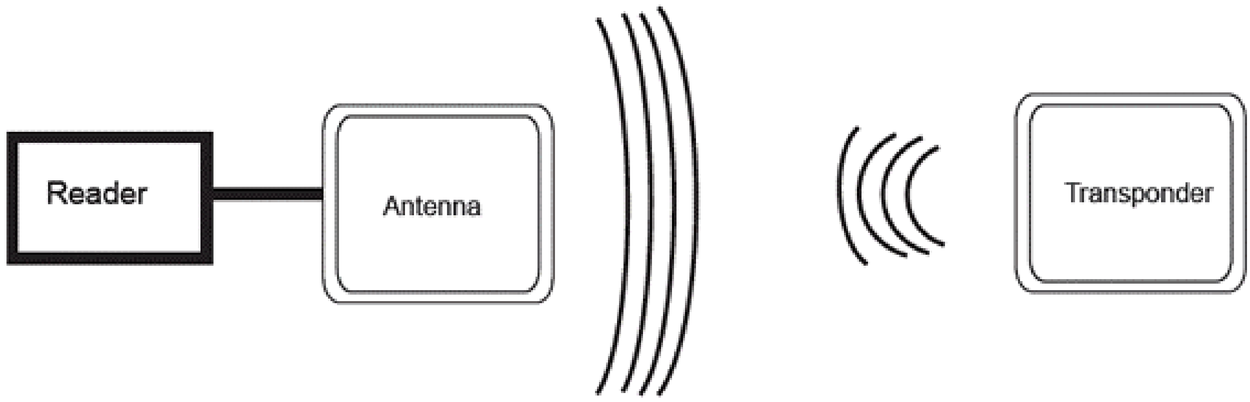


Figure 4-B : Schematic of a RFID-System [84].

An overview about some commercially available RFID systems and the respective manufacturers is shown in Table 4-A.

Company	Product	Website
Baumer Ident	OIS-P/U/W	www.baumerident.com
Androdat	Telides	www.androdat.de/
Pepperl & Fuchs	Ident M System T/V	www.pepperl-fuchs.com
Siemens AG	Moby/SOFIS	www.siemens.de/
Tagmaste AB	Tagmaster	www.tagmaster.se
Transcore	eGo/AmTech	www.TransCore.com
Balogh	HyperX	www.balogh-group.com/
Nedap	TransIT	www.nedapavi.com
Identec	i-D Tag/i-Q Tag	www.identec.at

Table 4-A : Product overview [87] [88].

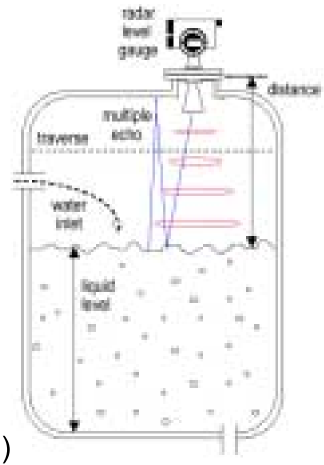
An integrated antenna system for a 5.8 GHz Radio Frequency Identification (RFID) tag proposed for predicting the pipe's lifetime and to provide inventory control is presented in [89].

A card-type 5.8 GHz passive transponder for possible use in the Dedicated Short-Range Communication (DSRC) systems and/or the RFID systems is presented in [90]. Four LHCP microstrip antennas are arranged in the transponder by using the Van Atta retrodirective design so that the transponder possesses the advantages of both a high responding signal level and a wide range of responding angles. In [91] a two-port bi-directional amplifier is proposed and used with a two-element active Van Atta retrodirective array. The fabricated bi-directional amplifier provides the transmission gain over the frequency band from 5.76 to 6.88 GHz with a peak value of 9.1 dB at 6.04 GHz. The active array is compared to a four-element passive array. Printed Yagi antennas with four directors are adopted to build both the active and passive Van Atta arrays.

5 INDUSTRIAL AND AUTOMATION SENSOR APPLICATIONS

Radar Tank Level Measurement

A significant industrial application of radar sensor technology is the measurement of liquid or solid material level in process tanks. Most level measurement principles require a mechanical contact to the process, but use of contactless measurement principles is increasing rapidly. Radar offers the best performance in terms of robustness to extreme temperature, pressure, dust and aggressive chemicals. The majority of installed radar level meters operate at 5.8 GHz, 10 GHz and 24 GHz. Sharp antenna patterns that maximize the level echo while minimizing disturbing reflections are needed to provide high accuracy and measurement reliability [2].

a) 

b) 

c) 

Figure 5-A : a) Radar tank level measurement [92], b) horn, dielectric rod, and planar antennas [93], c) radar level gauge [94].

An overview of some competitors in the radar tank level measurement sector is shown in Table 5-A

Company	Product	Website
VEGA-Grieshaber	VEGA Puls 60	www.vega.com
Saab Rosemount	Tank Radar Rex/Pro	www.saab.tankradar.com
Enraf	SmartRadar	www.enraf.com
Krohne	BM700/BM70X	www.krohne.com
Siemens	Sietrans LR	www.siemens.de
Endress&Hauser	E+H FMR	www.endress.com

Table 5-A : Competitors in the radar tank level measurement sector.

Railway applications

For railway applications Honeywell provides radar sensors for wheel independent speed measurement (Figure 5-Ba), continuous speed measurement of rail cars on hump tracks for automated train assembly (Figure 5-Bb) or radar scanners for automated monitoring systems for level crossing (Figure 5-Bc) [95].

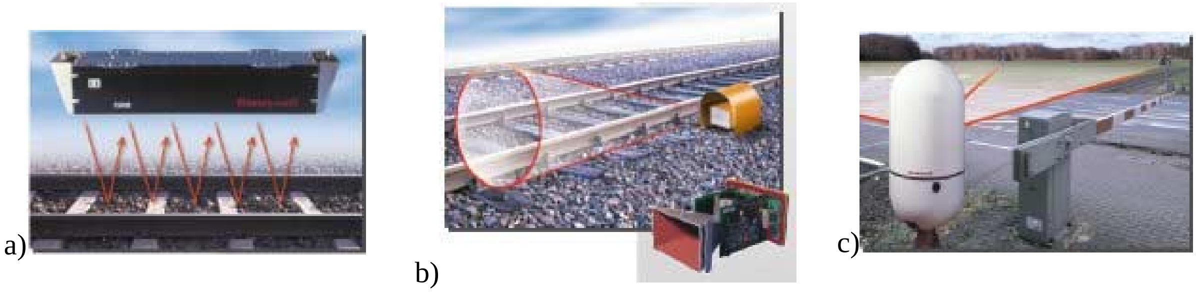


Figure 5-B : Honeywell radar sensors for railway applications [95].

A 24 GHz microwave Doppler sensor system for non-contact ground speed measurement is presented in [96]. Its potential for positioning tasks, as well as slippage control in railway applications has been demonstrated. The microwave front-ends are based on highly stabilised dielectric resonator oscillators and low-cost printed antennas. Figure 5-Ca shows a schematic of the measurement set-up. In the trapez form sensor box (Figure 5-Cb) three independent microwave front-ends are installed with different antenna radiation patterns: the front-end 1 in a so-called Janus configuration with two antenna beams, α =45° and the front-ends 2 and 3 with a single antenna beam, α = 15°

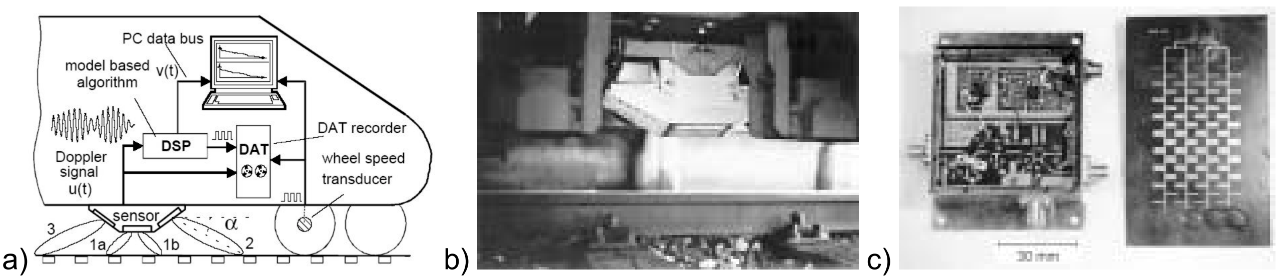
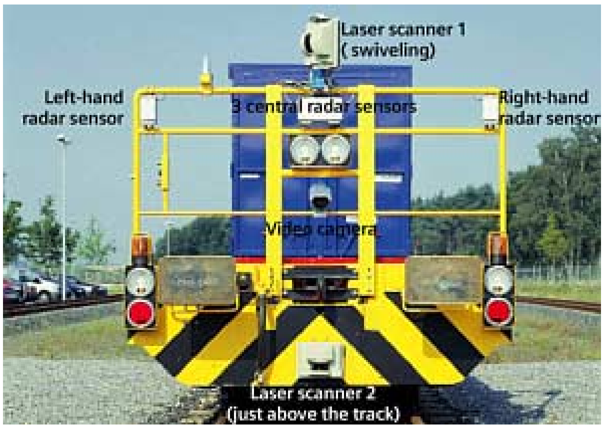


Figure 5-C : a) measurement setup, b) sensor on locomotive and c) radar front-end.

The radar front-end of this system is shown in Figure 5-C-c. It consists of a fundamental-frequency dielectric resonator oscillator, a schottky diode detector and a comb-line microstrip travelling-wave antenna.

The Siemens Cargo Mover is a fully automatic rail vehicle which can be booked individually by a company wishing to dispatch freight. This vehicle has the capacity of two road trucks but uses considerably less energy. The destination is entered into the Cargo Mover by the dispatcher. With the help of ETCS, the future European operations control system, the Cargo Mover then locks into the rail transport system and automatically finds its destination on the basis of preprogrammed route maps [97]. The CargoMover uses data from a wide range of sensors which are shown in Figure 5-Da. Five radar sensors observe the area up to 70 m ahead the vehicle an calculate distances to objects and the relative speeds of other trains. A video camera follows the course of the track. When combined with vehicle speed information, the data from this camera can be used to derive three-dimensional information about obstacles on the track. Two infrared laser scanners – one works at track height and the other swivels from side to side, scanning the area in front of the CargoMover – ensure that the car can maneuver with extreme accuracy. A standard industrial PC is used to combine and evaluate the data [98].

a) 

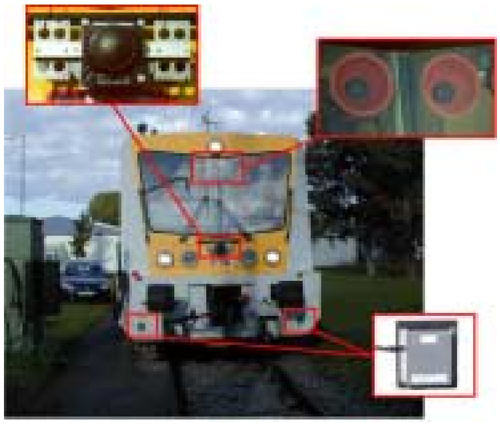
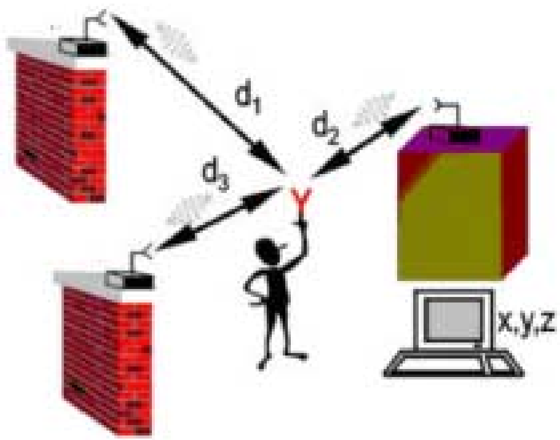
b) 

Figure 5-D : a) Multiple sensors mounted on the Siemens Cargo Mover [98]. b) Autonomously driving rail car equipped with radar and video sensors [99].

Investigations on a rail car for autonomously driving trains to enhance public passenger traffic is presented in [99]. A multi-sensor system containing radar and video technology is used in this application. It consists of a set of comparatively low cost sensors as used for automotive applications, comprising four different sensors (Figure 5-Db): a turnable tele camera, a 77 GHz far distance radar system, a survey camera, and a 24 GHz near distance radar-network [99].

Positioning Systems

Industrial Local Positioning Radar (LPR) is a system that offers real-time contact-free tracking of the coordinates of mobile transport equipment in a harsh industrial environment. The operating frequency is 5.8 GHz and the principal industrial uses of Siemens' LPR include tracking the locations of cranes, forklifts and other vehicles within a defined area, contact-free position measurement in the fields of automation, logistics and airfield navigation, plus automatic guidance and access control. As shown in Figure 5-Ea, the system comprises at least three transponders, which have to be installed in fixed locations (on e.g. masts, posts, or walls) around the perimeter of the area that is to be covered, plus moveable base stations, one of which is mounted on each of the mobile objects that is to be tracked [100].



a)

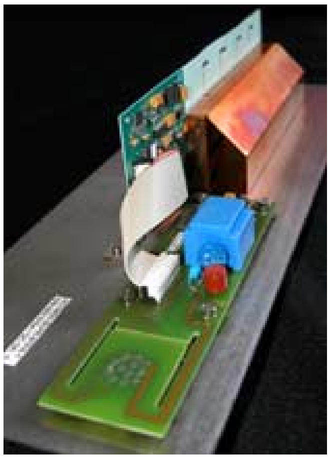

b)

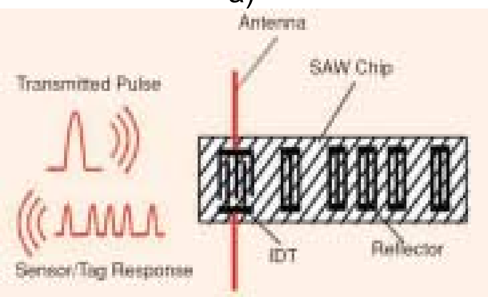
Figure 5-E : a) Functioning principle of the LPR system [101] and b) LPR transponder [102].

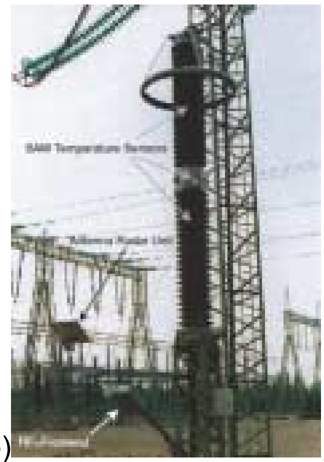
The antenna for the LPR transponder that is shown in Figure 5-Eb are dipole antennas on a curved copper reflector with beamwidths of 160° in azimuth and 10° in elevation [101].

SAW-based radio sensor systems [103]

A schematic drawing of a wireless sensor system is shown in Figure 5-Fa. A high-frequency electromagnetic pulse emitted from an RF transceiver, basically a low-cost radar unit, is received by the antenna of a SAW sensor. A comb-like interdigital transducer is connected to the antenna and transforms the received signal into an acoustic surface wave that propagates along the piezoelectric crystal. The waves partially reflected at some reflecting elements placed within the acoustic path are reconverted into an electromagnetic pulse train by the interdigital transducer (IDT) of the reflective delay line and are retransmitted in the direction of the reader unit. In the RF part, the received signal is amplified and down-converted to the baseband, where delay time, amplitude, and phase response, which are strongly correlated to the sensor effect, are accurately analyzed.

A change in the environmental temperature results in a variation of the path length and a variation of the SAW velocity. Thus, the propagation time τ changes. With a given signal-to-noise ratio and phase resolution of the reader unit, temperature resolution is mainly determined by the maximum reflector distance on the substrate. Generally, a temperature resolution better than 0.1 K can be achieved. The possibility to read out SAW sensors over great distances makes them ideal candidates for high-voltage applications, as isolation problems can be easily avoided. Highvoltage surge arresters protecting expensive high-voltage equipment from excessive overvoltages were successfully equipped with a SAW based temperature monitoring system for longterm measurements (Figure 5-Fb).

a)



b)

c)


Figure 5-F : a) Schematic drawing of a SAW reflective delay line, b) 420 kV surge arrester equipped with a SAW temperature monitoring system, and c) SAW sensor module for pressure measurement mounted on the rim [103].

Contactless slip-ring-free torque measurements can be performed with passive RF SAW torque sensors without the need to break up the driving shaft. SAW torque measurement systems can also operate in industrial environments subject to strong electromagnetic interference thanks to their high operating frequencies of several hundred megahertz up to the gigahertz range and the inherently broadband nature of the SAW sensors. Like resistive strain gauges, SAW sensors measure the torque indirectly by detecting the strain or stress distribution generated by a torque acting on the shaft.

A tire that provides information about its current state will considerably improve drivers' safety as well as vehicle stability. Several battery-powered systems have hitherto been implemented for the measurement of tire pressure. However, they suffer from a limited operating life of the pressure sensor unit due to the extreme environment inside a tire. This problem can be circumvented with passive wireless SAW pressure sensors (Figure 5-Fc) that are read-out by reader units mounted in the wheel arches.

6 ACKNOWLEDGEMENT

The authors would like to thank Dr. Hans-Ludwig Blöcher, and Pascal Hofmann from the DaimlerChrysler Research Center, Ulm, Germany, Dr. Peter Gulden from Siemens CT, Munich, Germany and Dr. Martin Schneider from Robert Bosch GmbH, Germany, for their kind support.

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European Commission - 6th Framework Programme	ACE (Antenna Centre of Excellence)	Information Society Technologies

REVIEW OF STATE-OF-THE-ART IN SPACEBORNE ARRAY ANTENNAS

Institution	Authors
Alcatel Space	Gerard CAILLE

Document Evolution		
Revision	Date	Reason of change
Rev. 1	31/05/2004	First Full Issue (Draft submitted to other ACE partners)
Rev. 2	03/06/2004	Minor updates
Rev. 2T	07/12/2004	Integration within ACE_2.4_Doc-template, to be annexed to A2.4- D1

Table of contents

Table of Figures

1 DOCUMENT PRESENTATION

This document is a Review of the present state-of-the-art in the field of Spaceborne Arrays. It takes into account mainly European realisations:

- directly known by the author (see especially [ref.1] & [ref.2]);
- found in recent Conference proceedings;
- found in some answers to the Array_questionnaire issued within ACE 2.4 activity
- reported in [ref.3] from ESA/ESTEC/Antenna Department (few figures & associated comments copied after agreement from Cyril MANGENOT – ESA/ESTEC/TEC-EEA, associated member to ACE)

But we added some best well-known arrays implemented in U.S. and Japan, mainly in the fields where they appear clearly in advance (main information has then been found in their internet web-site).

We deal mainly with Flight Array Antennas, but also with prototypes when they concern new concepts and appear mature enough to be implemented on Satellites in the next years.

We classified spaceborne arrays:

- at 1st level w.r.t. (with respect to) the type of Systems for which they were designed and implemented;
- secondly w.r.t. the used band, inside the Telecom chapter, because it refers also to different missions, and quite different array sizes.

2 TELECOMMUNICATION SATELLITES

2.1 Low Bands (L/S)

They are devoted mainly to Navigation and to Telecom with Mobiles.

2.1.1 Navigation Satellites

The main on-going programme in Europe is GALILEO. The array antenna must provide a fixed shaped beam (with a higher gain towards the Earth edge, for compensating for the longer range) in 2 subbands, L1 around 1.6 GHz, L2 around 1.2 GHz.

Two designs, developed under ESA contracts during the early program phases, are presented in the 2 following figures:

- Shaped isoflux beam from 24 000 km altitude
- Gain: 15 dBi at +/-12° Edge of coverage
- Dual Band: 1.164-1.300 GHz & 1.559-1.591 GHz
- Circular Polarisation / Axial Ratio: 1.2 dB

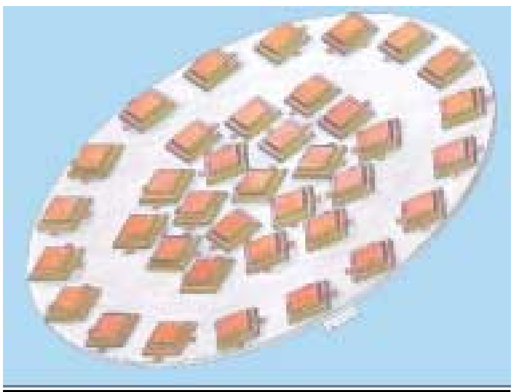


Figure 2.1-a : Galileosat Antenna Array / Alenia Spazio design

Wideband Transmit Antenna SYSTEM (WRAS)

WRAS antenna is an array of stacked photoprinted patches offering high performances, stability and low profile and mass.

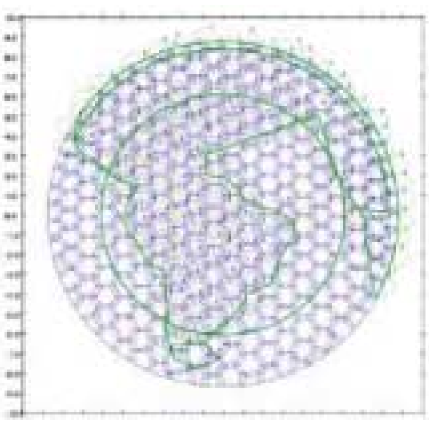
Figure 2.1-b : Galileosat Antenna Array / EADS-CASA Design.

2.1.2 *Telecom with mobiles*

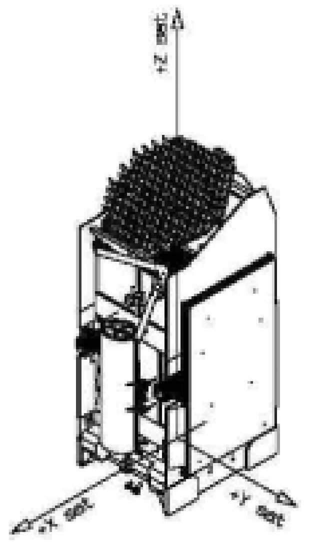
The array concept differs whether Communication goes through GEO (geostationnary), ICO (intermediate circular orbit) or LEO (Low Earth Orbit) satellites.

2.1.2.1 GEO satellites

The most established system is INMARSAT: it provided originally low-rate phone communication on boats, but has also extended its market to big terrestrial vehicles or remote fixed users. The data-rate has been increased in the last generation, and even more the future one. Due to the low gain of antenna users, the required aperture for the on-board antenna is around 10m; this leads naturally to an antenna with an unfurlable reflector (Astromesh provided by TRW). To provide the 19 required beams, Inmarsat 3 already used a semi-active focal array with analog beam-forming; Inmarsat 4, for which Astrium-UK is again the prime contractor, will use a large active focal array (120 helices provided by EMS-Canada) with digital beam-forming and on-board routing:



0.6° spot-beams cover all the Earth (x 2 to 3 satellites on the GEO orbit)



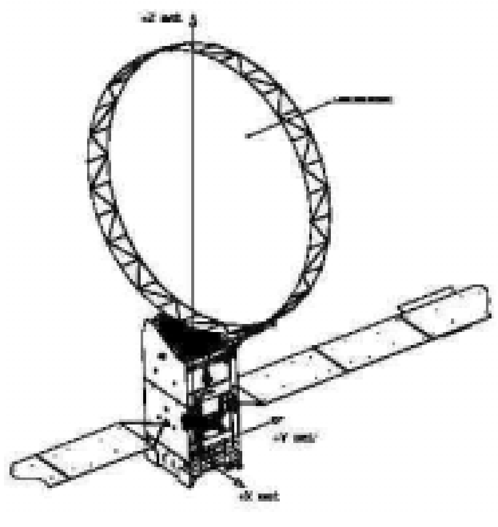
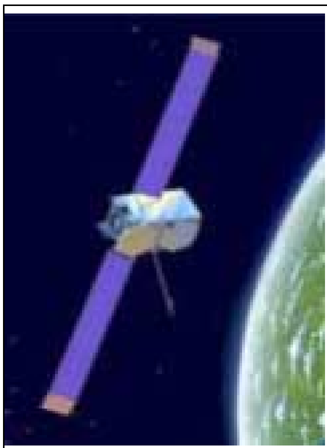


Figure 2.1-c: Inmarsat 4 antenna coverage - satellite with stowed/partially deployed reflector

2.1.2.2 ICO satellites

The ICO constellation will comprise 10 primary satellites and 2 orbiting spares. ICO is managed by Boeing, but the Tx and Rx planar arrays, each with 127 “patch excited cups” (PEC) were built by Saab Ericsson Space. The same industrial sharing was implemented on Thuraya, which is a GEO satellite with a 12m Astromesh reflector, and a focal array of 256 PEC’s.



ICO satellite ↑ (Boeing – USA)

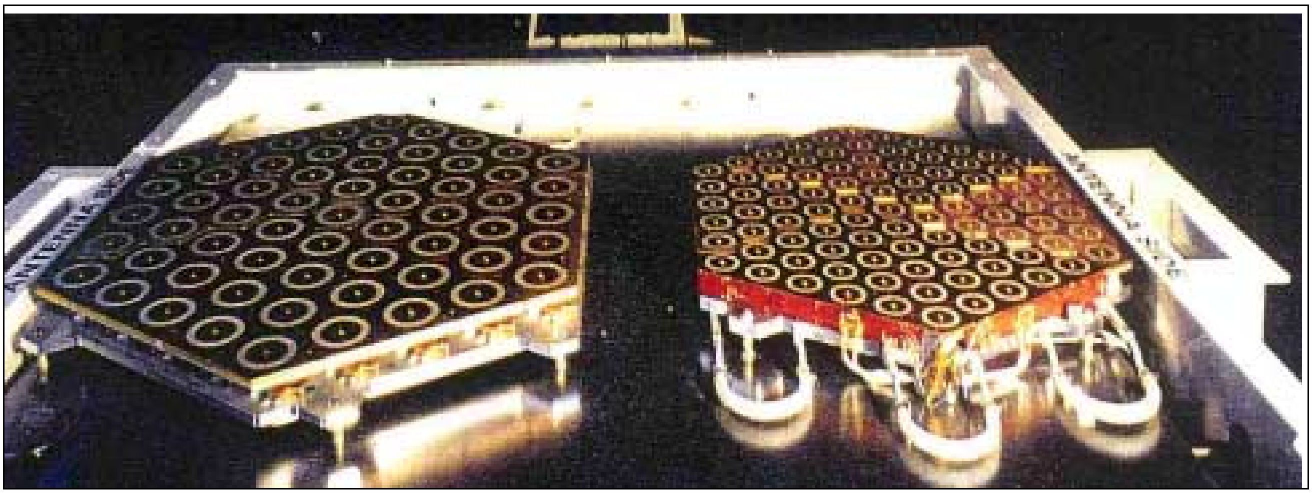
↑ Patch Excited Cup radiating elements, built by Saab Ericsson Space for ICO and Thuraya

← Tx & Rx multi-beam arrays providing 163 simultaneous beams, by digital beam-forming

Figure 2.1-d : a satellite of the ICO constellation, its array antennas and the PEC-type element

2.1.2.3 LEO constellations

The IRIDIUM and GLOBALSTAR programs chose to implement a large constellation of small satellites in LEO orbit. For the latter, the Tx and Rx antennas were 2 DRA (Direct Radiating Arrays), fully active with respectively 61 and 91 RF chains: so the same number of SSPAs / LNAs, and a complex multilayer analog passive BFN, forming 16 fixed beams covering all together the whole Earth viewed as a ± 54° disk



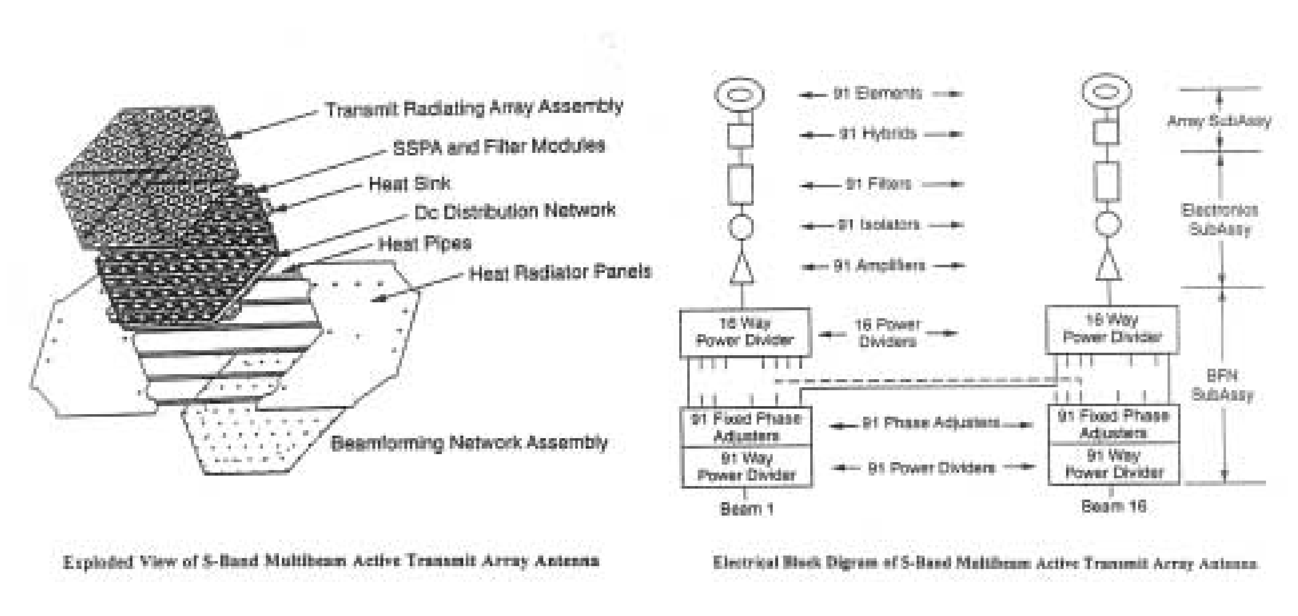


Figure 2.1-e: GLOBALSTAR active antennas manufactured by Alenia Spazio, integrated and tested at payload level by Alcatel Space

2.2 Medium bands (C to Ku)

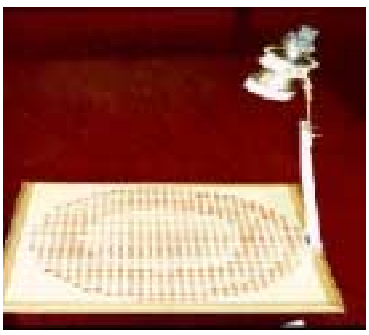
2.2.1 Classical GEO missions

In those bands, the very most satellites use classical reflector antennas, to provide:

- 1 shaped beam, with 1 feed and a reflector with a shaped surface;
- 2 shaped beams in orthogonal linear polarisations, with mostly 2 feeds or feed-clusters and a dual-gridded reflector (each shell reflecting one of the 2 polarisations).
- Possibly multiple fixed beams, with several feeds facing the same parabolic reflector.

But “reflectarrays” have been proposed to replace the quasi-parabolic reflector by a planar array, with printed elements providing the required phase-shifts for:

- compensating for the path-length differences w.r.t. a perfectly focusing parabolic surface;
- and shaping the beam by additional phase-shifts.



Several developments have been made especially by JPL in U.S. to design and implement Reflectarrays for Space applications. Important studies and prototypes have been presented also in Europe. Figure 2.2-a shows a printed Reflectarray composed of two stacked arrays with rectangular patches of variable size designed for dual linear polarisation (ETSI-UPM, Madrid). The capability to match the phase-shifts to quite different laws for each polarisation has been demonstrated.

A reflectarray antenna is a mix between reflector and arrays principles:

- as a space-fed array, it avoids any beam-former

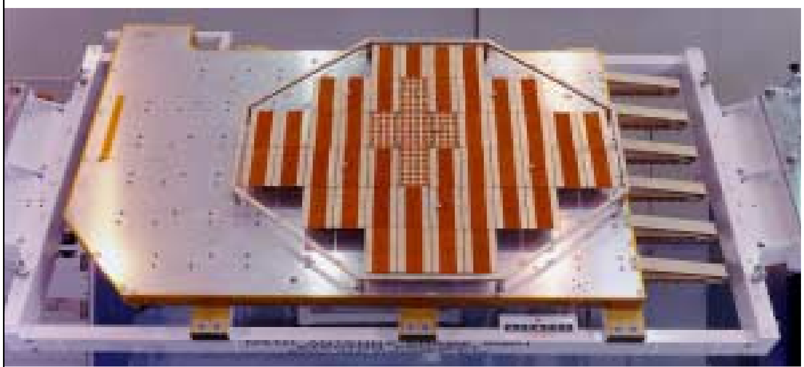
- for passive antennas, the main advantage is to provide shaped beams while avoiding the need of specific molds for each shaped reflector, expensive in Space-qualified technology.
- active versions are under study and prototyping, both in U.S. and Europe: diode or MEMS switches allow to control dynamically the phase-shifts: it may apply both to space Radars and to reconfigurable GEO telecom coverages. Especially in transmit mode, if the phase-shift elements induce very low loss, it appears more power-efficient and less expensive than fully active arrays, because using a single TWT instead of numerous decentralised SSPAs.

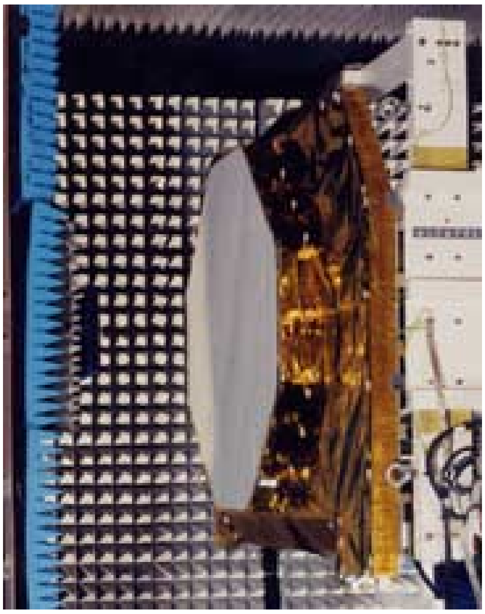
2.2.2 Fully flexible hopping beams

In the frame of the French experimental program STENTOR, a Flight Model of an active array providing 3 beams, independently steered over Europe, has been built by Alcatel Space. It aimed to demonstrate the capability of new telecom missions:

Dual-polarised planar radiating subarray

Partial Qualification Model (only 5 true radiating subarrays)





Flight Model under test in a planar Near Field range

Figure 2.2-b: 3-beams Ku-band Active Array for STENTOR

- either to re-configure a few times the satellite coverage (during a typical 15-year satellite life), for matching to the demand changes: e.g. extension of TV-DBS (Direct Broadcasting from Satellite) over new countries;
- or to provide numerous “hopping” spot-beams time-multiplexed in coherence with the rate of a TDMA frame.

Unfortunately, the STENTOR satellite has been destroyed by a fatal failure of one of the 1st Ariane 5 launchers.

2.2.3 Low Orbit constellations projects

SKYBRIDGE intended to provide “ADSL via satellite” to Users located anywhere around the world, thanks to 80 satellites orbiting around 1400 Km. Each satellite had 18 antennas: each should scan independently wide-band Tx and Rx beams over a ± 53° conical angular range, and continuously re-shape them from 5°-diameter circular footprint at nadir, until a narrow elliptical beam (≈ 0.6° x 4°) when the same footprint came near the Earth edge. The antenna developed by Alcatel Space (with Thales-Fr/UK, Mitsubishi-Japan and Comdev-Canada as sub-contractors) was a mixed array concept, in 2 senses:

- mechanical steering by 2 azimuth/elevation motors / electronic "beam-zooming" with a reduced number of amplitude-phase commands (6 to 8 for 64 patches);
- Tx and Rx panels on the same structure: fully active Rx beam-former based on LNAs + MMIC attenuators/phase-shifters / Tx one based on ferrite variable power dividers, with centralised TWT cooled inside the spacecraft, so not on the "mobile antenna".

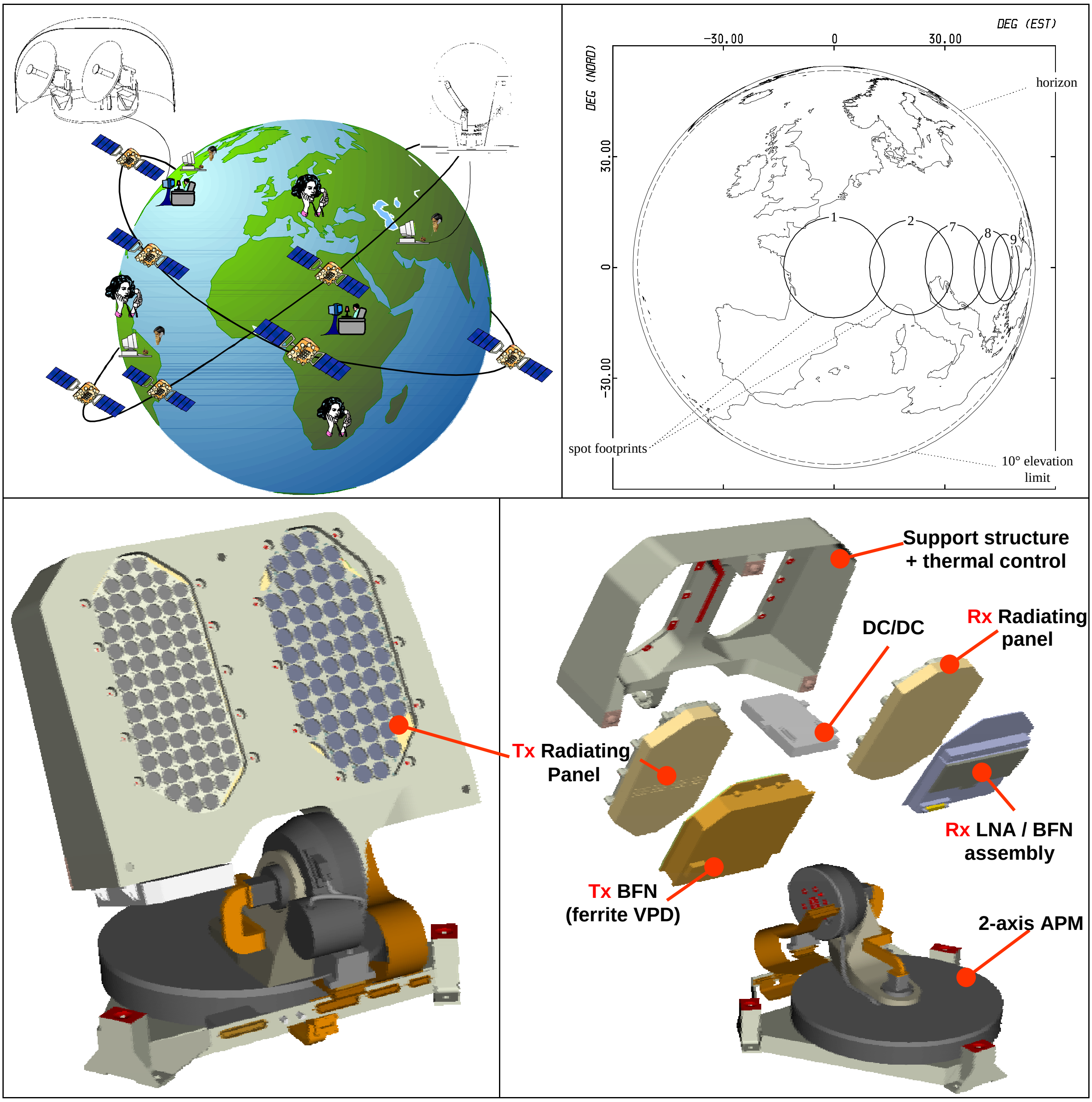


Figure 2.2-c: SKYBRIDGE constellation / example of 5 required beams from a satellite / one of the 18 "mobile mixed antennas" per satellite, which its various parts.

However, all constellations projects, including SKYBRIDGE, were stopped around year 2000, because they had not get the necessary high funding, especially in the period of the "telecom business crisis".

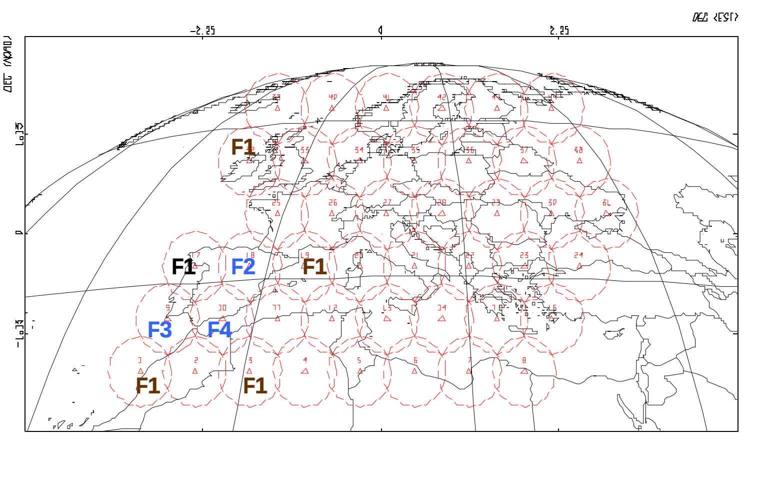
2.2.4 Governmental Communications

All detailed design and hardware is classified as "Defence Confidential", so cannot be described here. We can only say that it is known from specialised newspapers that both in U.S. and in Europe (in France at least), active arrays with anti-jamming capabilities are implemented for protected communication between headquarters and battle-fields wherever in the world.

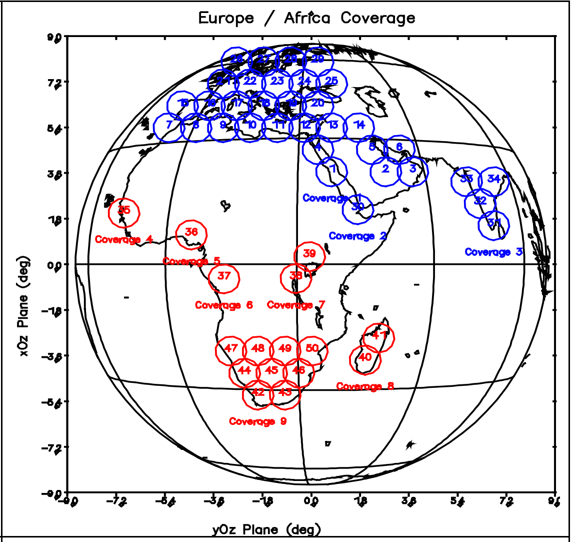
2.3 High frequencies (K/Ka and above)

Many projects to provide "multimedia services" through telecom satellite are on-going, in U.S., Japan and at with less maturity in Europe. Communication uses mainly the 28-30 GHz band for uplink, and 18-21 GHz for downlink. Numerous narrow beams with very high gain are requested, for 2 reasons:

- high data rate per user, while high possible rain-attenuation means stringent link-budget requirements;
- the same sub-band is re-used typically 10 to 16 times, thanks to a [f1,f2,f3,f4] regular pattern: So, for a given allocated band, the data-rate transmitted through the System is multiplied by the same factor, provided that a sufficient isolation is provided by the pattern of each antenna beam towards the next-plus-one beam re-using the same sub-band.



Regional multi-beam coverage with a regular lattice and 1:4 frequency reuse scheme (f1, f2, f3, f4)



Very large coverage with 50 regular / dispersed spot-beams

Figure 2.3-a: typical beams-assembly required by "multimedia via satellite missions"

Such requirement needs 4 different multi-feeds classical reflector antennas, with very fine mechanical pointing, to compensated the spacecraft instabilities. Single antenna solutions, including electronic self-pointing are:

- studied in Europe in the form of Focal Array Fed Reflector (FAFR) antennas, mainly for receive (with analog or digital beam-forming);
- implemented in U.S. and Japan by several companies, in the form of Direct Radiating Arrays, at least in transmit where it presents the main advantage to spread the RF power among numerous RF-paths, and average over all of them the power dedicated to each beam. These developements are descibed in the 3 following paragraphs.

2.3.1 Focal Array fed Reflector *antennas: European prototypes*

A first feasibility study and prototype development was led in 2000-2002 within the IST/MultiKara project: 7 very compact active feeds, each including a redounded LNA connected to a small horn (13mm wide), were built by Saab Ericsson Space (left part of Figure 2.3-b); the whole antenna was specified, integrated and tested by Alcatel Space, proving the possibility to interleave feed-clusters for generating all the beams from a single focal array (right part of the same figure here-below):

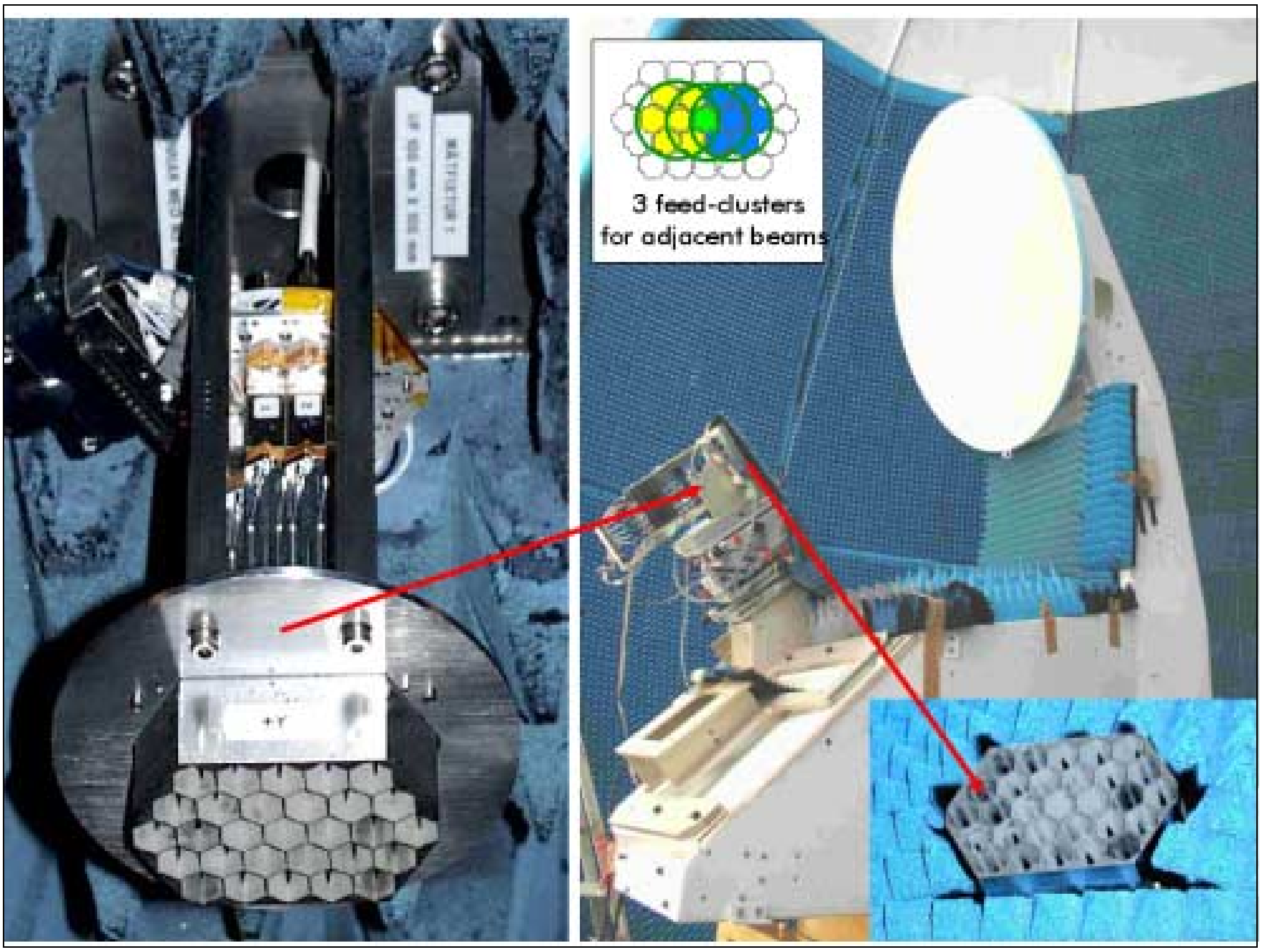


Figure 2.3-b: FAFR partial prototype built by Alcatel Space & Saab Ericsson Space

Further developments are on-going on this concept, especially by Alcatel Space.

2.3.2 SPACEWAY *by Boeing*

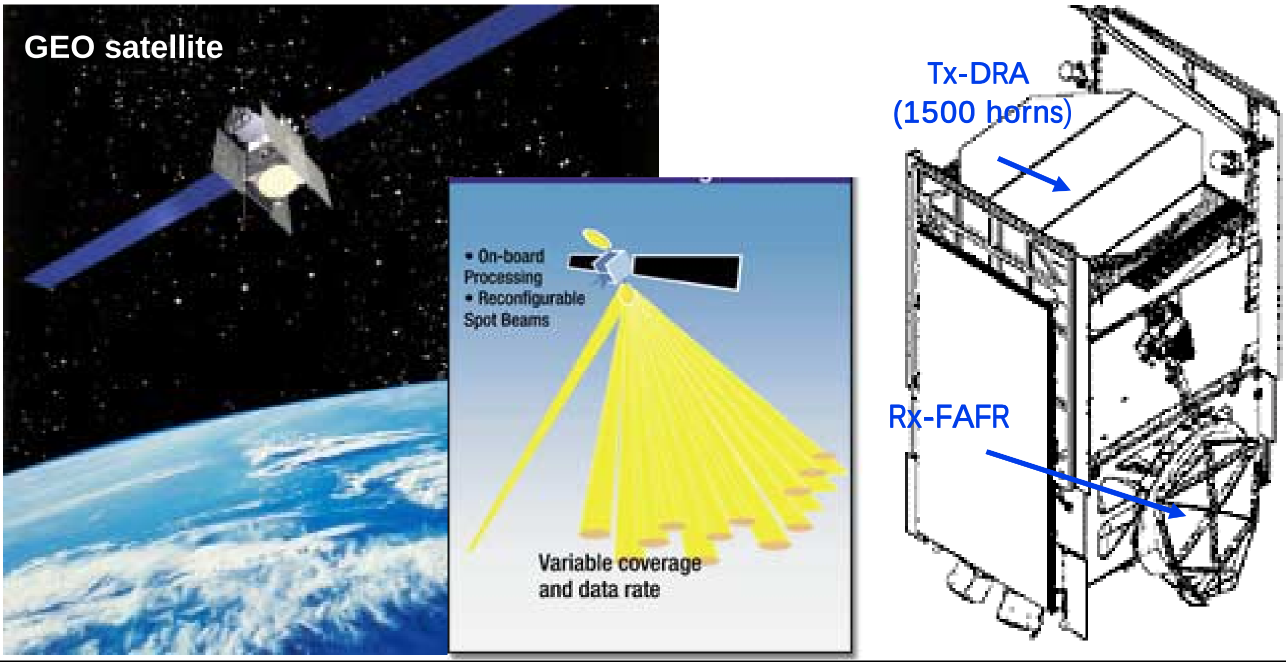
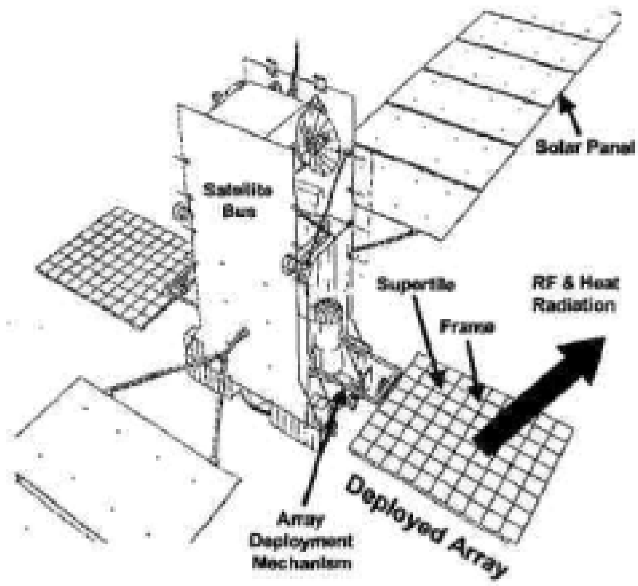


Figure 2.3-c : SPACEWAY Transmit active Antenna

SPACEWAY is a Ka-band next generation broadband satellite network from Boeing that will provide high-speed, two-way communications for Internet, data, voice, video and multimedia applications. The SPACEWAY satellites feature innovative, on-board digital processors, packet switching and spot beam technology. Spot beam technology will enable the satellite to provide services to small terminals, while on-board routers will enable mesh connectivity; users of the system will be able to directly communicate with any other user of the system without requiring connection through a central hub. The transmit antenna system is composed by 1500 element phased array, 2m diameter, forming multiple hopping spot beams.

2.3.3 *Other U.S. "APAA"s*

Lookheed-Martin described in IEEE-A.P. magazine-October 2003 extensive studies of modular Active Phased Array Antennas, dedicated to such missions (or military ones in EHF), using an assembly of identical "self-cooled active tiles", developed at least at prototype level:



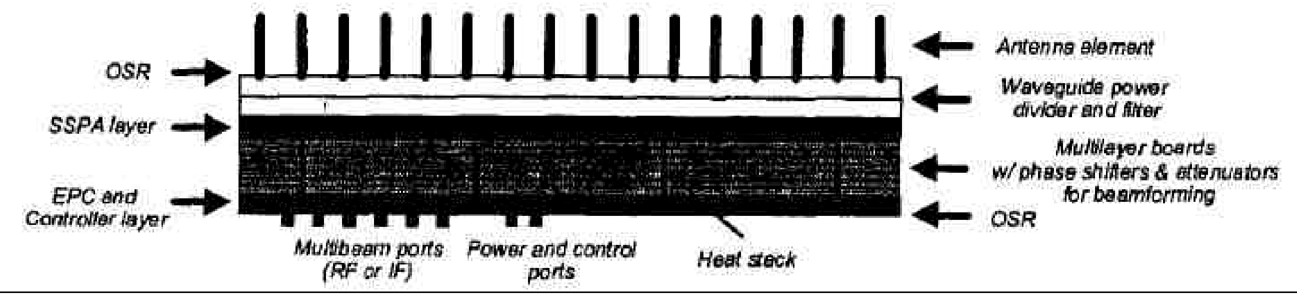


Figure 2.3-d: self-cooled active transmit tiles array by Lookheed-Martin (USA)

Besides, American newspapers announced that Northrop-Grunman has won the contract to deliver the transmit APAA for the next defence communication system using the EHF band.

2.3.4 WINDS *by NASDA (Japan)*

WINDS (Wideband Internetworking engineering test and Demonstration Satellite) is a geostationary orbit NASDA program aiming at conducting various experiments including improving connectivity with internet networks, constructing an information infrastructure for monitoring national lands and disasters, enhancing the field education system and bridging the digital divide. WINDS is a two-ton class communications satellite capable of 1.5 mbps -1.2 gbps uplink (from ground to space) and 155 mbps -1.2 gbps downlink (from space to ground). The satellite will be launched in 2005.

The WINDS project covers development of the following new technological elements that are considered necessary to be put into the practical use around 2010:

1) Multi-beam reflector antenna with Multi-Port Amplifier (MPA). It provides the main coverage sampling Japan by several very narrow beams. The MPA allows to average the Tx-power over all TWTs over this Japan coverage, while compensating for the rain attenuation effects by allocating variable power to each beam.
2) Electronically steerable Active Phased Array Antennas (APAA): In Tx and Rx, they provide 2 independently hopping beams (8-footprint each) scannable over the whole Asia.
3) On-board digital baseband switch. The digital payload can identify and switch the destination of high-speed data transmitted from the ground.

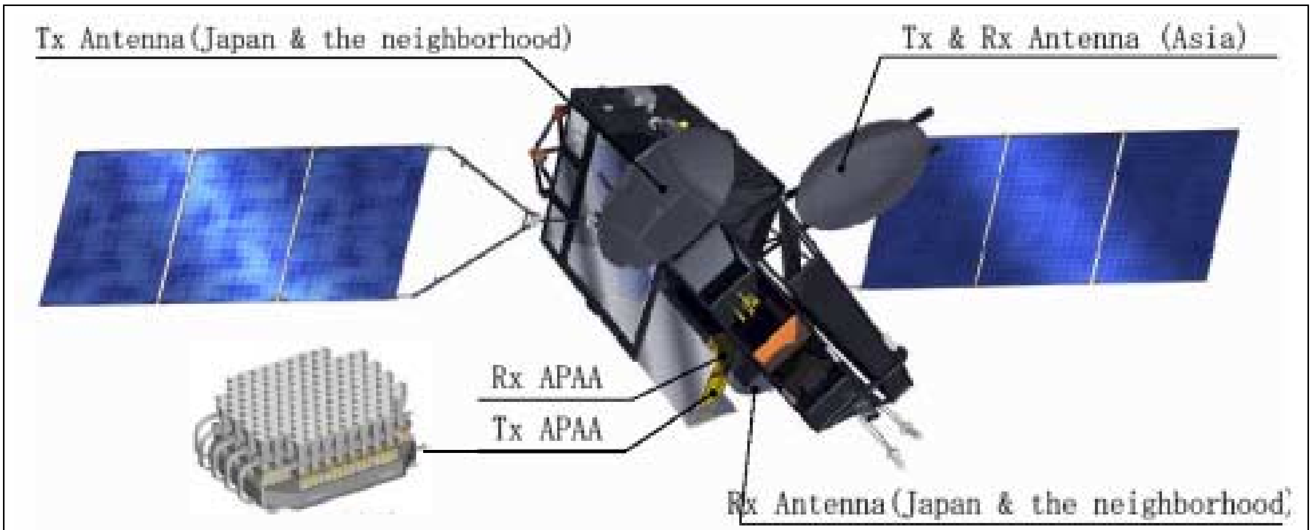


Figure 2.3-e : WINDS Japan wide-band communication satellite

3 Observation & Science Satellites

3.1 Imaging radars (SAR)

The main RF-instruments used on satellites are Synthetic Aperture Radars (SAR) providing precise Earth mapping (e.g. for vegetation and geology monitoring), seas, glaciers and icebergs remote sensing) from a repetitive orbit around 800 Km from the Earth.

A very long antenna is required: in both Observation Satellites managed by ESA, shown on Figure 3.1-a, the SAR antenna appears clearly as the largest ones among numerous other instruments (don't confuse with the solar panels, which present an area of the same order !) .

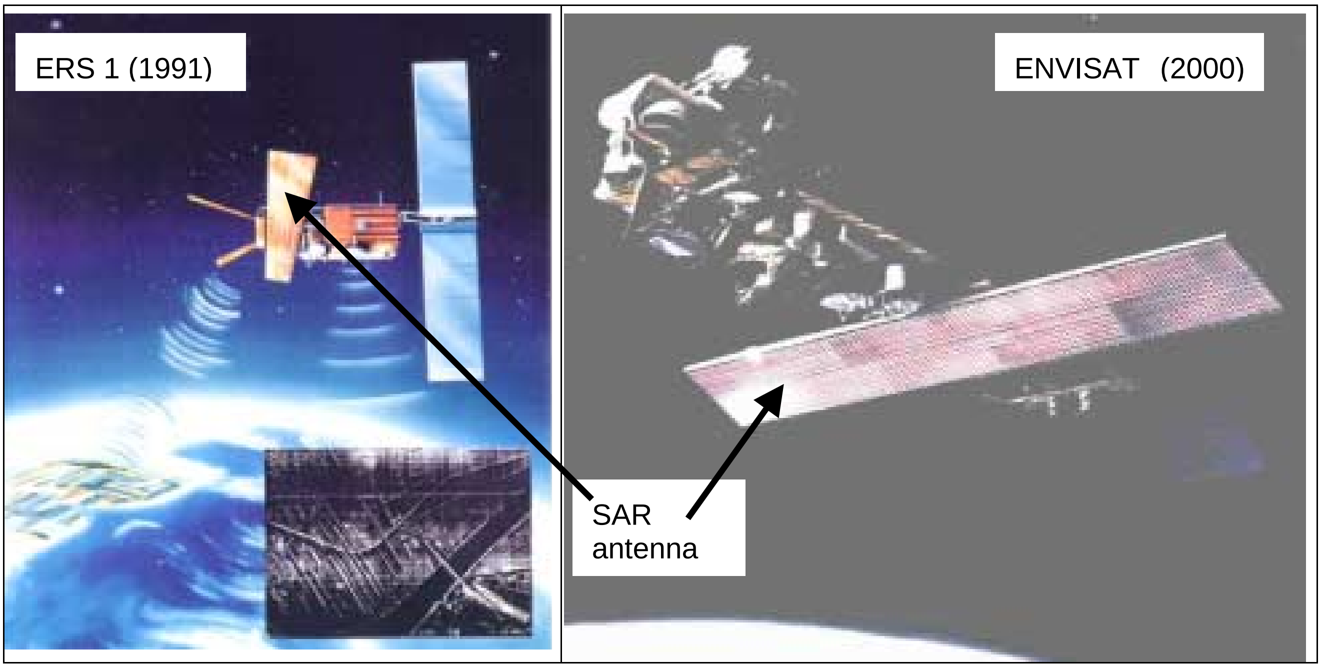


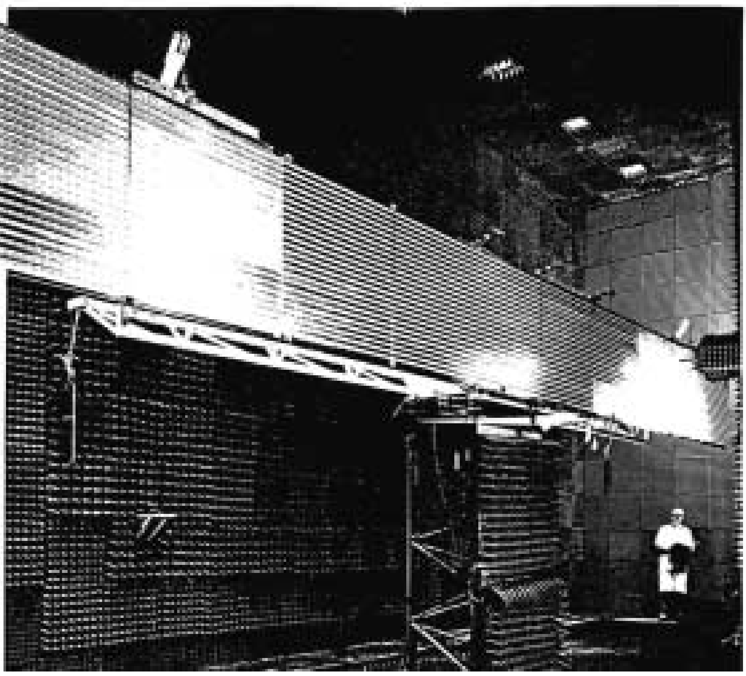
Figure 3.1-a 2 generations of Observation Satellites from ESA : ERS 1 launched in 1991, with a passive light-weight antenna (left) / ENVISAT (2000), with an active antenna (320 T/R modules)

Active antenna options (e.g. ASAR for Envisat) provide electronic scanning in the across-track plane (mostly called *elevation*). Various antenna types have been used in U.S., then Europe and Japan, from the 1st spaceborne US-SAR *Seasat* which flew in 1978, but operated only 3 months because of a failure of the *EPC* (DC/DC converter providing very high bias voltages & currents for the TWTA transmitting several kW during pulses, some tens µs long); some typical ones are described in the following paragraphs, especially those implemented in Europe.

3.1.1 Passive slotted wave-guide arrays

a) The 1st European SAR, *"ERS"* launched in 1992, used a 10m x 1m passive array of slotted wave-guides, featuring a good stiffness with very light weight 83 Kg) and low RF loss, thanks to a whole carbon-fibre structure, including vertical feeding wave-guides, and horizontal radiating ones, all gold-plated inside.

b) More recently, 3 similar slotted wave-guide arrays (but built in aluminium, with internal silver-plating) about 3m x 0.5m large, have been developed by Saab Ericsson Space for the dual-swath wind scatterometer (ASCAT) to fly on METOP:



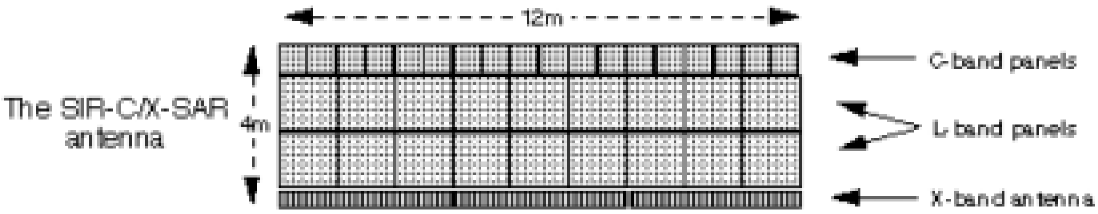
ERS 1 antenna designed by Saab Ericsson Space and manufactured by ex-Dornier (now Astrium-Gmbh)

ASCAT mid-antenna installed on the test range

Figure 3.1-b: slotted waveguide arrays (ERS1-SAR antenna / ASCAT mid-one, both under test at Saab Ericsson Space

3.1.2 Mixed passive/active arrays assembly

The SIR-C / X-SAR was a joint project between US-NASA and German + Italian Space Agencies, which flew on the U.S. Shuttle in the 90'ies:



NASA was in charge of the L & C-band active antennas, providing electronic scanning in elevation, thanks to numerous T/R modules directly connected on the back-side of the horizontal radiating rows (printed subarrays of dual-polarised square patches).

The X-band antenna was passive and single polarised, similar to ERS 1, built by ex-Dornier and Alenia Spazio.

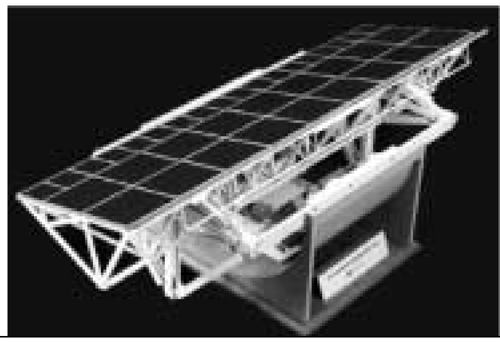


Figure 3.1-c: SIR-C / X-SAR multi-frequency antenna allowing specific Earth/Seas mapping by processing radar echoes received simultaneously in L,C & X bands

3.1.3 Advanced SAR (ASAR) on ENVISAT

Similarly to SIR-C C-band antenna (but for a 5-years mission in orbit, instead of 1to 2 weeks for the U.S. shuttle), this main instrument of the ESA-ENVISAT Earth observation platform, it can transmit & receive alternatively in H or V polarisation, with elevation scanning provided by 320 T/R modules, distributed over 20 identical "tiles".

- the radiating subarrays are annular slots, fed by suspended-stripline H & V networks printed on a lower layer built by ex-CASA (now Astrium-Spain);
- the active tiles, with 16 T/R modules on each, a signal-distribution microstrip network and an in-flight calibration one, were designed, integrated and tested by Alcatel Space;
- Astrium (Fr-Germany-UK) was prime contractor for the platform and for the SAR instrument.

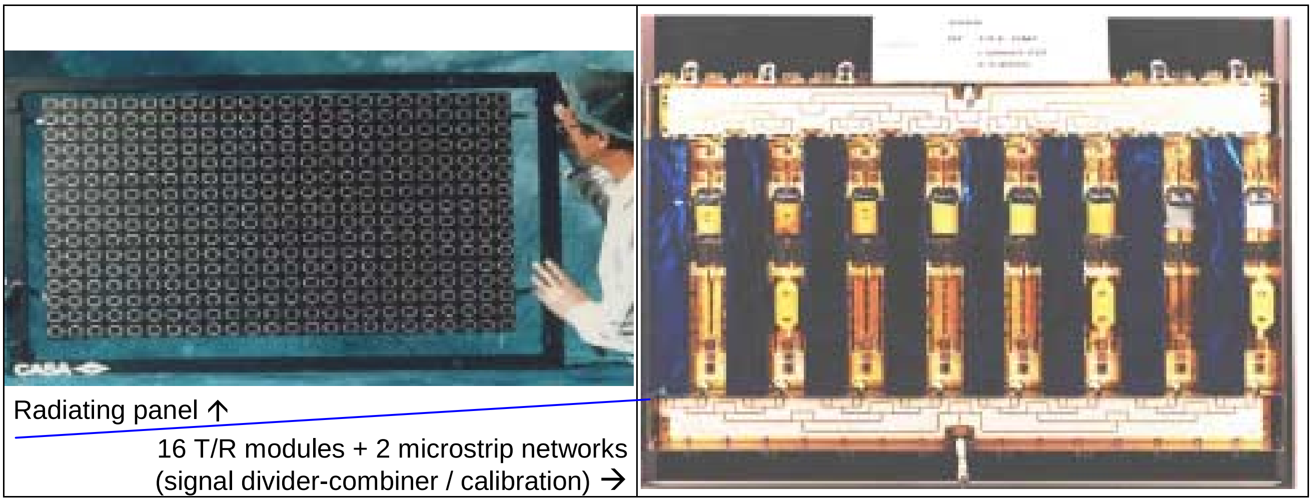


Figure 3.1-d: front and back side of 1 of the 20 active tiles of the 1.3m x 10m ASAR antenna

3.1.4 Japanese ALOS

The Advanced Land Observing Satellite (ALOS) is a Satellite following (JERS-1) and (ADEOS) which will utilize advanced land observing technology, The ALOS will be used for cartography, regional observation, disaster monitoring, and resource surveying. The ALOS embark a Phased Array type L-band Synthetic Aperture Radar (PALSAR) for day-and-night and all-weather land observation. The ALOS will be launched in 2004.

3.2 High data rate Transmission

All satellites dedicated to Observation & Science should transmit to ground stations the registered data, modulating a RF-carrier. This requests an antenna with a directive scanned beam (using the UHF, S, X or Ka band, depending on the amount of transmit rate required) in 2 cases:

- when the spacecraft is spun around a revolution axis, for natural beam scanning of the optical or infra-red instruments: then the data-transmission antenna must be despun, for pointing permanently towards a fixed Earth Station;
- when the satellite rotates in Low Orbit around the Earth, so sees the Ground Stations only during a short time, in a quickly moving geometry.

3 different concepts have been implemented for such missions, in Europe and U.S., presented in the 3 next paragraphs:

3.2.1 Switched cylindrical arrays

Meteo-satellites are placed in GEO orbit and slowly spun around a North/South axis, which makes the infrared sensor beams scan regularly the Earth from East to West or inversely. The 2 transmit antennas are cylindrical; in each, a switching network directs the RF signal towards the radiating elements facing the Earth at a given moment.

Figure 3.2-a :
UHF & S-band switched cylindrical arrays for the electronically de-spun (100 rpm) antenna of Meteosat Second Generation (MSG).

3.2.2 Planar fully active arrays

NASA X-Band Phased Array Antenna (XPAA)

The New Millennium Program's Earth Observing-1 (EO-1) mission is providing for the on-orbit demonstration of a high data rate, low mass XPAA for down-linking imaged data from the EO-1 solid state recorder. The XPAA offers significant benefits over current mechanically pointed parabolic antennas, including the elimination of deployable structures, moving parts, and the torque disturbances that moving antennas impart to the spacecraft.

The XPAA is composed of a flat grid of 64 radiating elements combined with low power, high efficiency solid-state amplifiers to achieve the required radio frequency power level. The antenna is mounted on the Earth-facing side of the spacecraft. The antenna's mass is 5.5 kilograms. It has an Effective Isotropic Radiated Power (EIRP) of approximately 160 watts, and transmits data at 105 megabits per second. Boeing Phantom Works, located in Seattle, WA, developed the antenna for GSFC.

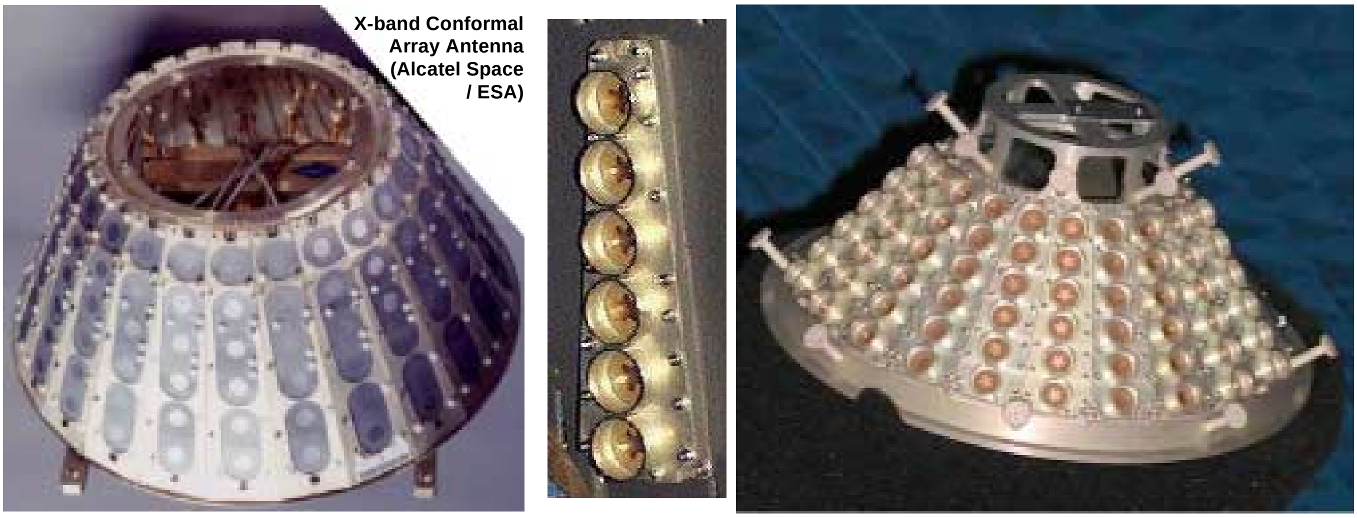
3.2.3 Truncated-conical semi-active arrays

This antenna-type is optimised to provide maximum gain for an off-axis angle θ from 40° to 70° (nearly perpendicular to the truncated cone generatrix). Besides the number of active modules is drastically reduced by controlling amplitude and phase of the excitation coefficients only at “column-subarray” level (each aligned along a cone generatrix): so only 24 control points instead of 144 patches in the presented figures.

- The beam is rotated around the revolution axis by matched amplitude/phase control at subarrays level, transformed from phase-only control through a set of quasi-Butler matrices. So the 24 SSPAs located before the matrices transmit all and always the same power: this maximises the DC-to-RF efficiency.

- The subarray pattern is optimised (via the network feeding the 6 patches) for each mission w.r.t. the exact template of the gain variation versus θ. Radiation from the concerned subarrays are put in-phase towards the required direction, so that the overall gain is equal to:
  (gain from circular array factor) x (sampled subarray pattern)

This concept has been applied successively to various missions with a large axi-symmetric scanning range, by teams led by Alcatel Space, under ESA contracts (1/ with CASA and EPFL; 2/ with TILAB for waveguide Butler-like matrices)



Option 1: antenna for Tx from LEO satellites   Option 2: antenna for Tx from a spun satellite at L2 Lagrange p^t

Figure 3.2-b: Conformal antennas built from patch-subarrays for full-turn azimuth scanning + 20° to 70° from axis in elevation

4 REFERENCES

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- [ref.2] “Space telecom Antennas with numerous beams for high gain with frequency re-use”, presentation by G.Caille in the Special Session at JINA-2002.
- [ref.3] “Arrays & Radiators Dossier”: Technical Note by G.Toso, C.Mangenot and others from ESTEC/TEC-EEA ; extracts from part 2 “Past Activities and Current Status”.

European Commission - 6th Framework Programme	ACE (Antenna Centre of Excellence)	Information Society Technologies

REVIEW OF STATE-OF-THE-ART IN DEFENCE RADAR APPLICATIONS

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Document Evolution		
Revision	Date	Reason of change
Rev. 0	7/6/2004	Draft
Rev. 1	14/6/2004	Assembly of the FOI/TNO-FEL draft contributions
Rev. 2	20/9/2004	Adding new system descriptions from FOI and TNO-FEL
Rev. 3	28/9/2004	Adding new system descriptions from FOI and TNO-FEL
Rev. 4T	20/12/2004	Taken off "Draft Version"; update of the entitle & style in compliance with ACE_2.4_Doc-template, to be annexed to Deliverable A2.4-D1

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1 INTRODUCTION ON DEFENCE RADAR SYSTEMS

In this document we present a review of the state-of-the-art in nowadays defence radar systems as well as proposed future defence radar systems. The description of the radar systems for several applications developed by the many different nations, are assembled to present an as complete as possible portfolio. We distinguish between Naval, Airborne and Ground-based applications. The effort of writing this review has been split into contributions from FOI and TNO-FEL. The Air Based Radar systems are covered by FOI whereas the Naval systems are described by TNO-FEL, a joint effort is performed on the Land Based Radar systems.

2 NAVAL SYSTEMS

2.1 Introduction

Naval forces and the national security of coastal countries face many tasks concerning the naval battlefield and effective border control: anti-surface warfare, anti-submarine warfare and anti-air warfare including anti-ship missile defence are tasks facing the naval forces that have to be met even under difficult conditions. In this chapter we will focus on actual radar systems worldwide that are in use or are going to be in use by the different nations to accomplish those tasks.

2.2 ARABEL (France)

The ARABEL radar is devoted to medium range search, acquisition, tracking and missile data transmission. The two dimensional antenna uses backward scanning for fast track acquisition and to monitor time sharing between functions. The antenna comprises a monopulse multi-horn source and a lens implemented with an array of diode phase shifters. Tilted in elevation, the lens authorizes elevation scanning up to zenith and azimuth back scans up to 60 degrees. The very short switching time of the diode phase shifter facilitates resources time sharing between functions. Working at I- to J-band, the lens enables frequency hopping over a 10% bandwidth for a 2 degrees pencil beam. The radar can track 50 targets up to a 70 km range (target 2 m^2), and has provision for 16 missile guidance channels. It is part of a medium range air-defence weapon system.

Figure 2.2-a: ARABEL (Thales France), a multifunction radar.

Category
- I- to J-band, TWT source, wide bandwidth

Capabilities
- Simultaneous target detection, multiple target tracking and missile up-link

Antenna
- Rotating phased-array antenna (60 rpm)
- Full electronic scanning, with large deflection (+/- 45° in elevation and bearing)
- Narrow beam, very low side lobe level

Transmitter
- Frequency-agile, variable pulse width

Receiver
- Advanced doppler, pulse compression, mono-pulse (tracking powerful and fast radar management computer

Other features
- Built-in test equipment (BITE)
- Provision for IFF/NIS integration
- Maximized ECCM capabilities through combined design features and specific techniques

Multiple tracking >100 tracks Multiple engagement Up to 10 simultaneous targets Reaction time
- A few seconds from first autonomous detection of target to firing of first missile.

X-band radar, Tx beamforming: space fed, rotating antenna structure, direction finding via monopulse, single antenna face. Arabel is a 3D multifunction radar for antimissile self-defence of major vessels. System is capable of three dimensional surveillance, full azimuthal coverage and 90 degrees in elevation. Tracking can be performed of more than 130 targets including up-link to in-flight missiles.

Ref: J.-M. Colin: 'Phased Array Radars in France: Present & Future', IEEE Int. Symp. on Phased Array Systems and Technology', Boston, MA, 15-18 Oct., 1996.

2.3 APAR

At the end of last century the Royal Netherlands Navy replaced the Guided Weapon frigates by the new Air Defence and Command Frigates (ADCFs). In 1991 the Royal Netherlands Navy asked the TNO Physics and Electronics Laboratory (TNO-FEL) for assistance in studying the air defence configuration for the ADCF. This configuration includes systems like Evolved SeaSparrow Missile and Standard Missile 2 centered around APAR (Active Phased Array Radar), and the Goalkeeper close in weapon system. APAR is a unique type of Multi Function Radar and is the result of a tri-national development, under Thales Nederland prime contractorship, involving governments and industries from the Netherlands, Germany and Canada. APAR is an I/J-band Active Phased Array Radar providing the multifunction capabilities required for the modern missile threat. This includes target detection, tracking, multiple missile control based on mid-course guidance and terminal homing and destruction assessment. CW generation and illumination is a built-in feature of the APAR system. The 3424 T/R elements in every single face provide a powerful and redundant system architecture. The complete APAR multifunction radar consists of 4 faces covering 360 degrees of possible threat, each face covers approximately a sector of 100 degrees. 200 possible targets can be handed to the APAR radar which combines the functions of the WM-25 (fire control) and SPG-51 (tracking/illumination) radar's with a limited volume-search capability. Each face of the APAR radar can simultaneously provide up to 4 illumination beams for missile guidance, for a total of 16 simultaneous illumination beams. The radar's bandwidth is to be 30% and its scan ±60 degrees.

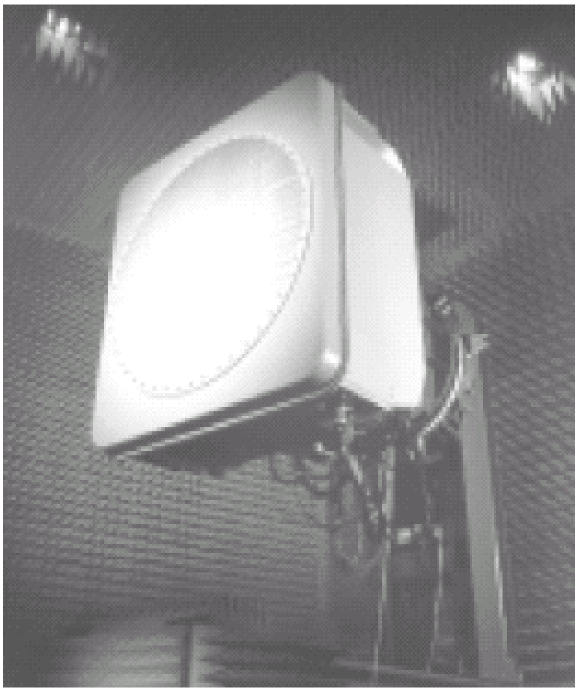

Figure 2.3-a: Weapon Control system. APAR search/track/fire control radar. One of the four array phases of the Active Phases Array Radar, inside are all the transmit and receive electronics (courtesy of Thales Naval Systems Netherlands, TNNL).

Figure 2.3-b: APAR mounted on ship. The polygonal tower contains all four array faces.

The antenna consists of active radiators, "active" here means that the radiated power is generated in the radiator module. The receive function is integrated with this design, the full radar has other system components for signal processing and management.
The development of a smaller version of a lighter version of APAR, using similar technology and system architecture for the use on smaller vessels is foreseen. It is designed to match the capabilities of the NATO Evolved SeaSparrow Missile (ESSM).

Ref: A. B. Smolders: 'Design and Construction of a Broadband Wide-Scan Angle Phased Array Antenna with 4096 Radiating Elements', IEEE Int. Symp. on Phased Array Systems and Technology, Boston, MA, Oct. 15-18, 1996.
Ref: http://www.thales-naval.nl/activities/radar-sys/surveillance/surveillance.htm.
Ref: Jane's Navy International, March 1996, pp. 6
Ref: Journal of Electronic Defence, May 03, pp. 55-62

2.4 SMART-L

SMART-L (Signaal (now Thales Naval Systems Netherlands) Multibeam Acquisition Radar for Targeting) is a 3D multibeam radar system for long-range surveillance in D-band. It provides a coverage of 400 km radius and it is able to cover up to 70° of elevation. State-of-the-art technology in combination with refined signal processing guarantees excellent performance, especially against stealthy targets. Also this radar provides anti-ballistic missile defence capabilities.
The SMART-L radar performs the volume search function and can track over 1,000 possible targets. Digital beamforming is used for this deployed 3D stacked beam radar, only on receive. The antenna consists of 24 rows. The signal from each row is down converted and pulse compressed with SAW lines and then A/D converted with 12-bit 20MHz Analog Devices A/D's. The signal is then modulated onto an optica signal and passed down through a fiber optic rotary joint to a digital beamformer where 14 beams are formed.

Figure 2.4-a: SMART-L, Thales Naval Systems Netherlands, TNNL.

Ref: Brookner, Plenary Paper, 2000

2.5 SMART-S

Surveillance system.
SMART-S is a 3D multi-beam F-band medium-to-long range surveillance and target indication radar operating to a range of 120km.

SMART-S Mk2 is the latest member of the Thales Naval Nederland (TNNL) 3D multi-beam family, of which nearly 70 systems have been sold world-wide and which comprises also the well-known SMART-S, SMART-L and MW08 systems.

The SMART-S Mk2 has full 3D coverage up to 70 degrees elevation and two operating modes (13.5 / 27 rpm) with 250/150 km range respectively. SMART-S Mk2 is optimized for medium-to-long range surveillance and target designation in complex environments such as the littorals with its mix of sea, land, islands, coastal rain and thunderstorms and multiple radar targets, including small surface targets, helicopters and anti-ship missiles. The range performance is matched with the requirements for modern AAW defence missile systems such as the Evolved SeaSparrow Missile (ESSM).

Figure 2.5-a: SMART-S mounted in the mast of the RNLN Frigate Karel Doorman.

The combination of SMART-S Mk2 and the Thales SEAPAR Multi-Function Radar generates a powerful AAW sensor weapon suite for ship types such as corvettes and frigates. Its dedicated helicopter and short-range capabilities allow SMART-S Mk2 to be the perfect sensor candidate for helicopter-carrying amphibious ships, LPDs or even small aircraft carriers.

SMART-S Mk2 has been designed for a minimum of maintenance. Its lightweight electronically stabilized antenna, absence of waveguides and small below-deck footprint facilitate the easy installation on board of a ship.

Maintenance-free mission capability is ensured by the application of solid-state transmitter technology and parallel processes. Any repairs will be performed by the replacement of LRUs. All these features make SMART-S Mk2 the most modern, flexible and reliable 3D radar system of choice for littoral operations.

2.6 HERAKLES

Multifuntion 3D primary surveillance and fire control radar integrated by Thales Naval Systems France (TNF).
"For self- defence, extended self- defence and the establishment of the medium- to long- range situation of vessels, Thales has developed the Herakles multifunction radar. HERAKLES is designed to equip frigates as the sole radar on board and can be associated to all types of active or semiactive homing missiles. Establishment of the 3D air, jamming and surface situation, missile detection (SSM and ARM) and weapon deployment (missiles and guns) are performed concurrently. The radar's antenna consists of a 3 meter diameter lens array of sandwich construction, built and tested at Thales Naval Systems Netherlands (TNNL), and a total of 1.761 phase shifters mounted on multifunction carriers. All wiring is on printed boards for cost reduction.
HERAKLES is a rotating passive phased array radar operating at S-band, the antenna mount's dimensions are 4.6x3.8x4 meter spinning around at 1 Hz. The performed integration by TNF includes the antenna, rotating structure, solid-state transmitter and other electronics. HERAKLES is a possible candidate for selection as the MFR for the French Navy's proposed 17-ship FMM multimission frigate program. The radar would be able to provide wide-area surveillance out to 200 km and local area defence coverage out to 80 km, if necessary simultaneously. Up to 200 air and 200 surface tracks are said to be managed by the system simultaneously. Electronic beam steering is possible up to 70 degrees, four independent reception channels can be used, operating up to four beams concurrently.

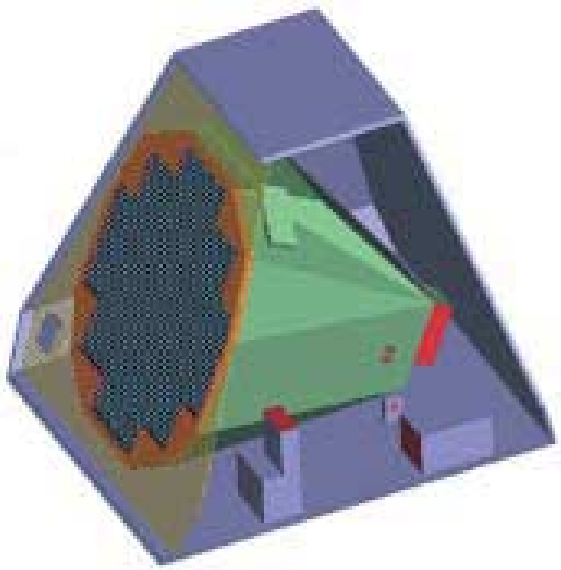

Figure 2.6-a: HERAKLES system (Thales Naval Systems France and Netherlands).

- Frequency band: E/F
- Peak Power: 50 kW
- Number of phase shifters: 1761 / face
- Number of faces: 1
- Aperture size: 3 m diameter
- Rotation: 60 rpm
- Weight: 3500 kg
- Manufacturer: TAD/ TNNL

Ref: Jane's International Defence Review, December 2002.
Ref: Signalen, dertiende jaargang februari 2002, pp 10 - 11

2.7 EMPAR

EMPAR (European Multi-function Phased Array Radar) operates at C-band performing concurrently 3D detection, multiple target tracking and missile guiding, TWT driven. Designed to be fitted on board medium and large tonnage vessels playing role of principal ship sensor.
G-band multi-function phased array radar. Multi-function capability provides simultaneous surveillance, tracking and weapons control. EMPAR is the primary sensor in the FSAF/SAAM-IT and PAAMS (FR/IT) missile system.
The system is a rotating phased array antenna radar which uses single pencil beam in transmission and multiple beams in reception. Each beam can be steered, within a wide angular sector, along any bearing and elevation direction with respect to the antenna broadside resulting in whole hemisphere coverage.

In 1986 a passive multifunction (search & track) phased array radar with a single rotating antenna was envisaged. An important requirement of the contract was the design of a lightweight antenna, suitable for installation on small / medium size ships (corvettes / frigates). The C band was selected as the best compromise to perform search & track in the context of a lightweight solution. After development and factory acceptance, the radar was installed on the Italian ship “Carabiniere” and was tested, with full success, by an exhaustive validation campaign. Subsequently, the Italian and French Customers agreed on a common development for a point defence naval system in the context of the FSAF programme. An updated version of EMPAR was considered the ideal candidate for the role of multifunction radar in the naval FSAF scenario. The integration of the radar with the Aster missile was performed within the phase 1 of the programme and currently, the radar is integrated in the whole defence system (radar, missile, C^2) on the *Carabiniere* ship.

The phase 2 of the FSAF programme, started on 1997, has included many modifications to the radar like: significant improvement of ECCM capability, improvement of availability, further reduction of antenna weight and dimensions. In addition, the evolution of the design has taken into account the requirement for local and medium area defence concept (PAAMS requirements).

EMPAR consists of a passive full filled “single-face” phased-array antenna with 2160 radiating elements arranged on a triangular lattice; it radiates one transmitter narrow pencil beam, four high gain receiving beams (one sum, two difference and a double difference) and low gain auxiliaries. The antenna rotates to achieve full azimuth coverage, and the beams are electronically steered to provide pitch and roll compensation while maintaining a wide scan angle capability (±45° in azimuth and ±60° in elevation). Antenna radiating elements are open waveguides optimised to reduce the scan-off losses. Each radiating element is fed by a pin-diode 4-bit phase shifter with integrated drivers. The beam forming, a corporate network, is made by a constrained wave guide Blass matrix providing element amplitude and phase tapering; dip brazing technology is exploited. The corporate design permits the full control of the RF distribution, with independent optimisation of sum and difference beams: very good performance are achieved in terms of antenna side lobes and mono pulse angle measurement accuracy independently of the radiated frequency. The radiators are positioned along 64 row planks. Each plank is made by an extruded mechanical cold plate housing phase shifter modules both on the lower and upper sides. The row plank provides the connection between the horizontal beam forming and the radiating elements, allowing phase shifter control for beam steering. The cabling for phase shifter power supply line and control signals is realized by a multi-layer printed rigid circuit. The cooling water flows through each extrusion and the rotary joint up to heat exchanger. Quick hydraulic connectors on the side of each cold plate allow easy removal of row planks with cold plates, thus permitting access to the phase shifters for maintenance.

The antenna control logic receives the synthetic beam steering commands from the below-deck radar management computer, then it computes the corresponding phase control values necessary for the array and distributes these phase values to each phase shifter. Suitable timing signals allow synchronised execution of beam steering commands.

The rotary joint is a high precision device with one RF power channel, several receiving IF channels, and water channel for antenna cooling. The RF power is provided by a TWT transmitter. The echo signals are collected into a multi-channel receiver, processed by an adaptive array signal processor and a management computer, to perform: adaptive jammer suppression, clutter cancellation, CFAR target detection, target position measurement, target tracking and environment analysis. Main lobe and side lobe jammer suppression is performed by suitable adaptive combination of the signals received by the high gain and low gain beams. The real-time radar management computer provides multi-task capability. The computer manages the radar resources (time and energy) adaptively to the operational environment and to the radar status, in order to optimise the performance in a wide spectrum of operational conditions. The signal processor is a programmable architecture based on COTS components. This allows high flexibility and reconfiguration capability.

Multifunction capabilities:
- Full volumetric search coverage;
- Low altitude and surface search;
- Multiple target tracking;
- Up-link transmission when needed for missile guidance.

Main features:
- Confirmation on Detection
- Initial Threat Evaluation and Support to System Kill Assessment
- Clutter and Jammer analysis and mapping
- Passive Track on Jammer and Burnthrough
- Main Beam Cancellation (MBC) for Continuous Jamming
- Sidelobe Cancellation (SLC) for Continuous Jamming
- Sidelobe Blanking (SLB) for Pulsed Jamming and Point Source Clutter Cancellation
- Advanced Anti Multipath Techniques
- Equipment Redundancy, Fault Tolerance and Graceful Degradation
- Equipment Monitoring and Automatic Reconfiguration

Figure 2.7-a: EMPAR System on the left (phase 2) and mounted inside a radome on the Italian ship Carabiniere. Alenia Marconi Systems, Italy.

C-band antenna, Tx beamforming via constrained feed, rotating antenna structure, direction finding via monopulse, single face.

Figure 2.7-b: EMPAR, Alenia Marconi Systems.

Antenna

- Rotating phased-array antenna (60 rpm)
- Electronic beam forming in bearing and elevation
- Narrow beam, very low side lobes
- Side lobe blanking and jammer mapping

Transmitter

- Frequency-agile, wave form adaptation

Receiver

- Advanced doppler, pulse compression, mono-pulse

Other features

- Built-in test equipment (BITE)
- Provision for IFF/NIS integration multiple tracking up to 300 tracks multiple engagement up to 12 simultaneous targets.

General:

- Frequency band: 5.6 GHz
- Number of modules: 2160
- Number of faces: 1
- Power: 120 kW
- Beamwidth: 2.6°
- Manufacturer: AMS

Ref: DefenceNews, p12, September 10-16, 2001

Ref: Journal of Electronic Defence, May 03, pp. 55-62

Ref: M. Cicolani, A. Farina, E. Giaccari, F. Madia, R. Ronconi, S. Sabatini: 'Some phased array systems and technologies in AMS', IEEE Proc. Int. Symp. on Phased Array Systems and Technology, Boston MA, 2003.

2.8 COBRA JUDY

The COBRA JUDY System is a deployed and operational data collection sensor that consists of an S-band phased array and an X-band dish radar. The radars are permanently mounted aboard a U.S. Navy Ship, the USNS Observation Island. The system's primary mission is to collect precise data against strategic ballistic missiles to verify several United States arms control treaties. A secondary mission is to collect data for United States missile development and theater missile defence systems testing. The system is capable of worldwide deployment.

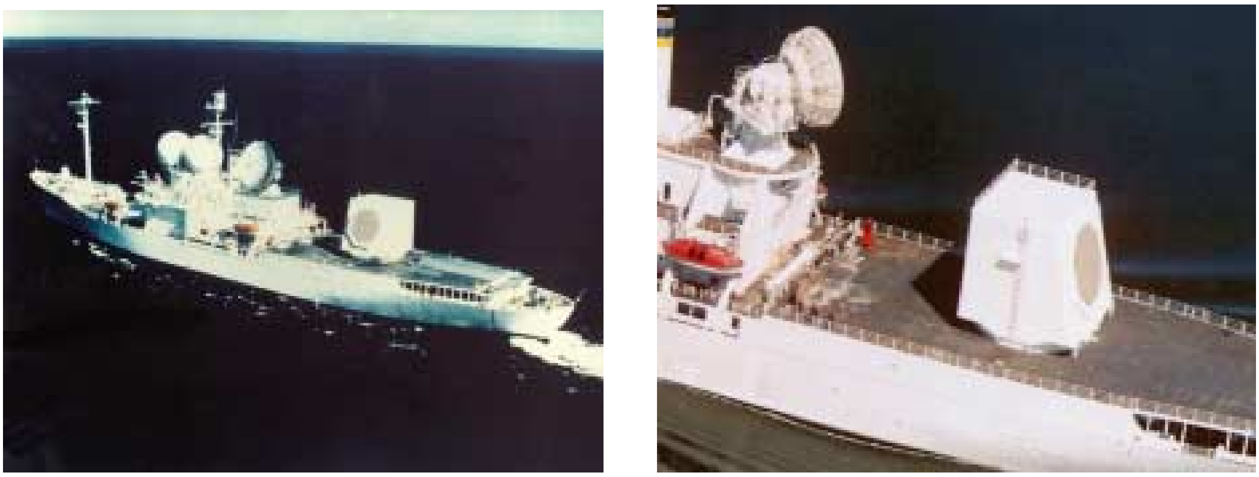

Figure 2.8-a: X-band dish antenna and the S-band phased array antenna system mounted on the USNS Observation Island.

The AN/SPQ-11 shipborne phased array radar is designed to detect and track ICBM's launched by Russia in their west-to-east missile range. The Cobra Judy operates in the the 2900-3100 MHz band. The octagonal S-band array, composed of 12 288 antenna elements, forms a large octagonal structure approximately 7 m in diameter. and is integrated into a mechanically rotated steel turret. The entire system weighs about 250 tonnes, stands over forty feet high. In 1985 Raytheon installed an 9-GHz X-band radar, using a parabolic dish antenna to complement the S-band phased array system. The five story X-band dish antenna is installed aft of the ship's funnel and forward of the phased array. The X-band upgrade was intended to improve the system's ability to collect intelligence data on the terminal phase of ballistic missile tests, since operation in X-band offers a better degree of resolution and target separation.

Description:

- The system collects dual frequency (S- and X-band), high precision metric and signature data on targets of interest. The S-band radar uses a mission profile to perform surveillance (target detection and acquisition), tracking, object classification, and wide or narrow band data collection. A wide repertoire of transmitter waveforms is available to aid in target discrimination and analysis. The X-band radar can perform wide band data collection on manually designated objects from the S-band radar.
- The S-band phased array consists of 12,288 active independent antenna elements. The S-band radar has a 45-degree maximum instantaneous field of view. The phased array is mounted in one face of a nearly cubical (30-foot) rotating turret that houses the transmitter, microwave circuits, and the inertial navigation unit. The S-band transmitter is composed of 16 broadband Traveling Wave Tube (TWT) power amplifiers.
- The X-band radar is composed of a 30 foot parabolic dish, horn and subreflector mounted on a pedestal. Some of the X-band electronics, including the TWT Power amplifiers, are in the on-mount room and are fed by flexible cables from equipment located on a lower deck of the ship.
- The S-band and X-band radars are controlled by a single CYBER 170 mainframe computer system. A second CYBER is available as backup. The CYBERs are of 1973 vintage. To ensure future system sustainability and maintainability, much of COBRA JUDY's data processing and RF subsystem equipment is scheduled to be replaced with modern (COBRA GEMINI) technologies during FY98-02.
- Mission data is provided to the National Air Intelligence Center (NAIC) for reduction and analysis.

2.9 AEGIS (SPY-1)

The Aegis (after the mythological shield of Zeus) weapons system is a surface-to-air integrated weapons system. It is designed to defend the fleet against any airborne threat. The heart of the Aegis system is the AN/SPY-1 Phased-array radar system coupled with the AN/UYK-1 high-speed computer system. This combination is able to detect incoming missiles or aircraft, sort them by assigning a threat value, assign on-board Standard surface-to-air missiles, and guide the missiles to their targets. Aegis can track up to 100 targets at any given time. The radar panels are flat structures, mounted to give 360 degree coverage around the ship. These are an improvement over the old rotating type of radar in that there are no moving parts. The old rotating radar covered ONLY the area they were scanning. Phased arrays switch rapidly and cover the entire range around the ship in milliseconds.

Figure 2.9-a: AN/SPY-1 phased array radar system is part of the AEGIS weapon system.

The Aegis system was designed as a total weapon system, from detection to destroy. The heart of the AEGIS systems is an advanced, automatic detect and track, multi-functional phased-array radar, the AN/SPY-1. This high-powered (four megawatt) radar is able to perform search, track and missile guidance functions simultaneously with a capability of over 100 targets. The first Engineering Development Model (EDM-1) was installed in the test ship, USS NORTON SOUND (AVM 1) in 1973.

The AN/SPY-l radar system is the primary air and surface radar for the Aegis Combat System installed in the Ticonderoga (CG-47) and Arleigh Burke (DDG-51)-class warships. It is a multi-function phased-array radar capable of search, automatic detection, transition to track, tracking of air and surface targets, and missile engagement support.

A conventional, mechanically-rotating radar "sees" a target when the radar beam strikes that target once during each 360 degree rotation of the antenna. A separate tracking radar is then required to engage each target. By contrast, the computer-controlled AN/SPY-1A Phased Array Radar of the AEGIS system brings these functions together within one system. The four fixed arrays of "SPY" send out beams of electromagnetic energy in all directions simultaneously, continuously providing a search and tracking capability for hundreds of target at the same time.

Strong points:

- ANSPY-1 multifunction, phased array, fire control quality radar.
- Very rapid transition from SPY-1 silent to full radiate and full situational awareness.
- Fast reaction, fully/semiautomatic combat systems. Initial detection to first missile movement in less than 10 sec.
- Salvo rate of less than 2 sec per launcher (CG-52 and above with MK 41 VLS)
- Mix of multiple SMs.
- Max field of fire and min blockage zones
- Must illuminate target only for a short duration prior to intercept.
- AN/SPY-1 radar variable sensitivity feature allowing radar sensitivity to be tailored to threat RCS, environment, and tactical situation.
- Weapons & ID doctrine capable of automatic and semiautomatic response/action.
- Doctrine software assists w/ ID

Weak points:

- The system is designed for blue water and littoral operations however AN/SPY-1 configuration must be modified to look above the terrain to avoid causing excessive false targets from land clutter. These configuration changes may increase ship susceptibility to low and fast targets.
- Once a target is engaged and the initial salvo fired, WCS will not allow the target to be reengaged (second salvo) until a kill evaluation has been completed.
- AN/SPY-1 antenna height is lower than the AN/SPS-49 radar system resulting in reduced radar horizon.
- DDG-51 Class are not equipped with a AN/SPS-49 radar (no secondary air search radar)
- Must hold an AN/SPY-1 track. Cannot engage on a remote or AN/SPS-49 track unless equipped with CEC.

Used in E/F-band, pulsed Megawatts. 4 passive electronically scanned array panels mounted pair wise on front and backside of the ships' superstructure to give 360 degrees azimuthal coverage. Each panel consists of 4100 radiating elements. Size of the panel: 3.65 times 3.65m. The radar operates at S-band. System is in operation since 1983. Lockheed Martin.

AN/SPY-1, S-band, fixed antenna structure, Tx beamforming via constrained feed, direction finding: monopulse/subarrays, number of faces equals 4.

- Frequency band: 3.1 - 3.5 GHz
- Number of modules: A 4096, B/D 4350, F 1856, K 912 (several versions)
- Number of faces: 4
- Power: 32 x 128 kW
- Aperture diameter: A 3.65*3.65 m, B/D 12 feet, F 8 ft, K 5.5 ft (several versions)
- Beamwidth: 1.7°
- Manufacturer: Lockheed Martin

Ref: DefenceNews, p12, September 10-16, 2001

Ref: Journal of Electronic Defence, May 03, pp. 55-62

2.10 SBX

Sea-Based X-band (SBX) Radar is the tracking and discrimination radar used for the Ground-based Midcourse Defence (GMD) system. SBX will consist of a large X-Band half-populated radar mounted on a modified fifth-generation semi-submersible platform with Battle Management Command Control and Communications, which will include In-flight Interceptor Communication System Data Terminals and associated communications; power generation; facility floor space; and infrastructure, similar to a fixed radar installation.

Figure 2.10-a: Sea-Based X-band radar system, SBX, mounted on an oil platform.

2.11 SLQ-32

Raytheon Electronic Systems.
The SLQ-32(V)5 is an electronic warfare (EW) system that adds the SIDEKICK active jamming capability to the U.S. Navy's SLQ-32(V)1 and SLQ-32(V)2 systems. The SLQ-32 systems feature a lens-fed multibeam array that generates very high jamming power at continuous wave so that an almost unlimited variety of jamming techniques can be used. SIDEKICK adapts this technology and uses smaller, lighter, solid-state components to provide electronic countermeasure defence for small and mid-size ships.

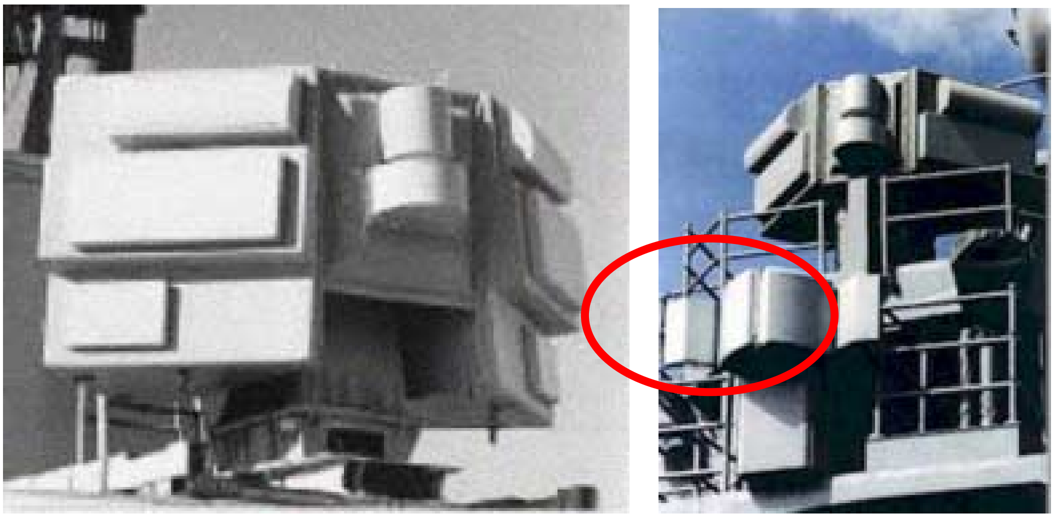

Figure 2.11-a: AN/SLQ-32 and in the right hand picture the SIDEKICK for ECM defence for small and mid-size ships.

The system achieves EW objectives by providing full threat band frequency coverage, instantaneous azimuth coverage, 100 percent probability of intercept and simultaneous response to multiple threats. It can detect aircraft search and target radars well before they detect the ship. The system's rapid response time ensures jamming protection is enabled to prevent long range targeting of the ship and deceive missiles launched against the ship. The system has an on-line library of emitter types for rapid identification.

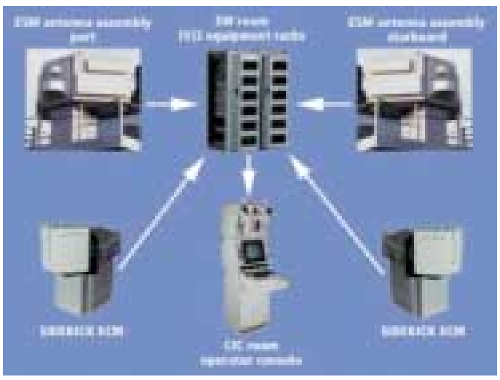

Figure 2.11-b: System diagram of the AN/S:Q-32.

Raytheon's lens-fed multibeam array is the key feature of its AN/SLQ-32 family. The system's multibeam architecture allows its ECM transmitter to produce very high-noise, jamming ERP, preventing burn-through of a typical targeting radar until source is within the hard kill envelope. The lens-fed multibeam array generates very high jamming power at continuous wave, so virtually unlimited jamming techniques can be used.

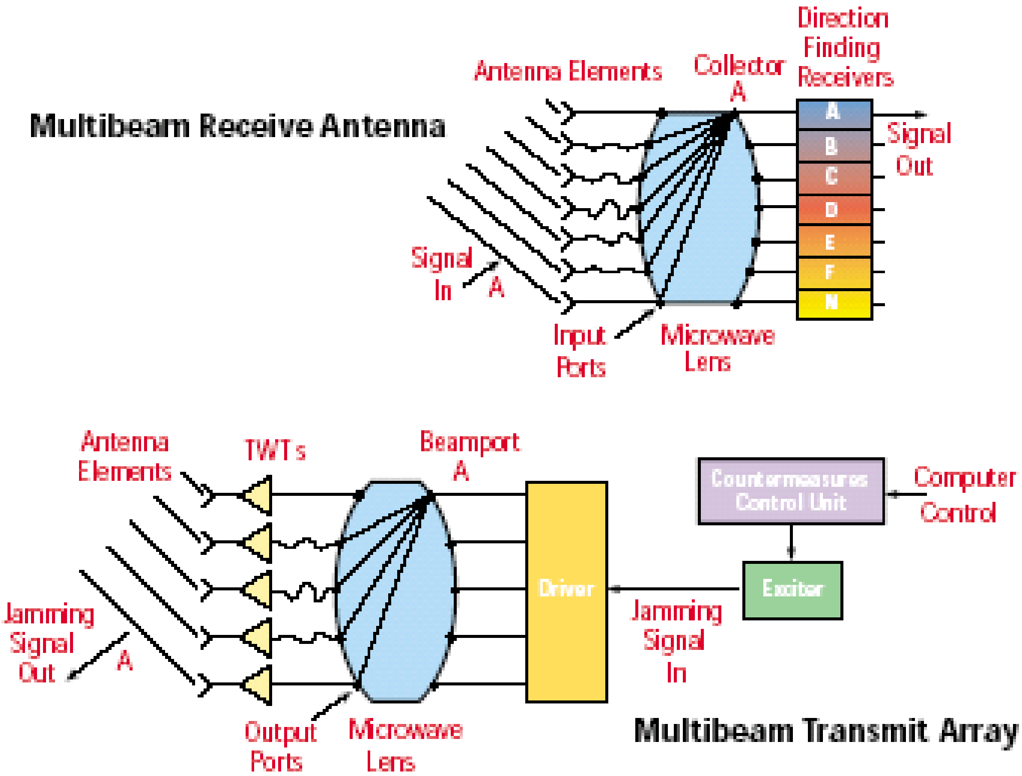

Figure 2.11-c: AN/SLQ-32 Multibeam Technology Features.

Some specifications of the system AS-3318A/SLQ-32(V):

- Height 70 inches
- Width 116 inches
- Depth 90 inches
- Weight 2642 lbs
- Operating Temperature Unavailable
- Frequency Range Unavailable
- Input Impedance Unavailable
- VSWR > 3:1
- Polarization Right-Hand Circular
- RF Power Rating Unavailable
- Power Requirement Unavailable
- Feed Type Unavailable
- Input Connector Unavailable

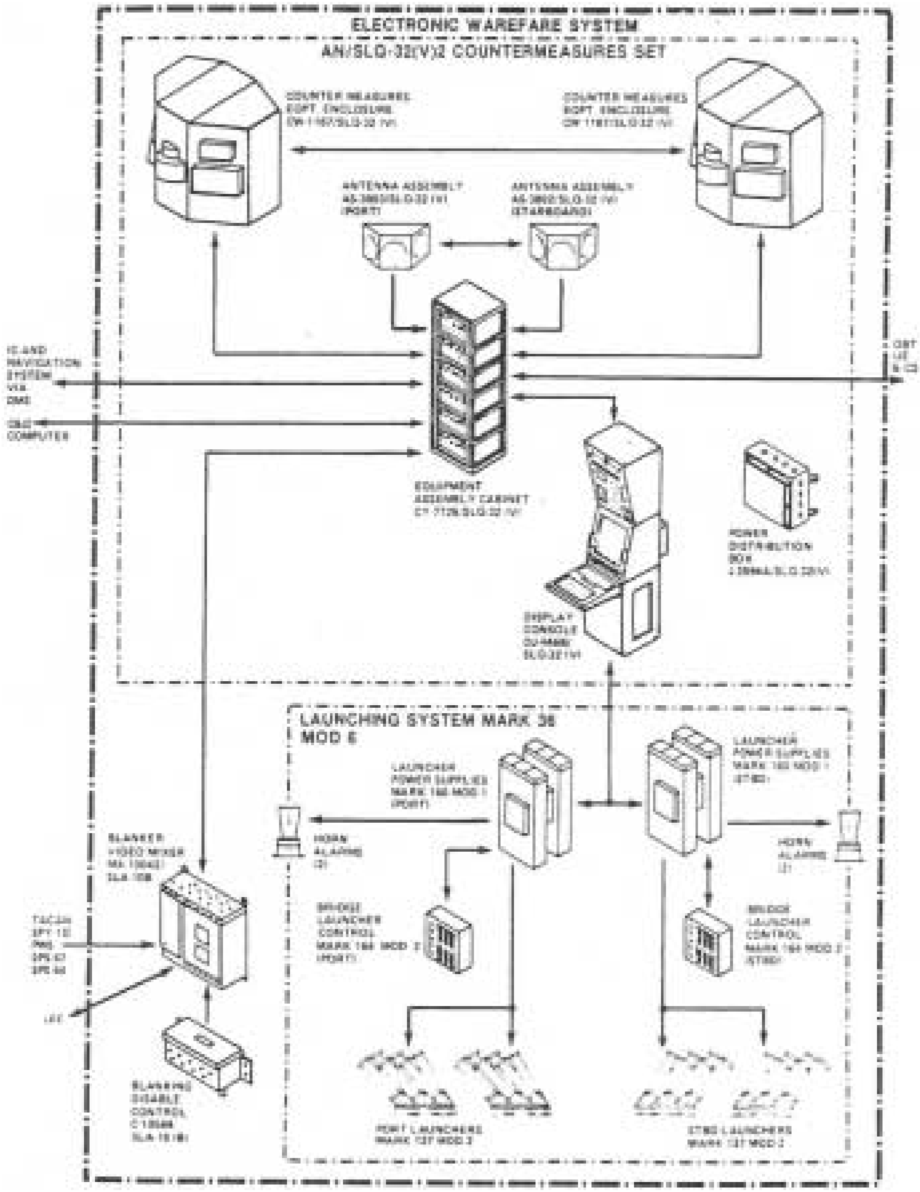

Figure 2.11-d: more elaborate system diagram of the AN/SLQ-32(V)2 system.

The AN/SLQ-32(V) provides a family of modular shipborne electronic equipment which is installed in most combatants, CV/CVN, amphibs and auxiliaries in the surface Navy. The systems, which consists of five configurations, performs the mission of early detection, analyses, threat warning, and protection from anti-ship missiles. The (V)1 and (V)2 are computer controlled Electronic Support (ES) Systems that detect , sort, classify, identify and continuously display signals within frequency ranges. The (V)3 and (V)4 provide the capabilities of the passive system plus an integrated Active Electronic Attack (EA) response for all signals classified as a threat. The (V)5 provides for an EA capability on smaller class ships.

2.12 SAMPSON / MESAR

SAMPSON’s active phased array antenna comprises thousands of small, solid-state transmitter and receiver units. These allow the radar beam to be moved at electronic switching speed rates. Its modular design reduces the through-life costs, whilst significantly increasing availability. SAMPSON is the result of over 20 years collaborative research and development within the MESAR (Multi-function Electronically Scanned Adaptive Radar) programme.

Figure 2.12-a: MESAR.

SAMPSON multi-function, dual-face active array radar operating at E/F bands. The radar comprises two antenna array faces, each containing 2560 T/R-modules connected to dipoles, with an output of 25W per element (each face comprises 25.000 gallium arsenide transmit and receive modules). The two array faces of the radar sit back to back in an A-frame structure in a near spherical design, which rotates up to 30rpm. Forced-air cooling is used to dissipate the heat from these modules, with cool air being supplied to the interior of the antenna cabin, before passing through slots in the base of the radome. Modes of operation include long- and medium-range search, surface search, high-speed horizon search, and high-angle search and track. Sampson uses digital adaptive beamforming, which makes it highly resistant to electronic countermeasures.
The BAE Systems Sampson multi-function, dual-face active array radar provides targeting data for the missile system. SAMPSON will be deployed as part of the Principal Anti-Air Missile Systems (PAAMS) for the Royal Navy's TYPE 45 next-generation destroyer.

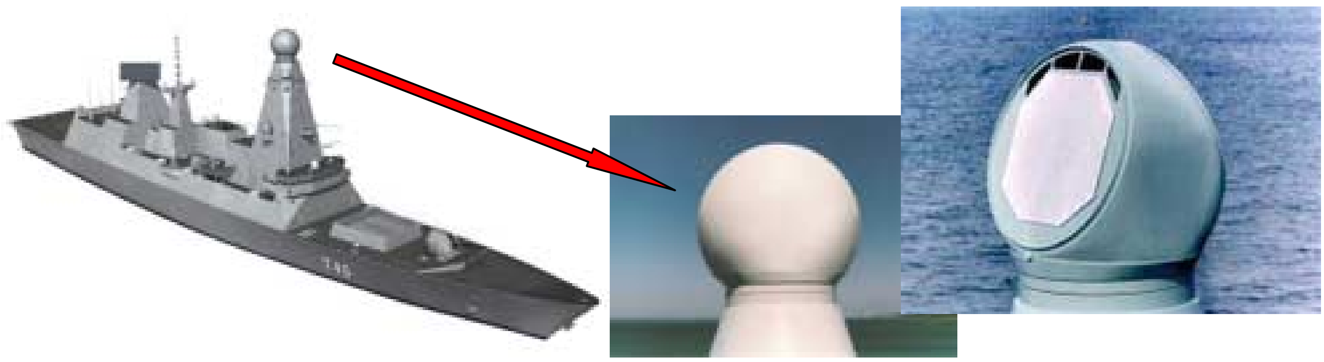

Figure 2.12-b: Type 45 next generation destroyer Royal British Navy, showing BAE’s SAMPSON radome and a revealed antenna face.

- Frequency band: E/F
- Number of modules: 2560 / face
- Power per element: 25 W
- Number of faces: 2
- Aperture size: 2.3 × 2.3 m
- Rotation : 30 rpm
- Manufacturer: BAE Systems

Ref: A. Rowe, I. Hamill: 'CDF Analysis of a Rotating Antenna', British Aerospace and AEA Technology and Ansys Company, Case Study, Autumn 1998. (www-waterloo.ansys.com/cfx)

Ref: http://www.geocities.com/Pentagon/Bunker/9452/SAMPSON.htm
Ref: Journal of Electronic Defence, May 03, pp. 55-62.

2.13 ALABAMA

“ALABAMA” = “**A**ntenne **LA**rge **BA**nde pour **M**ultifonctions **A**ssociées - THALES patent n° 97 16342 on December 23, 1997 is Thales Airborne Systems’ scalable, passive, wide-band, dual-polarised antenna array. The antenna array allows for multiple functionality, i.e.: ELINT/ESM, communication and radar functions. The antenna array can be used anywhere for different missions on naval, airborne, and ground based platforms. Operating frequency bands are specially C, X, Ku, but it can also be used in another band with the same frequency ratio of about 3. The antenna is based on low profile and measures less than 12 mm when used for the given frequency bands, this includes the baluns (one per polarisation), the radiating elements and the radome. The broadband antenna, suitable for 2D phased array , has been previously tested. In the presently detailed work, the step to a passive 400 elements manufacturing (6-18 GHz frequency band) is detailed: the mockups have complex multilayers stackings, which cover balun and feeding network (for both V and H polarization) layers. The manufacturing process is introduced and successfully implemented; it can be fitted to a conformal cylindrical shape. Radioelectrical performances for VWSR, Σ and Δ patterns (axis beam), and coupling figures are shown, with a thickness around 12 mm (radome / antenna / 2 balun levels).

Now, the concept “ALABAMA” is a passive array with radiating elements are associated with own balun (one balun by polarization) and feeding network (2 for the bipolarisation array). The array is made in a tile technology where all components of the antenna:

- Radome,
- Radiated element,
- Balun,
- Feeding network for sub-array, and
- “Active module” with associated circuits (in the future),

are manufactured in a multilayer stacking. All these components are compliant with elementary cell lateral size. The antenna uses no absorbing material. The antenna can be conformed according to a cylinder : for example, a conformal mockup has been manufactured according a cylinder (radius about : 0.5m).

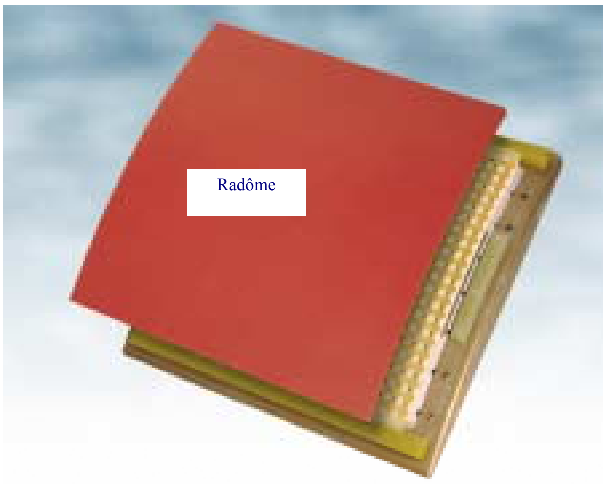

Figure 2.13-a: Example of conformal mockup (cylinder radius about 500 mm) of “ALABAMA” design realized in C, X, Ku bands (work supported by French DGA).

The new concept "ALABAMA" has been chosen for reasons of bandwidth (ratio 3:1), thin profile, global technology (tiles) and conformation compatibility. The antenna is a concept which allows any configurations, the size of sub-arrays is designed according to applications constraints, the task is to design the feeding network compliant to sub-array surface. Up to now, only passive antennas have been manufactured. The used manufacturing process and technologies that made this integrated antenna system exhibit:

- Multilayer circuit including balun, feeding network, manufactured in standard PC boards (example : Roggers / RT6002 ™)
- Use of standard engraving techniques. This multilayer circuit exhibits an high density.
- 3 kinds of propagation in multilayer : µstrip, strip-line and coaxial,
- Use of very low εr materials for some necessary spacings between layers,
- Radiating elements are connected with balun circuit by bifilar line,
- Use of compressive connection like "Cin::apse" or "Fuzz-button" between balun and output connectors (in future active modules),
- Use of vertical interconnection by metallic hole between layers inside multi-layers circuit
- Use of specific tools for manufacturing,
- Some antenna components like radome for example are glued,

The Development level of the new concept is: 4 and the reported properties of the antenna are

Pro	Con
Thin structure/low volume	High ciruit density
Light weight	
Wideband	
Polarisation diversity	Possible presence of blind angular directions in the radiated patterns depending on unit cell size, superstructure and frequency
Tile technology	
Conformal to platform	

Table 2.13-a : ALABAMA Antenna concept Pro'Cons Table

2.14 AN/SPY-3

The SPY-3 radar has been designed for several US Navy's next generation warships, of which the DD(X) class of surface combatant ships is an example. SPY-3 represents the first of the full-range of Raytheon technologies that will revolutionize the US Navy's capabilities in the years to come.

The SPY-3 is an active phased array X-band radar designed to meet all horizon search and fire control requirements for the 21st century fleet. The Multi Function Radar combines the functions provided by more than five separate radars currently aboard Navy combatant ships. SPY-3 supports new ship-design requirements for reduced radar cross-section (stealth), significantly reduced manning requirements and total ownership cost reduction.

The Multi-Function Radar (MFR) is a focal point for DD(X)'s Integrated Topside Design and embedded aperture technology. The Multi-Function Radar is an X-band active phased array radar designed to meet all horizon search and fire control requirements for the 21st-century fleet. The solid-state active arrays will be carefully engineered to preserve the ship signature requirements of DD(X) and require new topside technologies to incorporate embedded phased arrays into a composite superstructure.

Aimed at attributes of the system:

- Horizon and Volume Search
    1. Detection of stealthy targets in sea-land clutter,
    2. Periscope detection,
    3. Counter battery.
- Dual band approach (wave form integration)
    1. Avoidance of multi-radar track-to-track correlation,
    2. Improved performance in adverse environments,
    3. Reduced SW development and maintenance.
    4.

Figure 2.14-a: DD(X) littoral combat ship and integrated deckhouse (right).

Volume Search- / Multifunction Radar Suite

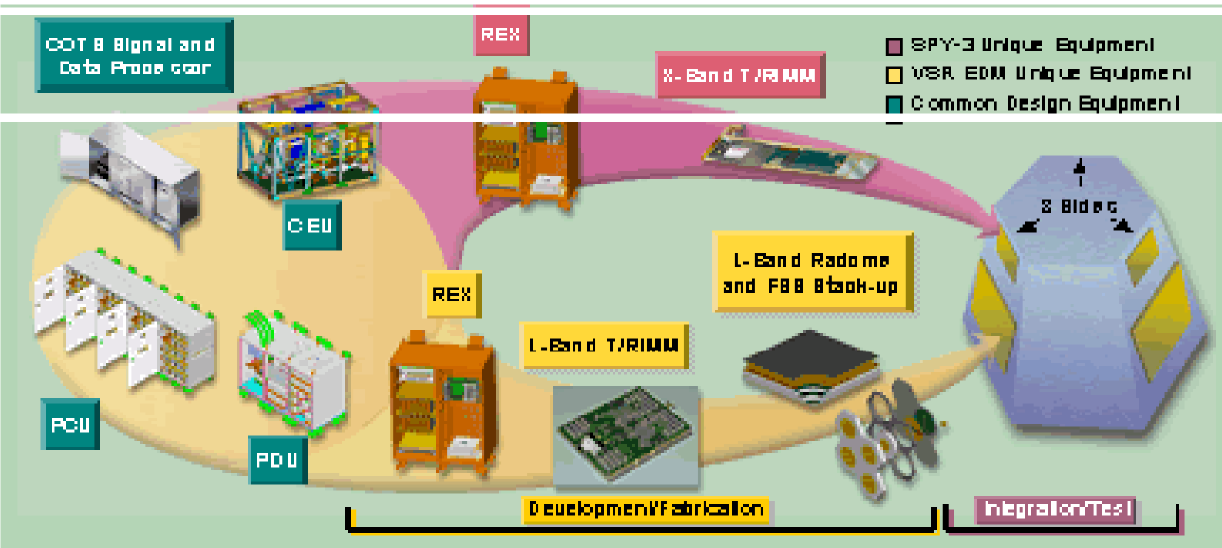

Figure 2.14-b: Integrated Deckhouse and Apertures.

The integrated deckhouse and apertures will demonstrate electromagnetic compatibility with reduced signatures. The deckhouse EDM will demonstrate:

- Nuclear overpressure resistance
- Effects of externally and internally bursting conventional (blast, fragmentation) warheads
- Electromagnetic Compatibility (EMC)
- Electromagnetic Protection (EMP)
- Radar cross section and Infrared signatures

Attributes:

- Low RCS and IR signatures
- All composite superstructure
- Low signature electronically steered arrays
- Integrated multi-function mast

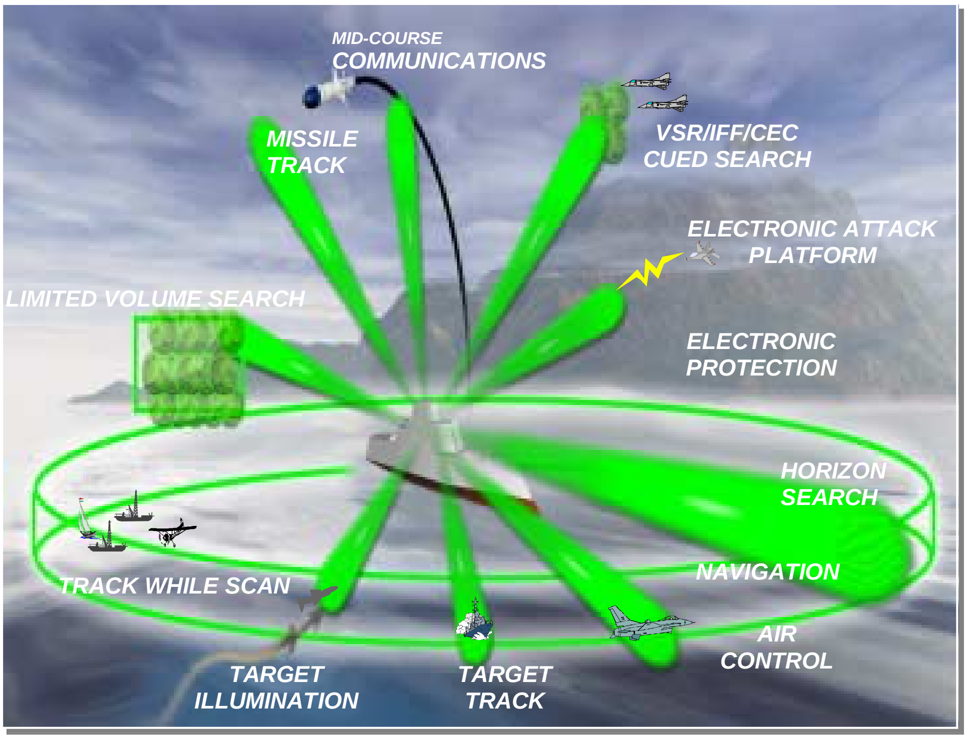

Figure 2.14-c: Artist's conception of Littoral battle space.

Depicted in the Figure 2.14-c:

- Land Attack
  1. Counterfire
- Local Air Dominance (Ship Self Defence)
  1. Detect and track high speed, stealthy low-flying targets
  2. Horizon search and fire control track
  3. Rear reference & illumination for ESSM and SM-2
  4. Missile communication
  5. Electric protection
  6. Limited above-horizon volume search
  7. Kill assessment
  8. Support non-cooperative target recognition
- Surface Dominance
  1. Surface surveillance
  2. Navigation
- Undersea Dominance
  1. Periscope detection
- Air Intercept Control (CVN-77)
- Precision Landing (CVN-77)

Key issues:

- Solid State, Active Phased Array
- X-Band

- 3 Array Faces
- High P_{RA}; Low false track rate
- 0.98 A_o
- Production cost (5th unit) : Goal $30M, threshold $45M
- Manufacturer: Raytheon.

3 AIR BASED SYSTEMS

3.1 Introduction

Figure 3.1-a illustrates various airborne systems where antennas in general and arrays in particular are critical components. This document considers only the radar systems. Most part is devoted to the fighter aircraft radar in the nose of the aircraft which probably is the technologically most demanding but surveillance radar is also considered somewhat. The text shall be considered as the status for 2002. Useful review references from the last year are [1-3].

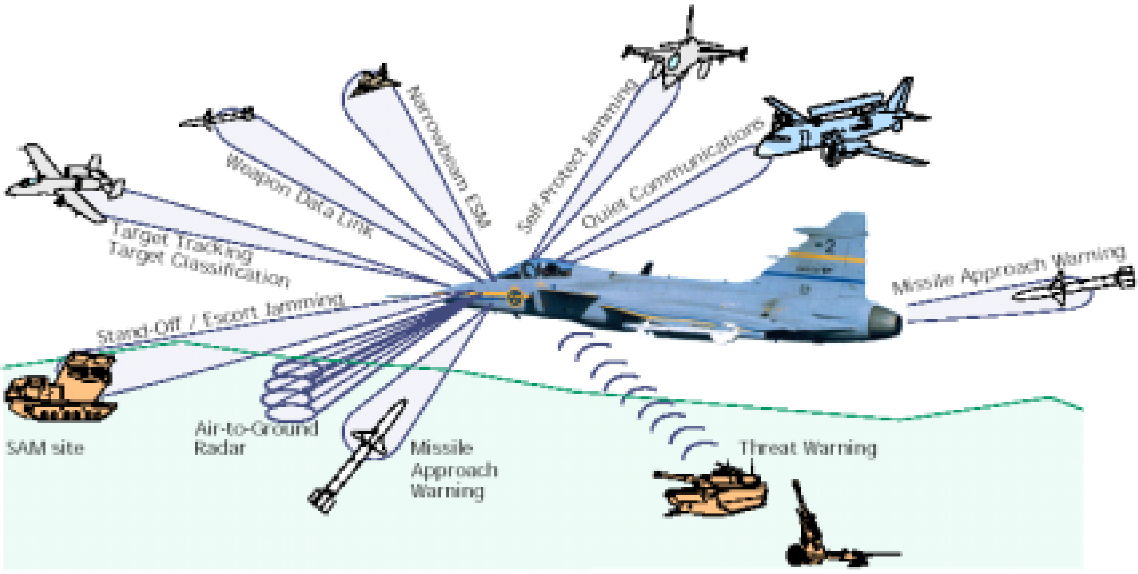

Figure 3.1-a. Various radar and electronic warfare functions.

3.2 Fighter Aircraft Radar

The radar of a combat aircraft is essentially forward looking with a scanning requirement of at least ±60º azimuth and possibly slightly less in elevation. Its most important use is for situational awareness and air combat. The use of it as a multipurpose system would be very advantageous and is the area for much R&D and, as one important consequence, would require a significantly wider bandwidth and also larger scan coverage.
A property which is of great importance for fighter radars is also its radar cross section (RCS) which must be low. Its radome is here of vital importance as well as the matching of the array and its feeding network.
Most fighter aircraft radars operate at X-band and with a diameter of 60−90cm (given by the limited space available) there are about 1000−2500 antenna elements and the beam width becomes approximately 2−4º.
Table 2.13-a shows some data for a number of existing as well as operative fighter aircraft radars. The type of antenna elements used is not very well published but slotted waveguides are common for the mechanically steered and for those steered electronically in one dimension only while for the more advanced arrays with one TR module per element, open waveguide apertures, slotted notches, and also dipoles (for lower frequency bands) seems to be used.

The beam scanning has previously been done mechanically, with a relatively fast azimuth scans and stepping in elevation. In most present operating system this is done with a slotted waveguide (flat plate) antenna. The signal feeding is done with waveguide network on the back side and usually the feeding is split into four quadrants to obtain monopulse functionality. There is good control on aperture distribution resulting in low sidelobes. The transmitter is a high power tube, usually a TWT.
Figure 3.2-a and Figure 3.2-b show two examples of such antennas, one from Russia and one from Israel.

Figure 3.2-a: ZHUK-ME radar used in Mig 29 and Su 27, using a flat plate antenna, [I] (including four antennas for IFF).

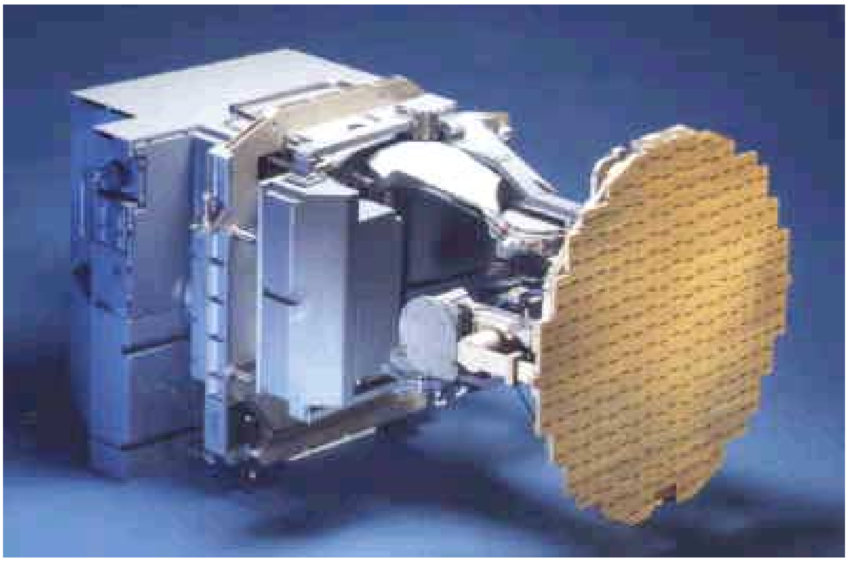

Figure 3.2-b : EL/M-2032 radar from Israel, using a flat-plate antenna, [II].

The next step in array progress is scanning the beam electronically by varying the phase in each of the array elements in an ESA (Electronically Scanned Array). Sometimes the limited scan volume is increased by also having the possibility to point the array mechanically in some fixed directions. In a passive array the transmitter and the receiver(s) are still in a central position so that any losses

between the radiating elements and the transmitter/receiver will reduce the array performance. Since the transmit power is high and losses are important the phase shifters are usually made in ferrite technology (ordinary diode phase shifters are usually considered too lossy). Another method (the Radant technology) is to make the phase shift by varying in an artificial lens with diodes between parallel metallic plates to vary the effective index of refraction. For 2D scanning two sets of plates are required.
A somewhat simpler method of scan is to utilize the dispersion in a waveguide to get a frequency dependent scan in one plane while using phase shifters to scan in the other plane.
The ferrite phase shifters are used in the American radars for B-1B and B2 (AN/APQ164 and AN/APQ181) developed in the 1980s and 1990s and also in a radar for the Russian Mig-31 shown in Figure 3.2-c while the radar RBE2 from France using the Radant technology is shown in Figure 3.2-d.

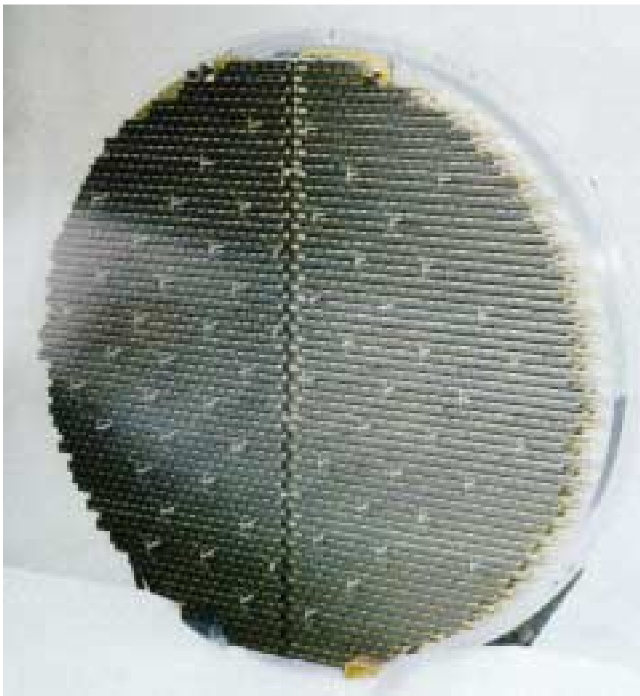

Figure 3.2-c: Mig 31 radar, [III], (including antennas for IFF and communication).

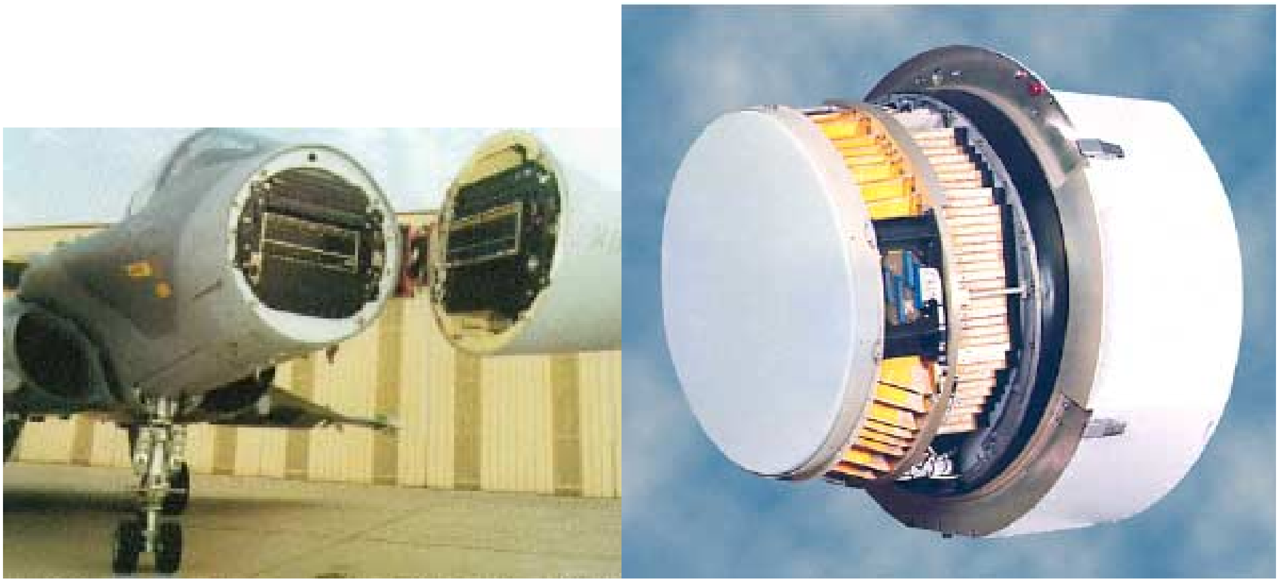

Figure 3.2-d: RBE2 radar for Rafale, [III and 3].

In an active electronically scanned array (AESA) each radiating element, or subarray, is connected to an active transmit/receive module (TRM) which contains high power solid state amplifiers, low noise receivers and phase shifters, usually common to both transmission and reception. Hereby the losses in cable, waveguide and phase shifters etc. are less important, the total power can be higher, noise figure lower, beam control better and faster. Also steerable attenuators for amplitude control are often included, at least in the receiver mode. The array can also be subdivided in subarrays (preferably overlapping and maybe in the future with one element in each) to improve the performance in terms of adaptive jammer suppression, direction of arrival estimation and multiple functions. The reliability, in terms of MTBF, is also expected to be higher due to a "graceful degradation" when the number of TRMs is high. There are also new problem areas of course such as cooling and weight and, maybe most important, its complexity and cost.
Some American AESAs in various levels of development are shown in figure 3.2-e (for F-15 C/D) in Figure 3.2-f (for F/A-18 E/F) in Figure 3.2-g (for F-22) in Figure 3.2-h (for F-16 Block 60) and in Figure 3.2-i (for F-35 Joint Strike Fighter, JSF).
The radar for JSF, with working name MIRFS (Multi-Function Integrated Radio-Frequency System) will also be used for ESM and jamming. There will be several digital receiver channels used for signal processing and adaptive control.
The United States Defence Science Board shows in a report, [4], from 2001 that USA are planning to upgrade the present approx. 700 and the (then) planned approx. 2800 fighter aircraft with AESA-based radars at X-band.

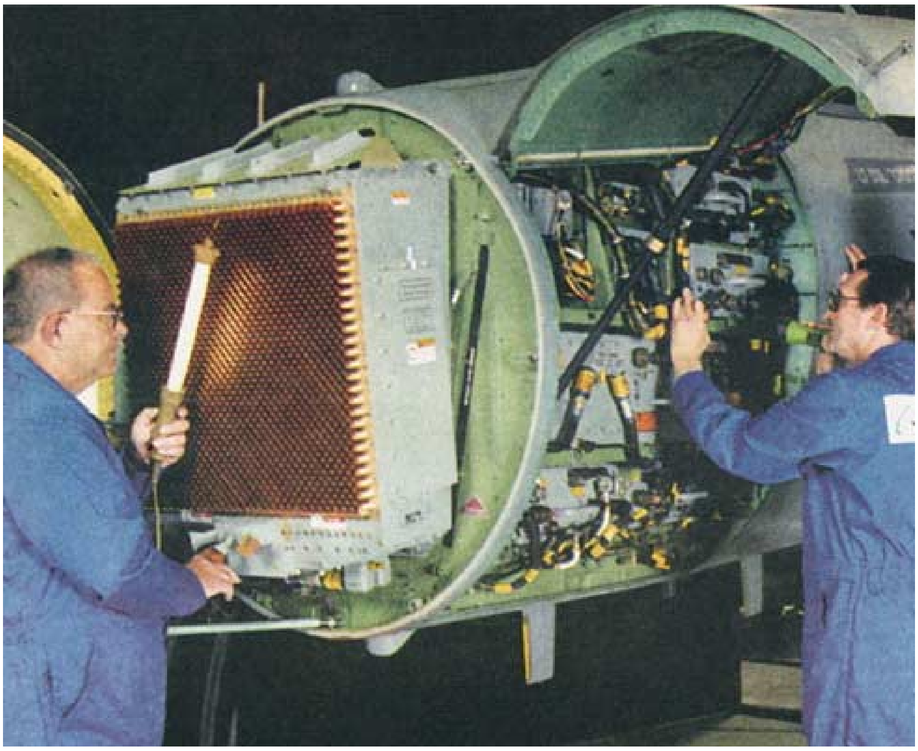

Figure 3.2-e: AN/APG-63(V)2 in F-15, [IV].

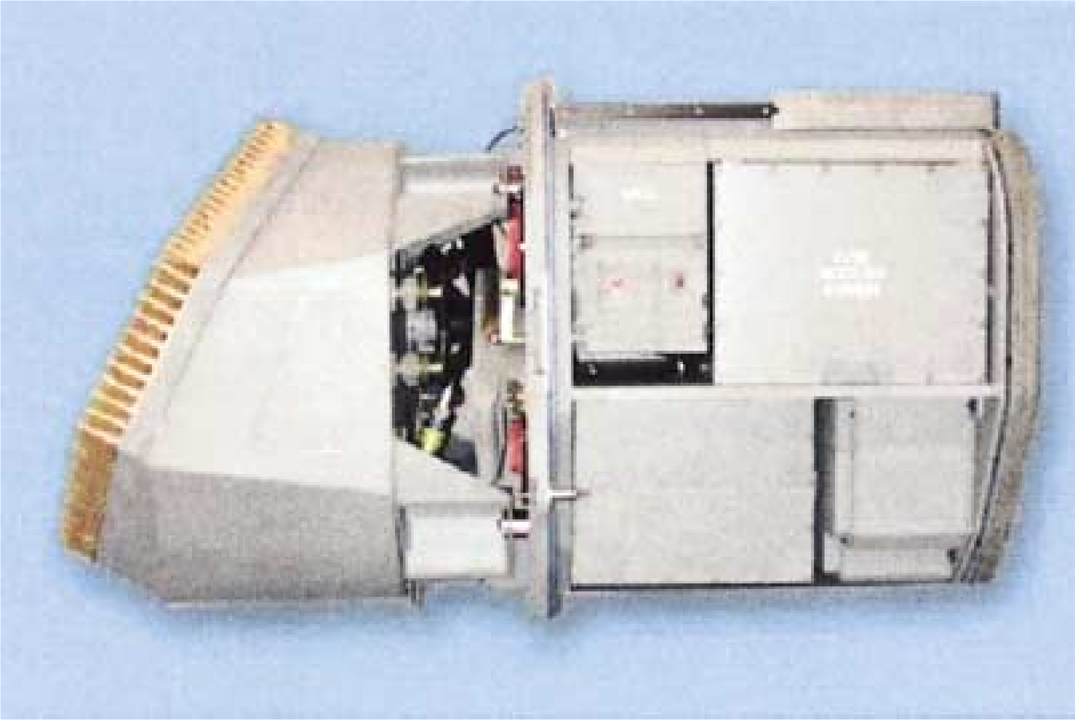

Figure 3.2-f: Active ESA radar AN/APG-79 in F-18, [VII]. The purpose of the slightly upward pointing surface is to reduce RCS in the forward direction.

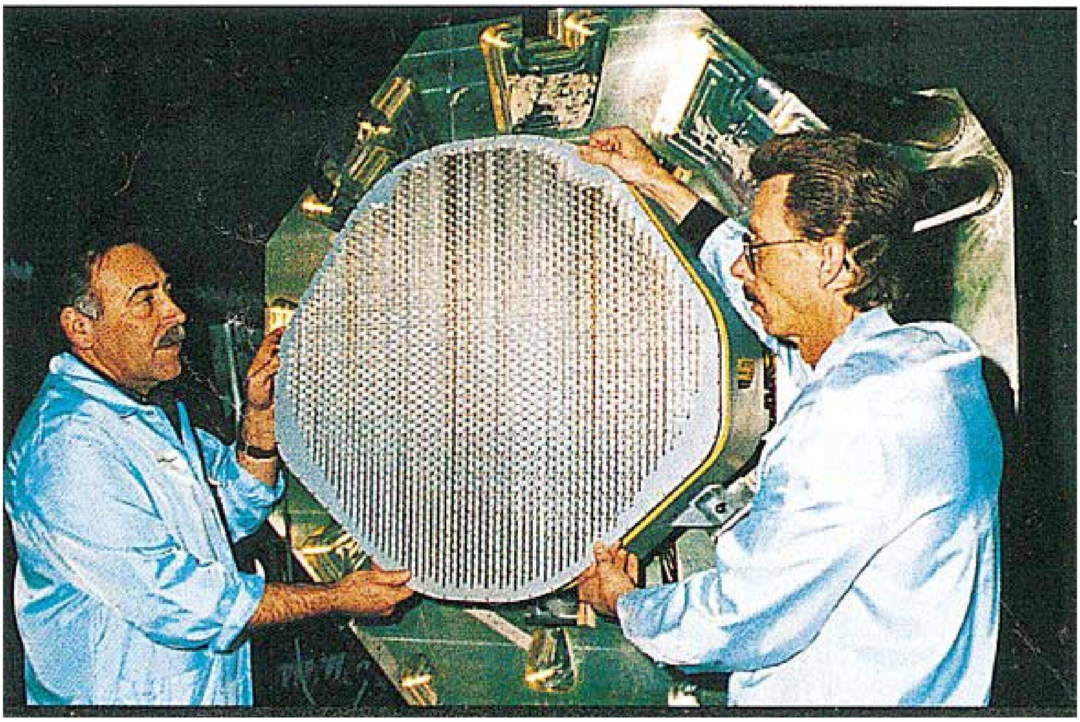

Figure 3.2-g: AN/APG-77 in F-22, [V].

Figure 3.2-h: AN/APG-80 in F-16 Block 60, [VI].

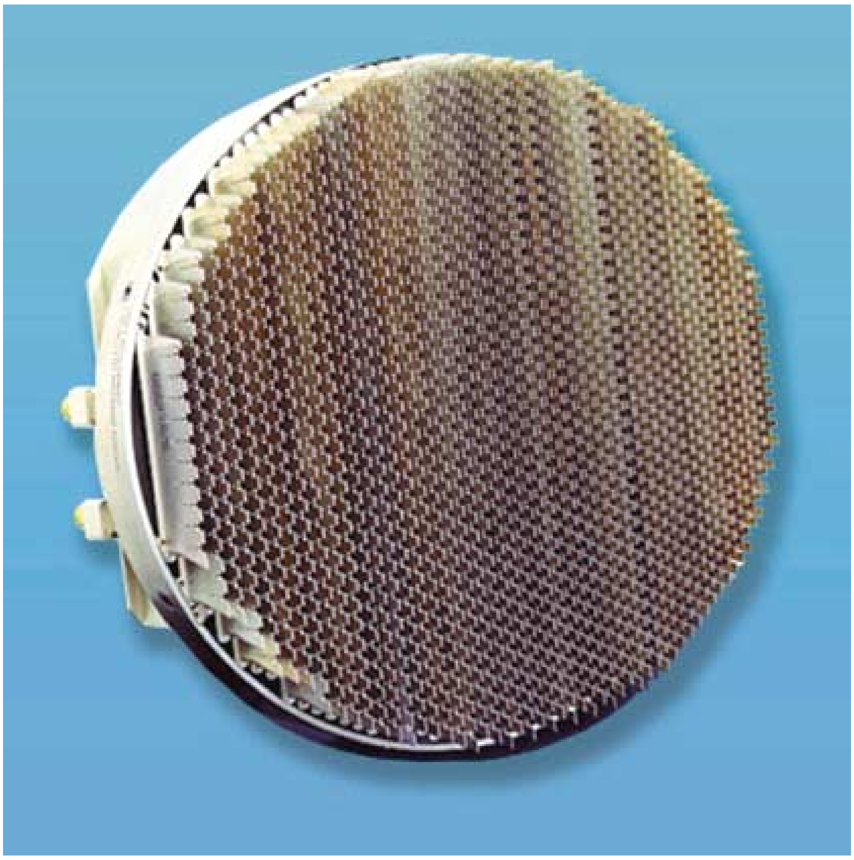

Figure 3.2-i: The radar for JSF F-35, with working name MIRFS (Multi-Function Integrated Radio-Frequency System), will be possible to use also for ESM and jamming purposes, [VIII].

Also Russia has presented an AESA prototype which is planned to be implemented in about 10 years. The array is shown in Figure 3.2-j and the approach is somewhat less ambitious than the American.

Figure 3.2-j: A prototype of an AESA from Phazotron-NIIR shown at the air show in Moscow 2001.

Within the Eurofighter project in Europe the radar AMSAR (Airborne Multi-role Solid-state Active Array Radar) is developed. Figure 3.2-k and 3.2-l shows a CAD model and a prototype respectively. The radar is deeper discussed in [6]. Sweden is also developing an AESA.

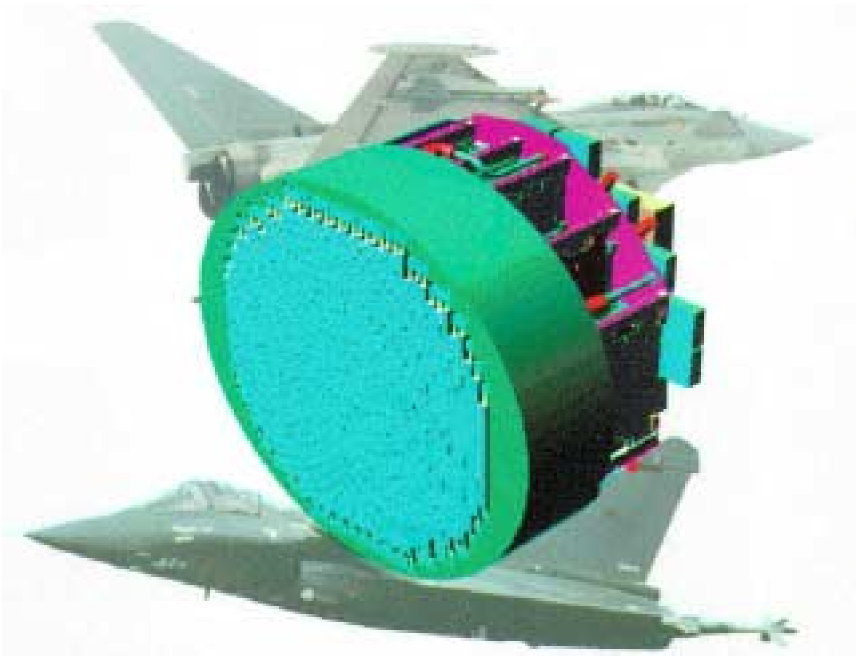

Figure 3.2-k: A CAD model of AMSAR to Eurofighter, [III].

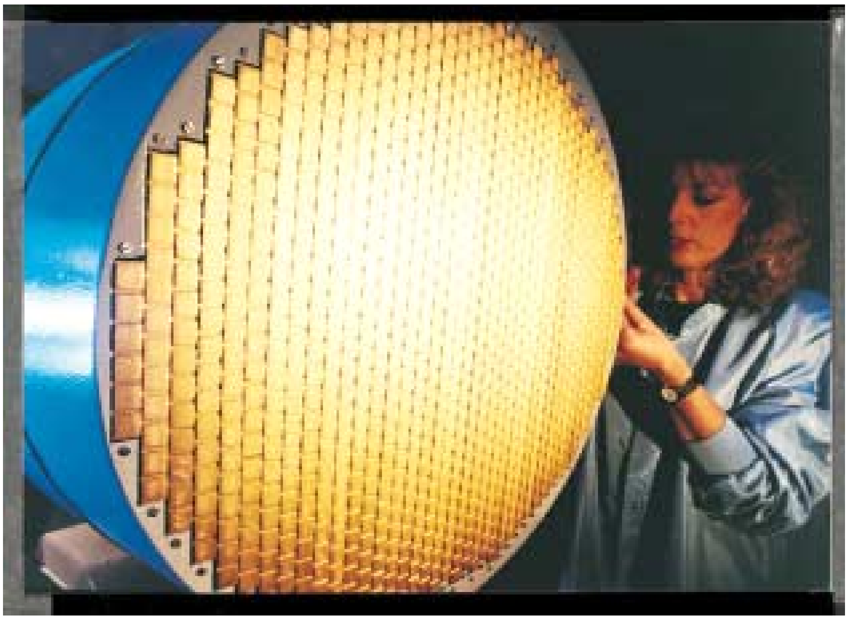

Figure 3.2-l: Prototype (2002) of AMSAR, [XI].

The total cost of an AESA fighter radar is very much dependent on the TR module cost. Figure 3.2-m, from [4], illustrates the various steps that have and will be taken to make these affordable.

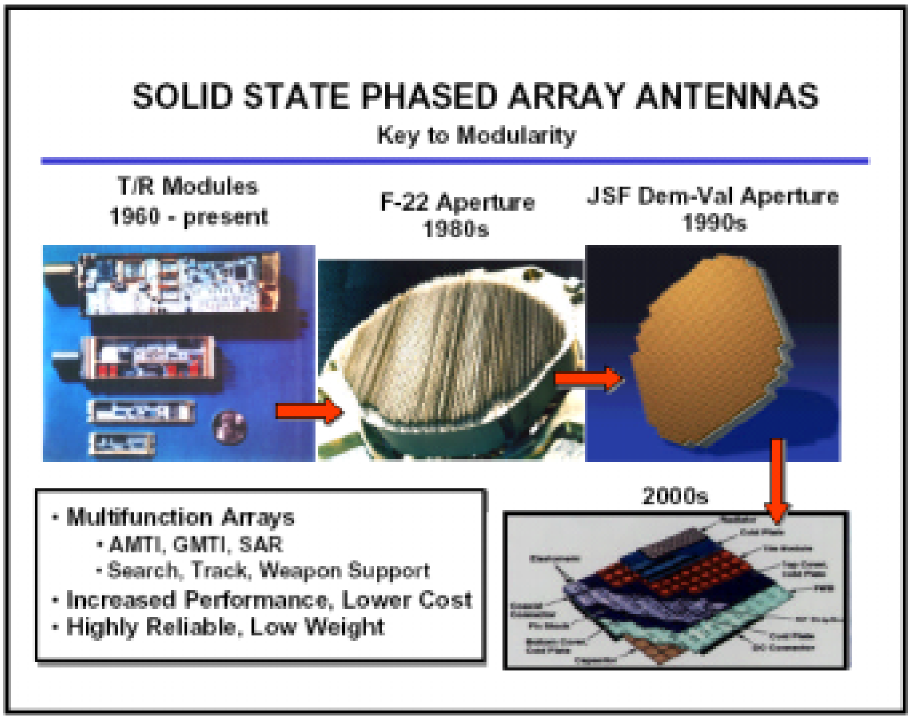

Figure 3.2-m: Development of TR modules and apertures, [4].

References [1–9] are a few, but far from complete list of, references used. Finally it should me mentioned that much of the material about fighter aircraft radars reported here has been extracted from reference [10] (written in Swedish).

Table 3.2-a : Technical Data for various fighter aircraft radar (status 2002)

Radar designation / Parameters	AN/APG-70 (USA)	AN/APG-71 (USA)	AN/APG-73 (USA)	AN/APG-68 (USA)	AN/APG-79 (USA)	AN/APG-80 (USA)	AN/APG-77 (USA)
Platform (aircraft)	F-15E	F-14D	F/A-18E/F	F-16C/D	F-18, Super Hornet	F-16 Block 60	F/A-22
Status of development	Operative	Operative	Operative	Operative	Development Operative-2005 ?	Development	Soon operative (few years)
Functions & Modes	HPD, MPD, LP, TWS, SAR, GMTI, IFF, TF/TA	HPD, MPD, LP, IFF, SAR, TWS, TF/TA	HPD, MPD, LP, IFF, SAR, TWS, TF/TA	HPD, MPD, LP, SAR, TWS, TF/TA	HPD, MPD, LP, SAR, TWS, TF/TA, IFF, LPI	HPD, MPD, LP, SAR, TWS, TF/TA, IFF	HPD, MPD, LP, SAR, TWS, TF/TA, IFF, LPI
Weight of radar	250 kg	590 kg ?	155 kg	170 kg			
Frequency band	X	X	X	X	X	X	X+
Antenna type	Slotted wg flat-plate	Slotted wg flat-plate guard channel	Slotted wg flat-plate	Slotted wg flat-plate	Active ESA	Active ESA	Active ESA
Antenna scanning	Mechanical ± 60°-70°	Mechanical ± 60°-70°	Mechanical ± 60°-70°	Mechanical ± 60° in azim. at 4 levels in elev.	Electronic scan	Electronic scan	Electronic scan ±60°
Antenna size	80-85 cm	ca.90 cm	75-80 cm	74x48 cm	ca. 80 cm	70x70 cm	
No. of elements / Phase shifters	——— / No	——— / No	——— / No	——— / No			1500-2000
Transmitter type	TWT	TWT	TWT	TWT	Solid state modules	Solid state modules	Solid state modules, 10W typ.
Reliability	>80 h MTBF		170 h MTBF	300 h MTBF	Ca. 1500 h MTBF		Ca. 2000 h MTBF

Radar designation / Parameters	AN/APQ-181 (USA)	AN/APQ-164 (USA)	AN/APG-63(V)2 (USA)	MIRFS (USA)	PS-05/A (Sweden)	NORA (Sweden)	ECR-90/ CAPTOR (Europe)	AMSAR (Europe)
Platform (aircraft)	B-2	B-1B	F-15C/D	JSF F-35	JAS-39	JAS-39 - development	Eurofighter	Eurofighter, Rafale development
Status of development	Operative	Operative	Few copies produced	Early develop. ca. 2008	Operative	Development	Operative	Development ca. 2010
Functions & Modes	SAR, navigation, TF/TA, beacon, GMTI, weather, LPI	SAR, navigation, TF/TA, beacon, GMTI, weather, LPI	HPD, MPD, LP, IFF, SAR, GMTI, TWS, IFF	"All possible modes"	HPD, MPD, LPD, LP, SAR, GMTI, TWS, TF/TA	HPD, MPD, LPD, LP, SAR, GMTI, TWS, TF/TA	HPD,MPD,LP, SAR,GMTI, TWS, TF/TA, IFF	HPD, MPD, LP, SAR, TWS, TF/TA, IFF, LPI
Weight of radar	950 kg (with 2 antennas)	570 kg			160 kg		190 kg	
Frequency band	K_u	X	X	X	X	X	X	X
Antenna type	Passive ESA, 2 antennas	Passive ESA and mech. movements	Active ESA	Active ESA	Slotted wg flat-plate	Active ESA, dual pol.	Slotted wg flat-plate	Active ESA, dual pol.
Antenna scanning	Electronic scan ca. 150° in total Ant. slanted	± 105° incl mech. movement (±60° without)	Electronic scan ± 60°	Electronic scan	Mechanical	Electronic scan	Mechanical	Electronic scan
Antenna size	ca. 2,2x0,3 m	110x55 cm	70-75 cm		60 cm		70x70 cm	60x60 cm or larger
No. of elements / Phase shifters	ca. 2000/antenna / Yes, in every element	1528 / Yes, in every element		1000-1500	———	> 1000	———	1000-1500 dep. on antenna size
Transmitter type	TWT	TWT	Solid state modules	Solid state modules	TWT	Solid state modules	TWT	Solid state modules ca10 W
Reliability					170 h MTBF			

Radar designation / Parameters	RDY (France)	RBE2 (France)	AESA (Japan)	Zhuk 27 (SLOT BACK) N-019, N-010 (Russia)	SBI-016 Zaslon (FLASH DANCE) (Russia)	Zhuk PH N-011(M) (Russia)	Super Kopyo-PH (Russia)
Platform (aircraft)	Mirage 2000-5	Rafale	F-2A/B (FS-X) F-15J	Su-27, Mig-29 Mig-29M	Mig-31	Su-30, Su-35 (Su-27M)	
Status of development	Production since 1995	In production for mass 1998)	Development	Operative	Operative	Development	Development
Functions & Modes	HPD, MPD, LP, IFF, SAR, GMTI, TWS, IFF	HPD, MPD, LP, SAR, GMTI, IFF, TWS, TF/TA		HPD, MPD, LP, IFF, TWS, (SAR, GMTI-N-010)	HPD, MPD, IFF, TWS	HPD, MPD, LP, SAR, GMTI, IFF, TWS, TF/TA	HPD, MPD, LP, SAR, GMTI, IFF, TWS, TF/TA
Weight of radar				220-240 kg	240-270 kg antenna, radar 1000 kg	275 kg	
Frequency band	X	X	X	X	X-	X	X
Antenna type	Slotted wg flat-plate with guard antenna	Passive ESA	Active ESA	Reflector or slotted wg flat-plate	Passive ESA	Passive ESA + mech. rotation	Passive ESA + mech. rotation
Antenna scanning	Mechanical ± 60°-70°	Electronic scan in azim and elev. 120°	Electronic scan	Mechanical ± 70° (90°) in azim.	Electronic scan ± (60°)-70°	Electronic scan ±60° (70°) in azim & elev.	Electronic scan
Antenna size	60 cm	ca. 70 cm	66 cm	80 (85) cm	110 cm	90-100 cm	Different sizes
No. of elements Phase shifters	------ No	Two lens antennas Yes, sep. for az/el.	ca. 750	----- No	1700 Yes (ferrites)	>1000 Yes	Yes
Transmitter type	TWT	TWT	Solid state modules	TWT	TWT	TWT	TWT
Reliability				150 h MTBF		150 h MTBF	

3.3 Surveillance Radar

Airborne surveillance radars will generally require longer range but the requirements for fast scan etc. is lower. The frequency is lower and antennas hence are required to be larger. They are thus often placed on the back of a larger aircraft. Figure 3.3-a shows the most well-known of these types of radars, the AWACS radar, with its antenna (the aircraft contains a lot more than the radar). It is basically a rather old design It operates at S-band uses a slotted waveguide with very low sidelobes and horizontal polarization. It is scanned mechanically in azimuth and electronically with ferrite phase shifters in elevation.

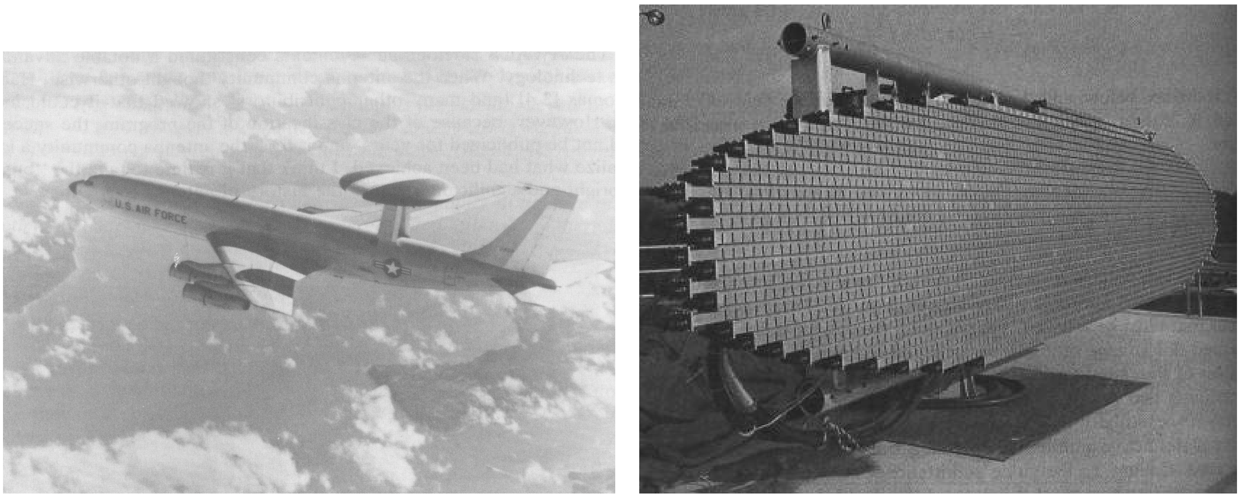

Figure 3.3-a: Slotted waveguide array in AWACS. Mechanically rotated in azimuth and phase steered in elevation.

Another surveillance radar which does not require such a large aircraft is the ERIEYE in Figure 3.3-b. It is also a S-band slotted waveguide array with horizontal polarization but with electronic steering in azimuth and a few fix lobes in elevation. Each of the vertical radiating waveguides is connected to a TR module.

Figure 3.3-b: The ERIEYE with its pod with slotted waveguide on the back. Phased steered in azimuth.

A surveillance radar where the drawbacks of mechanical scanning have been eliminated is the Phalcon system from Israel in Figure 3.3-c, operating in L-band. Here there are several arrays on the sides of the aircraft as well as in its nose.

Figure 3.3-c: The Phalcon airborne system from Israel.

3.4 Picture sources

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4 GROUND BASED SYSTEMS

4.1 Introduction

The detection and interception of opposing military aircraft in air defense has been the predominant military use of radar. Ground based radar systems are essential for tracking, locating and eventually eliminating enemy threats such as mortars, missiles and other projectiles. To cope with these threats in a dynamic environment, highly mobile radar systems are utilized that enable military forces to increase local awareness and deal with threats when it is necessary. The detection of intercontinental ballistic missiles is mostly covered by large stationary systems that operate at relative low frequencies and high radiated power necessary for the detection of targets at large distances. This ground based radar systems chapter has conveniently been divided into stationary systems and mobile systems.

4.2 Stationary Systems

4.2.1 PAVE PAWS (USA)

The PAVE PAWS (Phased Array Warning System) radar system is primarily intended for surveillance of intercontinental ballistic missiles (ICBM) and other space objects. The system is placed in four locations around the US borders to detect and track incoming missiles and satellites. The radar antenna has two faces to cover a large angular sector and consists of two planar active phased arrays at UHF-band with 25 m diameter. Each radar system has about 3500 antenna elements per face and the average transmitted power is about 60 kW. The radar system can search and track several targets simultaneously and this is one of the main reasons for using a phased array antenna. The radar system has a range of several 1000 km for typical targets.

Figure 4.2-a : AN/FPS-123 (V3) PAVE PAWS radar for ICBM and space surveillance.

4.2.2 COBRA DANE

Coastal Battlefield Reconnaissance and Analysis (COBRA)
Raytheon.
The COBRA DANE is a deployed and operational, ground based, L-band large phased array radar (LPAR) located in Shemya, AK. COBRA DANE has historically fulfilled three concurrent missions: intelligence data collection of strategic missile systems; treaty verification; and early warning to CINCNORAD/CMAFS of ballistic missile attack against CONUS and southern Canada. COBRA DANE also passes Inter-Range Vector (IRV) data to other downrange sensors. In 1990, the USAF invested $60 million in the COBRA DANE System Modernization (CDSM). In 1993, budgetary constraints forced discontinuation of all but the primary mission of intelligence data collection.

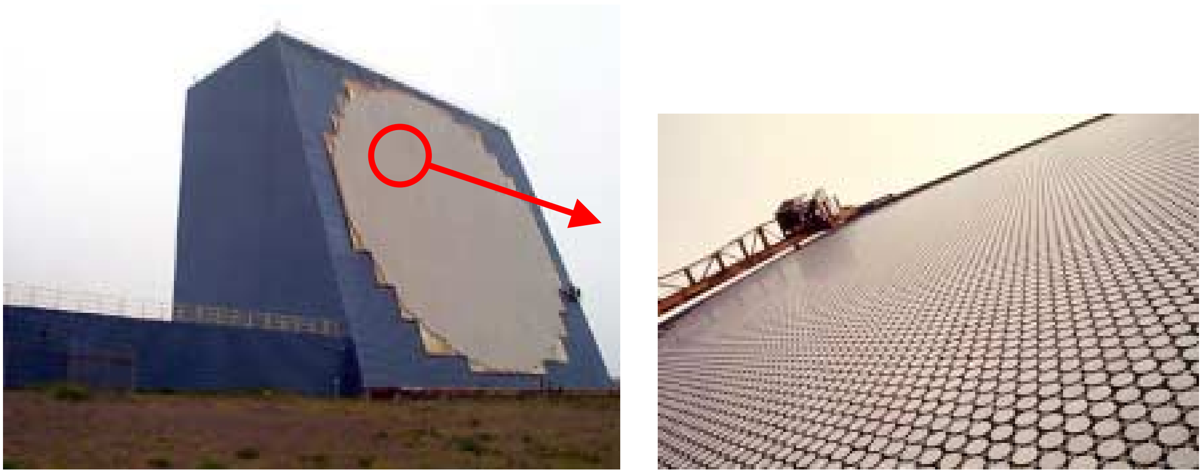

Figure 4.2-b: COBRA DANE and close up of a section of the aperture.

Description

- Cobra Dane is an Early Warning Radar (EWR) designed to acquire precise radar metric and signature data on developing foreign ballistic missile systems for weapons system characterization. COBRA DANE was developed in the mid 1970s and became operational in 1977.

- Beginning in 1990, the COBRA DANE system was upgraded. The modernization involved replacing aging and unsupportable radar, computing and communications interface equipment, including: the Receiver/Waveform Generator, Digital Pulse Compression Unit, and all ADPE and recording peripherals. The majority of the transmitter, array and facilities subsystems remained intact. All operations software was rewritten and enhanced using the ADA language. The entire system is controlled by dual redundant VAX 6000-520 mainframes (13 MIPs each) for increased mission reliability.

- COBRA DANE generates approximately 15.4 MW of peak RF power (0.92 MW average) from 96 Traveling Wave Tube (TWT) amplifiers arranged in 12 groups of 8. This power is radiated through 15,360 active array elements, which together with 19,408 inactive elements comprise the 94.5 ft diameter array face.

- The system, designated AN/FPS-108, has a phased array L-Band antenna containing 15,360 radiating elements occupying 95% of the roughly 100 by 100 foot area of one face of the building housing the system. The antenna is oriented toward the west, monitoring the northern Pacific missile test areas.

- Mission data is provided to the National Air Intelligence Center (NAIC) for reduction and analysis.

- Organizations: primary requirements are established by the Arms Control and Disarmament Agency. Headquarters Air Intelligence Agency (HQ AIA) is responsible for radar operations and maintenance. HQ AIA/LGM, located at Kelly AFB TX, is the responsible Operations and Maintenance (O&M) office for the system. On site O&M is performed under a Contractor Logistics Support (CLS) contract managed by HQ AIA. NAIC provides processing and data exploitation services.

4.3 Mobile Systems

4.3.1 RAT 31DL

Air Defence and Battlefield System; Long Range Radar.
Multiple pencil beam. High performance transportable D-band (NATO band) land based phased array 3D long range radar (solid state) effective to a range of over 500 km. Multiple independent and simultaneous narrow pencil beam scanning architecture with monopulse technique for height measurement. Of latest state-of-the-art technology and classified as NATO Class-1 radar, the RAT 31DL incorporates advanced technical capabilities for counter-measures (ECCM). Designed to operate in a modern and complex environment, the RAT 31DL is able to rapidly adapt to a broad spectrum of changing scenarios where jammers coexist with heavy clutter. The RAT 3DL also has Anti-Tactical-Ballistic Missile (ATBM) capabilities.

As an example, in the TBM tracking role the RAT31DL is capable to dedicate one beam to illuminate the TBM while the other three beams are scheduled differently to cover the remaining part of coverage. This guarantees the maximum ToT on TBM compatible with the antenna rotation speed. This capability can be exploited in adaptive way applying it in the relevant azimuthal sectors only.

The radar is composed by: (i) the antenna group, including radiating array, spine with TRMs, antenna cabinet with analogue receiver, base, (ii) the equipment shelter, containing the processing cabinet, the IFF, the RES (radar environment simulator), and HMI (human machine interface like console, service monitors), UHF/VHF communication, modems, time standard, (iii) the cooling unit consisting in a redundant air cooler for the equipment shelter while the antenna group is cooled by natural ambient air circulation.

Figure 4.3-a : Air Defence and Battlefield System; Long Range Radar, RAT 31DL.

The Antenna

The active antenna architecture is the key to an easy and competitive implementation of the MIS technique. The radiating aperture is realized with 42 row planks, each one supporting the horizontal beam former. This is a strip line power splitter, distributing the signal to the radiating dipoles with a suitable amplitude and phase to obtain the horizontal pattern with desired beam width and side lobes. Each row is connected to a TRM combining a reception and a transmission channel. Placement of power and low-noise amplifiers at the antenna aperture eliminates transmit and receive losses. A filter and a coupler are used both in transmission and reception. The filter is used both to limit the radiated spectrum and to filter out disturbances during reception. The receiving chain has a duplexer, a low noise amplifier and a set of four independent phase & amplitude adjustment modules (PAAM). This last component uses GaAs MMIC technology and includes RF and logical interface circuits. Each PAAM is devoted to a specific beam and is combined, with the analogous components located on the other rows, into the sum and difference beam forming networks. The amplitude control of PAAM is mainly used to recover, via calibration, the gain change of the receiving chain. The transmission contains a RF power amplifier fed by a single PAAM; the latter is sufficient because the transmitted signal is made by a cascade of four different pulses that can be controlled in time sequence. A single set of PAAMs is suitable both for sum and difference signals because the pointing directions of these two beams are always made coincident. To calibrate the antenna a test signal is injected into each TRM through the coupler permitting to keep the performance (pointing accuracy and the vertical side-lobe levels at specified values) unaffected with large temperature variations, ageing of components and component replacement. To reach low side lobes both in transmission and reception a Taylor tapering has been extensively used except for the transmission pattern in elevation, where a two 6 dB steps taper has been adopted.

The distributed architecture has significant advantages respect to the solid-state bulk transmitter.

- The power rotary joints are not needed: they are expensive and introduce mechanical constraints caused by their huge dimensions and weight. The connection between antenna group and equipment shelter is via IF cable only, because the front-end receiver is contained into the antenna cabinet, which is rotating with the antenna. This approach reduces cost and simplifies the cabling permitting long connection paths.

- Lower generated RF power due to absence of insertion losses caused by power phase shifters and RF connections. Thus a lower number of active devices is used, less prime power supply is needed and less heat has to be removed. Natural air circulation is sufficient also because the dissipating surfaces on the antenna are large.

- Growing capability: beams can be added with a reasonable increase of modular components. Exercises have been done to compare the cost of a simple one-beam configuration respect to an alternative four beams obtaining an increase of cost at sensor level in the range of 12% - 20% depending on the specific application and the technology used for the receiver.

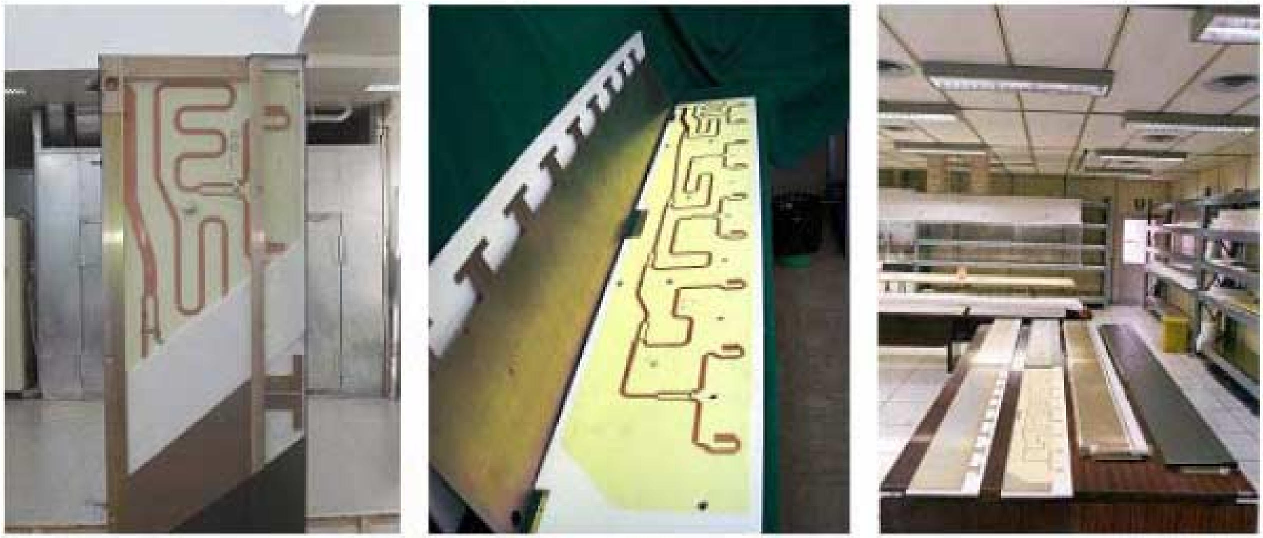

Figure 4.3-b : Radiating elements and distribution network. Row of the the RAT 31DL.

A relevant aspect of active array antenna is the accessibility of the components for removing and repair. This antenna is based on modular components easy to plug; an elevator, which is an integral part of the antenna spine, allows the operator easy servicing. Furthermore, the distribution of power source across the antenna aperture implies graceful degradation.

4.3.2 PATRIOT

PATRIOT is a long-range, high-altitude, all-weather system designed to defeat advanced threats, including aircraft, tactical ballistic missiles, and cruise missiles. PATRIOT can simultaneously engage multiple targets under the most severe electronic countermeasure conditions. Multifunction phased array radar, track-via-missile guidance, and automated operations are the key features of the PATRIOT system. The phased array radar carries out search, target detection, track and identification, missile tracking and guidance and electronic counter-countermeasures (ECCM) functions. The radar consists of a TWT transmitter, a passive phased array antenna and a coherent pulse doppler receiver all mounted in a trailer vehicle. The radar operates at C-band with an average transmitted power of 10 kW that gives a typical range of 100 km to missile targets. The antenna is a planar space fed waveguide lens array with 5000 antenna elements for phase steering in azimuth and elevation. The antenna size is 2.4 m diameter and the beam can be steered 90° in azimuth and elevation. Nine simultaneous targets can be engaged and several hundred can be handled in the command and control system.

Figure 4.3-c : PATRIOT AN/MPQ-53 phased array radar.

4.3.3 AN/TPQ-37

The AN/TPQ-37 Firefinder is a long-range weapon-locating radar system that quickly detects and pinpoints the location of adversary long-range weapons. It can locate up to 10 different weapons in seconds at a range of 3 to 50 km. The stationary phased array antenna allows the radar to electronically switch beam positions (90 degrees scan range), thus enabling it to search for new targets while simultaneously tracking previously detected targets. On any target detection an immediate verification beam is generated and an automatic tracking sequence begins. When long-range surface-to-surface missiles must be located, a special 60-degree sector mode extends the AN/TPQ-37's range. Friendly fire can then neutralize further fire from those weapons.

Operation frequency: 15 frequencies at S-band.

Peak power transmitted: 120 kW

Manufacturer: Raytheon

Figure 4.3-d : AN/TPQ-37 firefinder is a long-range weapon-locating radar.

4.3.4 AN/TPQ-36

AN/TPQ-36 is a medium range firefinder radar which is lightweight, small and highly mobile capable of detecting weapon projectiles launched at any angle within selected 90-degree azimuth sectors over 360 degrees of coverage. The AN/TPQ-36 can locate simultaneous and volley-fire weapons. It can also be used to register and adjust friendly fire. The AN/TPQ-36's stationary antenna sweeps a rapid sequence of beams along the horizon, forming an electronic radar curtain over a 90° area. Any target penetrating the curtain triggers an immediate verification beam. On verification, an automatic tracking sequence begins. Upon projectile detection, the weapon location is computed and is used to direct counter-battery fires.

Operation frequency: 32 frequencies at X-band
Peak power transmitted: 23 kW

Manufacturer: Raytheon

Figure 4.3-e : AN/TPQ-36 firefinder radar.

4.3.5 AN/TPN-25

Radar Set AN/TPN-25 is the Precision Approach Radar (PAR) required to guide an aircraft to a safe GCA (Ground Control Approach) landing during IFR (Instrument Flight Rules) weather conditions.

Figure 4.3-f : AN/TPN-25 is the Precision Approach Radar (PAR).

4.3.6 ARTHUR (Sweden)

ARTHUR (Artillery Hunting Radar) is counter-battery radar that can locate enemy artillery using measurements of projectile trajectories and also locate target areas for our own artillery. The radar consists of a TWT transmitter, a passive phased array antenna and a coherent pulse doppler receiver all mounted in a tracked vehicle. The radar operates at C-band with a average transmitted power of 0.5 kW that gives a typical range of 40 km to larger projectiles. The antenna is a planar slotted ridge waveguide array with phase steering in azimuth and frequency steering in elevation. The antenna size is 1.2 m x 2.1 m and the beam can be steered 90° in azimuth and 8° in elevation. Eight simultaneous targets can be tracked and several hundred can be handled in the command and control system. The target accuracy is about 100 m at maximum range.

Figure 4.3-g : ARTHUR (Artillery Hunting Radar) for artillery location and fire control.

4.3.7 FLAP LID (Russia)

The SA-10A launch complex consists of a missile battery which includes a battery command post and engagement control center, the large CLAM SHELL 3D continuous wave pulse Doppler target acquisition radar, the FLAP LID A I-band multi-function phased-array trailer-mounted engagement radar with digital beam steering in hardened sites, and up to 12 semi-trailer erector-launchers which mount four tubular missile container-launchers.

The SA-10B mobile missile battery comprises the combined FLAP LID B engagement radar and engagement control/command post station mounted on a MAZ-7910 chassis, up to 12 TELs (SPU: mobile launcher unit), a trailer-mounted 36D6; CLAM SHELL 3D 360º scanning target designation radar, and a maintenance section.

The combined FLAP LID-B radar/engagement control vehicle has the 2.75 m2 planar array antenna on a box-like antenna mount and support systems container. When traveling the array is carried horizontally, and when deployed it is raised above the container to an angle of approximately 60º.

SA-10 missile guidance is of the Track-Via-Missile (TVM) type with the FLAP LID guidance radar capable of engaging up to six targets simultaneously, with two missiles assigned per target to ensure a high kill probability.

Figure 4.3-h : 30N6 FLAP LID B engagement radar on mobile platform.

4.3.8 MARTELLO (UK)

The Marconi Radar Type S.723 is an 'L' Band (23 cm), long range, transportable 3D surveillance radar system designed for world-wide use in military applications.

The Antenna is a planar array, consisting of a stack of 40 linear arrays and is rotated at six revs/min about a vertical axis to provide all round surveillance. Each linear array is fed with R.F. modules power from its own solid states power amplifier module. The R.F. modules are fed with the appropriate power level from a single similar R.F. module and phased so as to produce the required vertical transmit radiation pattern.

Each linear array has an associated receiver and the return signals are converted to the system IF and amplified before being passed to a beam formign system. The individual are combined in this unit to form a stack of six simultaneous surveillance and height-finding beams whitch provide cosecant squared cover to above 20°.

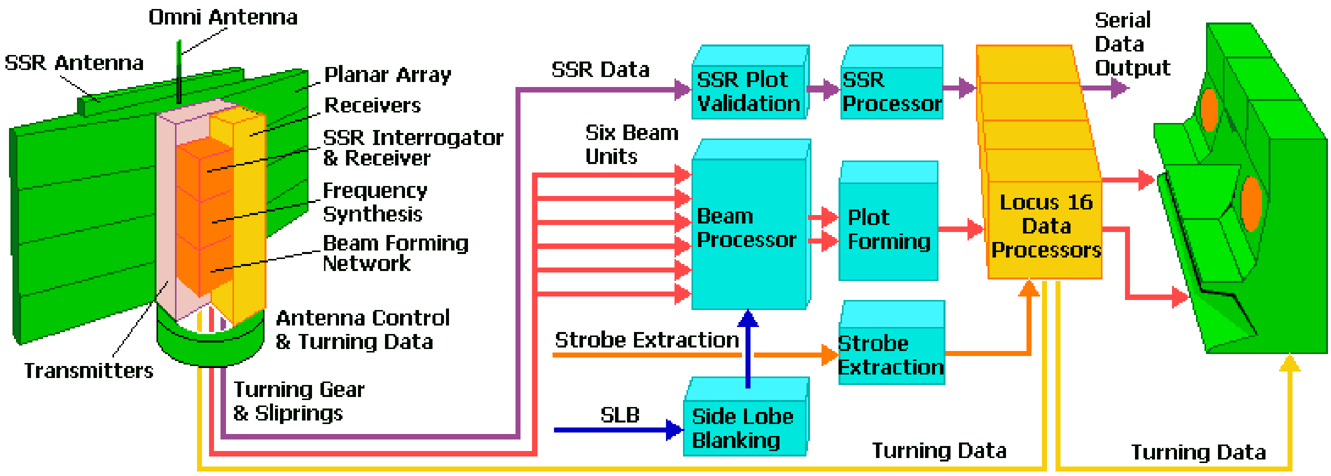

Figure 4.3-i: MARTELLO System schematic.

In the S713 there are 60 rows, each with a duplexer and receiver but the transmitter power is obtained from a power source common to all. The transmitter is a substantial equipment housed in a separate vehicle and coupled to the antenna by waveguide.

By comparison, the S723 has 40 dipole rows, again each with a duplexer and receiver, but each row now has a locally mounted transistor transmitter, all 40 of which are fed coherently from a common r.f. source.

In both cases, the planar array is built up of detach-able 'antenna modules' which are accurately located in position by jigged fixings on the supporting spine. For transportation, the modules are removed from the spine and carried on a separate vehicle, but the detailed arrangements differ between S713 and S723 because of the difference in module size. S713 has 12 modules, each with 5 rows of dipoles; the modules are 20 feet in length and 3 feet wide. S723 has 4 modules, each of 10 rows, but they are 40 feet long and 6 feet wide. Power assistance for handling is built into the deployment system in both cases.

4.3.9 ROTHR (USA)

ROTHR (Relocatable Over-the-Horizon Radar) AN/TPS-71 is a land-based, high-frequency (HF) radar which can cover a 64-degree wedge-shaped area at ranges of 500 to 1,600 nautical miles. This extended range is achieved when transmitted HF energy is refracted by the ionosphere onto distant targets. Radar to target ranges of 1000 nmi and more are typical. Use of the 10 to 60 meter wavelengths associated with HF radar requires physically large antennas. Each ROTHR achieves a nominal half degree azimuth angular resolution with a 2.58-km-long linear phased receiving array consisting of 372 twin-monopole elements. Each monopole pair has a receiver and analog-to-digital converter attached to it. A digital beamformer forms 18 beams which are then Doppler processed to separate the moving targets from the ground clutter. Range resolution is achieved by transmitting a 25-kHz continuous frequency-modulated waveform. A radar resolution cell on the ocean surface is therefore about 6 km in range by about 15 km in azimuth, for the frequency and range used. Radar frequency is variable and is selected using real-time sweep frequency ionospheric soundings.

Manufacturer: Raytheon.

Figure 4.3-j : Monopole array of the ROTHR system.

4.3.10 THAAD GBR

Terminal High Altitude Area Defence (THAAD)

- Frequency band : I/J
- Number of modules : 25000
- Number of faces : 1
- Aperture size : 12 × 8.4 m
- Manufacturer : Raytheon

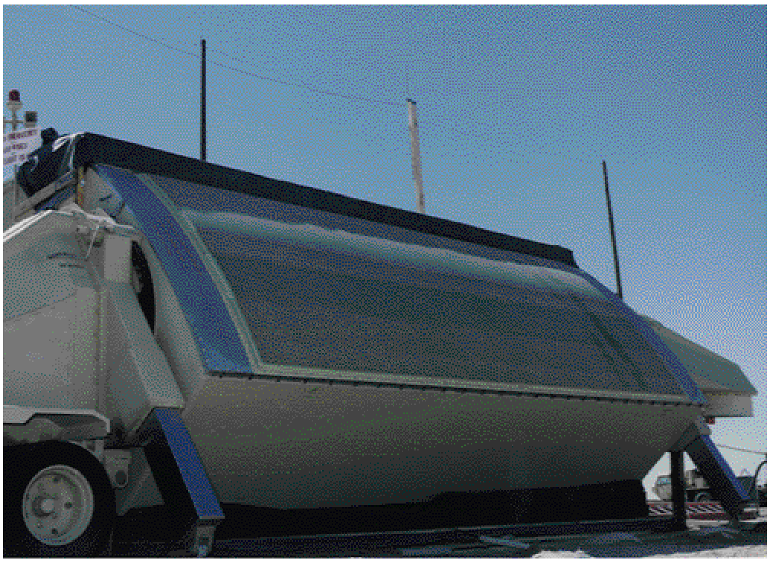

Figure 4.3-k: THAAD GBR.

Ref: IEEE Symposium on Phased Array Systems and Technology, Boston, 15-18 October 1996, pp. 260 - 265

4.3.11 CEA-FAR GSR

CEA-FAR GSR is an active phased array radar air craft detection system. Keywords are: modular, programmable and scalable. CEAFAR is suitable for use in a range of military and civil applications, ground surveillance radar (GSR), air surveillance and air traffic control and even ship self defence. The smallest configuration is man portable and the largest is suitable for area defence shipboard applications.

- Frequency band : E/F
- Number of modules : ?
- Number of faces : 6
- Aperture size : ? × ? m
- Manufacturer : CEA

Figure 4.3-I : CEA-FAR GSR.

Ref: Jane's International Defence Review February 2002, pp. 42-43

4.3.12 MEADS

MEADS (Medium Extended Air Defense System) is a tactical missile defense system that is mobile for battlefield operations yet capable of successfully defending against modern tactical ballistic and low-flying cruise missiles. The system employs a UHF Surveillance Radar (SR) built around an open architecture configured with high-power UHF T/R modules, digital adaptive beamforming and a programmable waveform generator. The UHF radar hands off to a low-cost, high-performance X-band Multifunction Fire Control Radar (MFCR). The MFCR is using a UHF/X-band common processor for data and signal processing, digital adaptive beamforming, digital receiver/exciter and X-band T/R modules. The UHF-band is preferable for efficient wide area search, while X-band is capable of great precision and accuracy for tracking, and wide bandwidth for discrimination.

The SR is a rotating, solid state, phased array radar, with an integrated IFF antenna above the main radar antenna. Likewise the MFCR is a rotating, solid state, phased array radar, but it has an optional ESM subsystem in addition to IFF. Both sensors can operate in a staring mode to cover a limited azimuth sector or a rotating mode to cover 360°. While the two radars are very different in RF frequency, they share a common mechanical platform and digital signal/data processor. The SR uses digital beamforming and pulse-doppler waveforms. The UHF antenna is a 12 x 12 array with element digital demodulation and beamforming in the frequency domain. The X-band antenna is a 96 x 96 array with 12 x 12 subarray digital demodulation and beamforming. The MFCR antenna "octopack," contains 8 radiating elements and their associated T/R modules and the subarray is 8 x 8 elements. The digital processor is identical to the SR's, proving digital beamforming from subarray signals, and pulse-doppler processing. The MFCR truck and stationary platform are identical to the SR's.

Figure 4.3-m: MEADS UHF Surveillance Radar and X-band Multifunction Fire Control Radar.

- Manufacturer : MEADS International

Ref: Jane's International Defence Review February 2002, pp. 42-43

4.3.13 COBRA

COBRA (Counter-battery Radar) is a counter-battery radar that can locate enemy artillery using measurements of projectile trajectories and also locate target areas for our own artillery. The radar consists of an active phased array antenna and a coherent pulse doppler receiver mounted in a wheeled vehicle. The radar operates at C-band with an average transmitted power of 2 kW that gives a typical range of 80 km to larger projectiles. The antenna is a planar dipole array of 2700 antenna elements with phase steering in azimuth and elevation. The antenna size is 2.5 m x 2.5 m and the beam can be steered 90° in azimuth and elevation. Several tens of simultaneous targets can be tracked and several hundred can be handled in the command and control system. The target accuracy is about 100 m at maximum range.

Figure 4.3-n : COBRA counter-battery radar.

- Manufacturer : Euro-Art

Ref: http://www.rrl.co.uk/case_studies/cs_cobra.html
Ref: COBRA Lessons learned, Microwave Symposium 1994, pp. 1423-1426

4.3.14 ATBM EL/M PINE TREE

Early warning and fire control radar. The radar includes the trailer mounted antenna array, the power generator, a cooling system and a control centre. System is an electronically scanned, solid state, phased array radar, and was developed from the Elta Music phased array radar.

- Frequency band : D
- Number of modules : 2300
- Number of faces : 1
- Aperture size : 12×4.8 m
- Manufacturer : IAI Elta

Figure 4.3-o: Pine Tree.

Ref: Jane's International Defence Review February 2002, pp. 42-43

4.3.15 GIRAFFE AMB

The GIRAFFE AMB (Agile Multi-Beam) air defense surveillance radar is the latest in 3D radar technology. Tailored for operations with medium and short-range surface-to-air missile systems, the GIRAFFE AMB includes an integrated C3 system enabling it to act as the command-and-control center in an air defense system. It can simultaneously be integrated in a cluster of netted GIRAFFE systems, providing outstanding radar cooperation. Unlike conventional 3D search radar that rely on elevation scanning technology, the GIRAFFE AMB covers a large elevation range simultaneously by using one wide beam for transmission and multiple digitally shaped narrow beams for reception. The antenna is a vertically polarized phased array and it has digital beamforming on receive in elevation. The transmit beam is phased controlled in elevation while the antenna rotates mechanically in azimuth. In the normal surveillance mode four stacked receive beams are generated by digital beamforming. In the tracking mode and in long-range surveillance modes a narrow high gain transmission beam is used for which two receive beams are adapted. The radar consists of a TWT transmitter, a passive/active phased array antenna and a coherent pulse doppler receiver all mounted in a wheeled vehicle. The radar operates at C-band with an average transmitted power of 2 kW that gives a typical range of 100 km to air targets. The antenna size is 2.4 m x 0.8 m and the beam can be steered over 90° in elevation. The antenna is placed inside a radome and consists of the following main parts: power divider in elevation, 18 high power ferrite phase shifters, 18 antenna boards, 9 dual channel receiver modules, received signals multiplexer, antenna controller board, receiver calibration/test network, LO signal distribution network and waveguide filters. Each antenna board employs 48 rectangular radiating waveguide antenna elements and the total array is composed of 18 x 48 antenna elements. This multi-beam antenna concept provides not only superior altitude coverage but an unparalleled 3D target updates rate of one per second, effectively maintaining the inherently high rate of a 2D system.

Figure 4.3-p : GIRAFFE AMB surveillance radar.

4.4 References

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European Commission - 6th Framework Programme	***ACE (Antenna Centre of Excellence)***	Information Society Technologies

REVIEW ON USER TERMINAL ARRAYS

Institution	Authors
DLR	Michael THIEL

Document Evolution		
Revision	Date	Status
Rev. 1	12/07/2004	First Public Issue
Rev. 1T	10/12/2004	Integration within ACE_2.4_Doc-template, to be annexed to A2.4- D1
Rev. 2T	14/12/2004	3 missing figures included & small corrections

Table of contents

Table of Figures

1 TASK

Within the NoE ACE work package 2.4 (Planar & conformal arrays; multibeam, reconfigurable & adaptive Antennas) a review on different type of array antennas was decided to perform.

The present document contains the review on **user terminal arrays**, especially for countries outside Europe.

2 LITERATURE RESEARCH

2.1 Literature data base

Different types of data base where used:

- Internet search via Google
- Literature search in several specialised data bases

This review can only show a part of the big amount of user terminal arrays and does not claim for completeness. Only short-term available information could be included (Internet, IEEE Transactions on AP, AP-S and other available journals or conference proceedings).

The search was performed by the help of the keywords: user terminal array/antenna, smart antenna terminal, microstrip antenna, satellite user terminal, satellite communication user terminal, digital beam forming terminal, research and other keywords with further combinations.

2.2 Abbreviations

GBS - Global Broadcast Service
MILSTAR - Military Strategic and Tactical Relay Satellite
DBS - Direct Broadcast Satellites
UAV – Unmanned aerial vehicle
WLAN – Wireless local area network

2.3 Literature search results

2.3.1 NASA Glenn Research Centre & Boeing

A broadband active phased array SatCom transmit antenna was developed with a possible data rate of 256 kbps. This antenna development together with an existing receive solution was included in a two-way broadband communication link to commercial aircraft, called Connexion by Boeing. More information may be obtained e.g.

- http://www.grc.nasa.gov/WWW/RT2000/6000/6150kerczewski.html
- http://www.grc.nasa.gov/WWW/RT1999/6000/6150zakrajsek.html

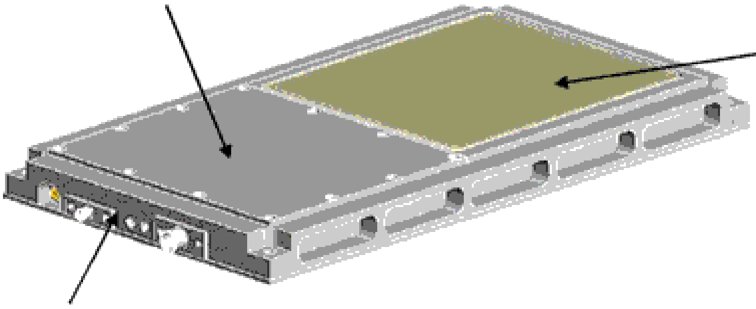


Figure 2.3-A : Ku-band transmit antenna developed by Glenn & NASA

Further interesting descriptions of Boeing phased array antennas can be downloaded from

- http://eo1.gsfc.nasa.gov/miscPages/TechForumPres/23a-XPAA_Background.pdf

2.3.2 Military SATCOM terminals

Military applications need broadband SATCOM terminals from VHF to millimetre waves. Concepts are described in

- http://www.mitre.org/work/tech_papers/tech_papers_01/comparetto_multiband/comparetto_multiband.pdf

2.3.3 TV SatCom terminals

Flat panel TV satellite-receive antennas in combination with a so called Digital Satellite Seeker (DSS) are product of SATCOM Electronics company. TV-receive antennas are part of a big market. The goal for ongoing development is to reduce size and increase functionality.

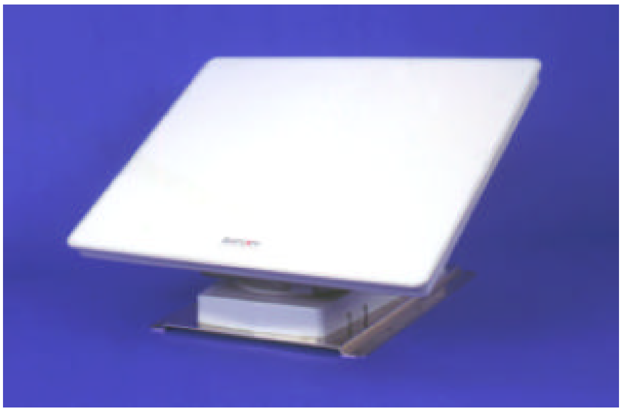


Figure 2.3-B : Satellite-receive antenna

Figure 2.3-C : Digital Satellite Seeker

More information can be found at

- http://www.satcomweb.com/SatCom%20Electronics%20Products%20Bulletin%20August%202002.pdf

2.3.4 GBS/MILSTAR SatCom antenna

At Air Force Research Institute a 20 GHz SatCom antenna was developed and already tested in an airborne environment. The antenna is foreseen as a low cost solution and is equipped with four Luneburg lens radiators. The antenna is a receive antenna, shown in the following figures. During the demonstration flight data rates of up to 6.0 Mbps were transferred.

Figure 2.3-D : Airplane with mounted antenna on top a) in flight and b) detailed view of top mounted antenna

Figure 2.3-E : GBS/MILSTAR antenna consisting of a mechanically steered assembly of 4 lens hemispheres on a ground-plane.

Information can be found online:

- http://www.its.bldrdoc.gov/meetings/art/art99/slides99/ole/ole_s.pdf
- http://www.its.bldrdoc.gov/meetings/art/art99/slides99/ole/ole_abs.pdf
- http://www.afrlhorizons.com/Briefs/0009/IF9906.html
- http://www.mitre.org/work/tech_papers/tech_papers_99/airborne_demo/airborne_demo.pdf

2.3.5 EMS Space Technologies

ACTS Ka band tracking antenna

EMS Space Technologies has developed a 20/30 GHz receive/transmit terminal which has already been used on several platforms. It is used to communicate with NASA's Advanced Communication Technology (ACTS) Satellite.

Figure 2.3-F : ACTS Ka band tracking terminal

Other EMS antennas

EMS products include airborne Ku-band antennas. The receive DBS/GBS terminal is mechanically steered in both azimuth and elevation and apart from TV reception used for data links only.

a)

b)

c)

d)

Figure 2.3-G : Mechanically steered Ku-band receive antenna. a) Complete antenna. b) Antenna installed on Military aircraft. c) View of the waveguide slot array. d) Antenna installed on commercial aircraft for TV satellite reception.

Also the uplink in Ku-band is covered by EMS. The transmit antenna was foreseen for the Darkstar UAV program. It is electronically scanned in elevation and mechanically rotated for azimuthal coverage.

Figure 2.3-H : Ku-band uplink

A low profile reflector array has also been developed at EMS and may serve as a solution on large platforms. It is called Contiguous Paraboloid [1].

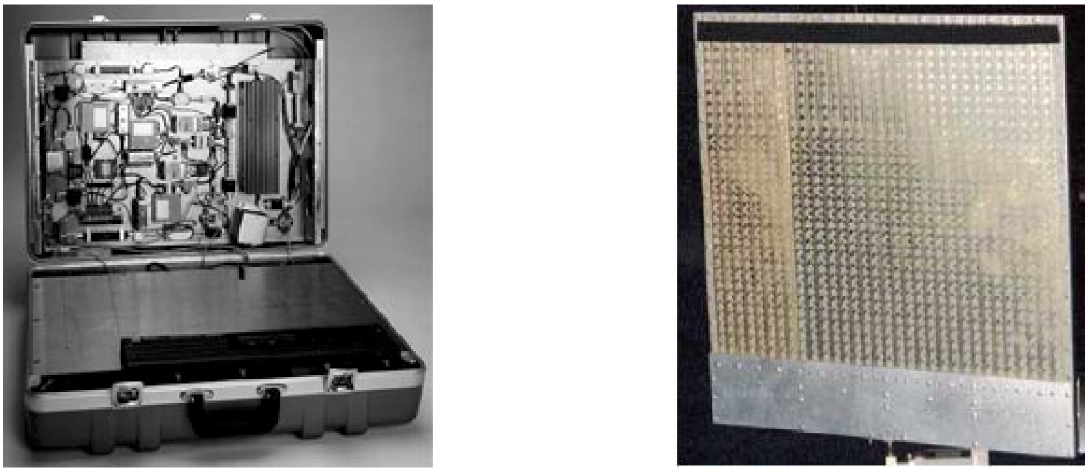
Figure 2.3-I : Contiguous Paraboloid

For further information refer to

- http://www.emsstg.com/defense/ant_mobile.asp
- http://www.emssatcom.com/solutions/s_land_mobile.asp

2.3.6 Portable Ka-band terminals at CRC

At Communications Research Centre Canada (CRC) a portable Ka-band terminal was developed. There are so called suitcase and even smaller briefcase terminals with different types of antennas connected. The original antenna was a planar one, whereas now they use a reflector type antenna.



a) b)

Figure 2.3-J : Suitcase terminal. a) Inside view. b) Original antenna.

Further information can be found online

- http://www.crc.ca/en/html/rss/home/projects/term

2.3.7 AIRLINK high gain antenna system

The airlink antennas are mounted conformally on side of the aircraft and are operated in L-band for transmission. These are electronically steered phased arrays. They cover 360° around the aircraft and 210° above.

Figure 2.3-K : AIRLINK High gain antenna

Further information can be downloaded from

- http://www.ball.com/aerospace/airlink_high.html

2.3.8 CMC Electronics (Canada) – SatCom high gain antenna system

The system is developed for communication use in L-band and will be top mounted to achieve hemispherical coverage.

Figure 2.3-L : SatCom high gain antenna system.

Detailed information is available at

- http://www.cmcelectronics.ca/Pdfs/ComAv_AeroCom_Brochure2102.pdf

2.3.9 Satellite-terminals Technology review

The review can be found online

- http://www.wtec.org/loyola/satcom2/

The future market situation is discussed and also the future need of user terminals. The growth in number of user terminals is shown in the following figure in relation to the size of the antennas.

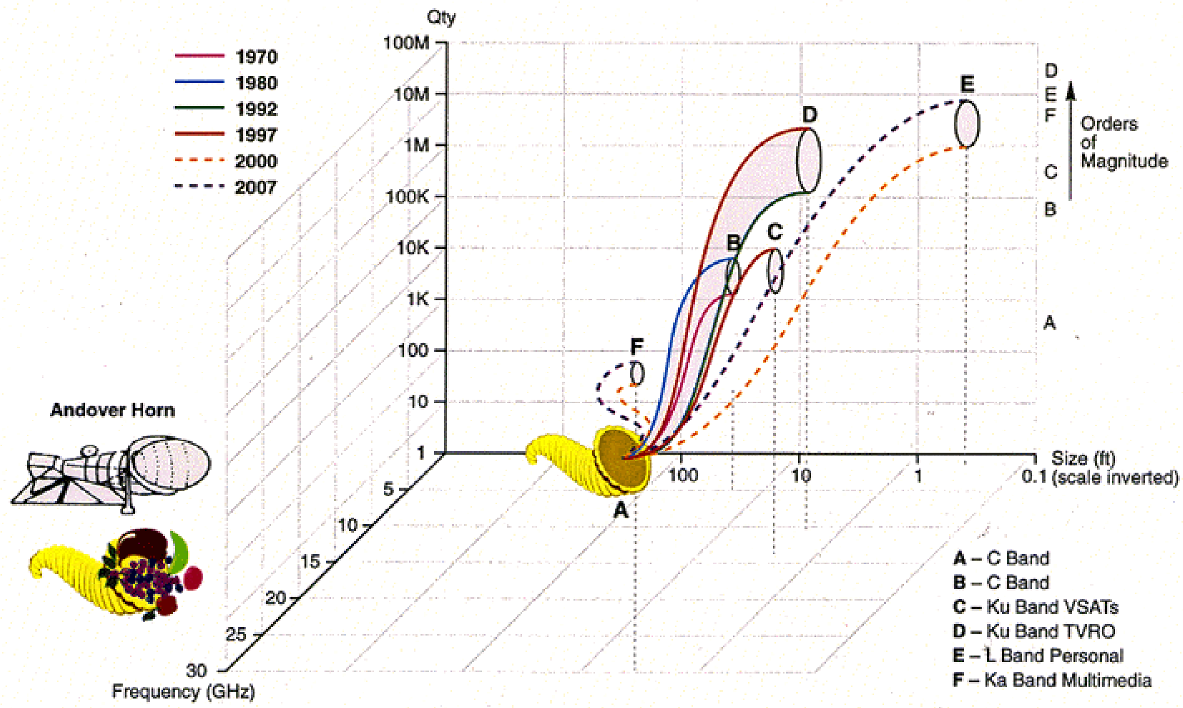


Figure 2.3-M : Evolution of satellite terminals in number of terminals, frequency and size (1965-2007).

Several recently proposed solutions for satellite user terminals listed in the report are shown in Figure 2.3-N.

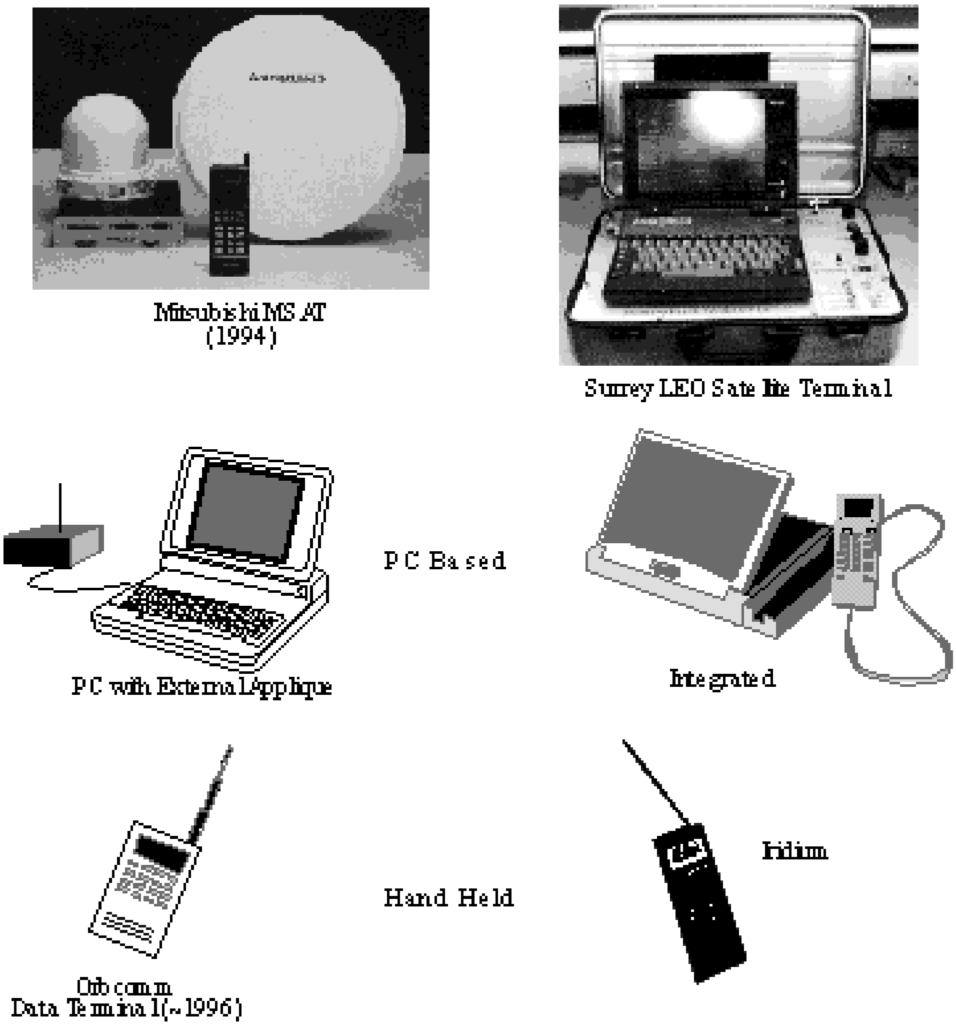


Figure 2.3-N : Handheld and highly portable communications satellite terminals

2.3.10 Smart antennas for third generation TDMA at AT&T

Different types of smart antennas are discussed in

- http://www.sce.carleton.ca/bcws/oldsource/softlibrary/27Nov00.pdf

One example of a smart laptop antenna is shown below. The laptop antenna is foreseen to be used in a MIMO system.

Figure 2.3-O : Prototype smart antenna for laptops

2.3.11 ESPAR antenna

At ATR Adaptive Communications Research Laboratories, Kyoto, JAPAN an electronically steerable passive array radiator (ESPAR) was developed. This type of antenna should enable the use of adaptive array techniques in a user terminal. Some publications give more details about the performance of the antenna [2], [3]. The antenna is foreseen for use in wireless ad hoc computer networks.

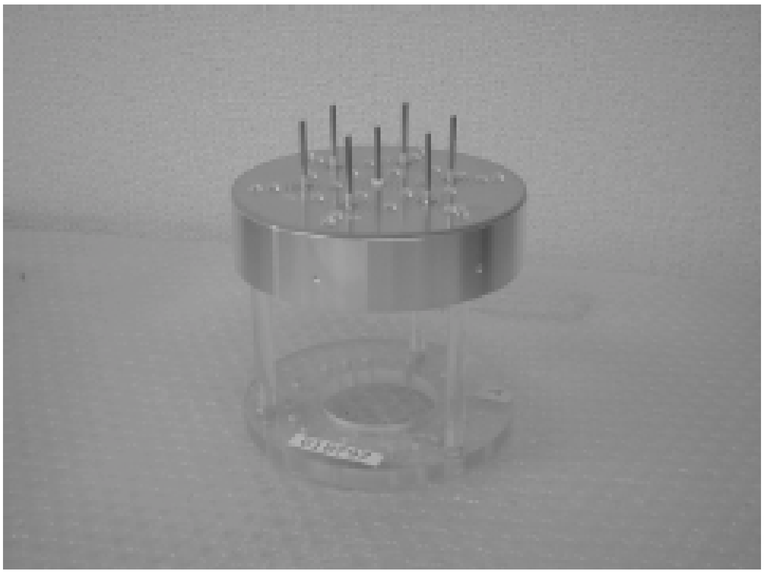


Figure 2.3-P : A fabricated ESPAR antenna

More links regarding ESPAR antenna are listed online

- http://www.acr.atr.jp/acr/general/report/dept3/ESPAR2002/ESPAR-e.html

2.3.12 60-GHz-band Beam-steerable Planar Array Antennas Using Varactor Diodes

Another smart antenna development at ATR is a 60 GHz planar array. This is foreseen to be used for indoor multi-channel video transmission or a home network.

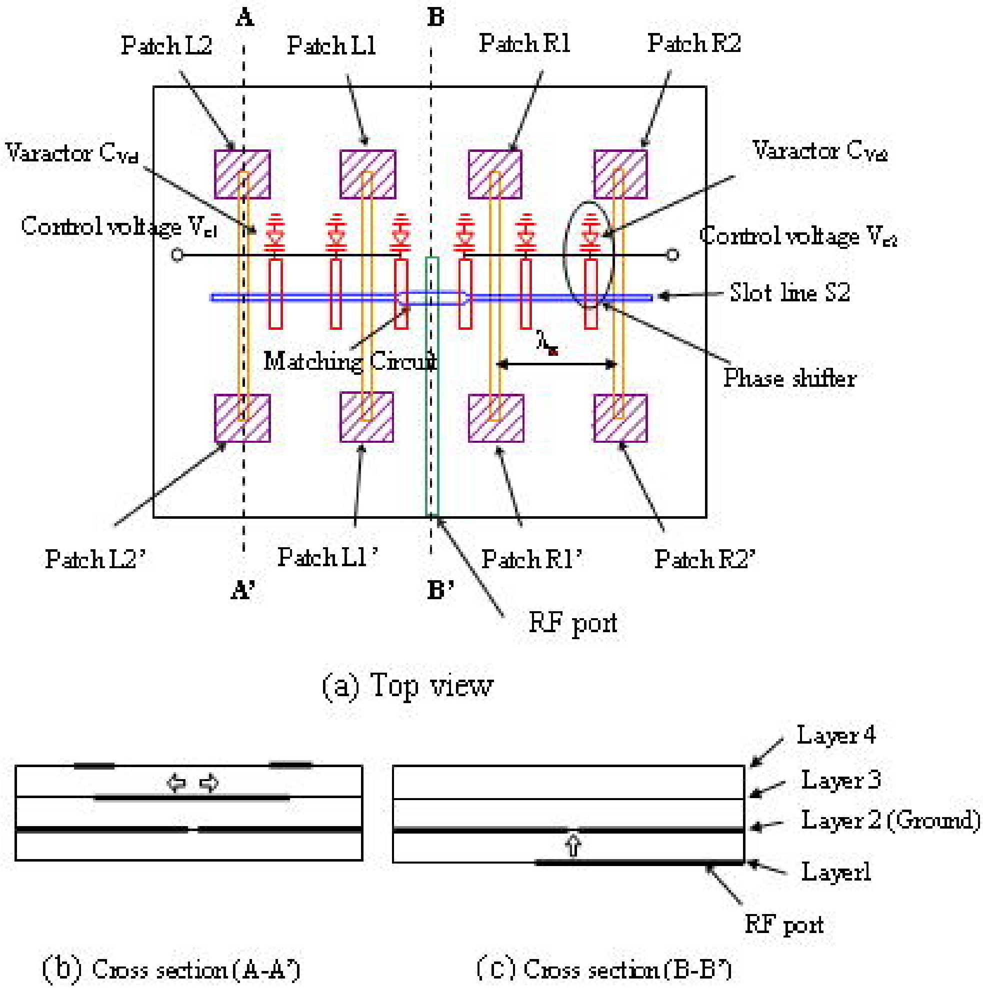


Figure 2.3-Q : Antenna structure

Some details and references are given online at

- http://www.acr.atr.jp/acr/general/report/dept3/varactor-diodes/varactor-diodes-e.html

2.3.13 Study of Smart Antennas for High Speed Wireless Communications

Investigations have been performed on different types of smart antennas for use in high-speed wireless communications. The main issue was to separate desired signal and delay or interference signal. The figure shows a 6-sector antenna.

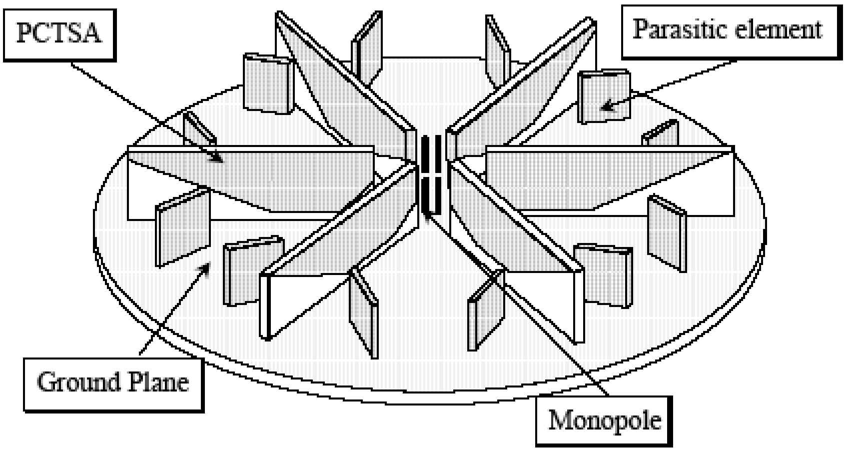


Figure 2.3-R : 6-sector antenna

The complete report can be downloaded from

- http://www.arailab.dnj.ynu.ac.jp/thesis/h13/kohei.pdf

2.3.14 Smart mobile wireless LAN card antenna [5]

A smart antenna was developed for use in a wireless local area network (WLAN). The antenna can be used for portable and mobile terminals. The antenna uses eight PIFA (planar inverted-F antenna) element cylindrical array wrapped around a 2 cm high and 5 cm diameter conducting cylinder placed on a LAN card. The antenna can generate eight individual equally spaced beams suitable for portable and mobile applications. More details are given in [5].

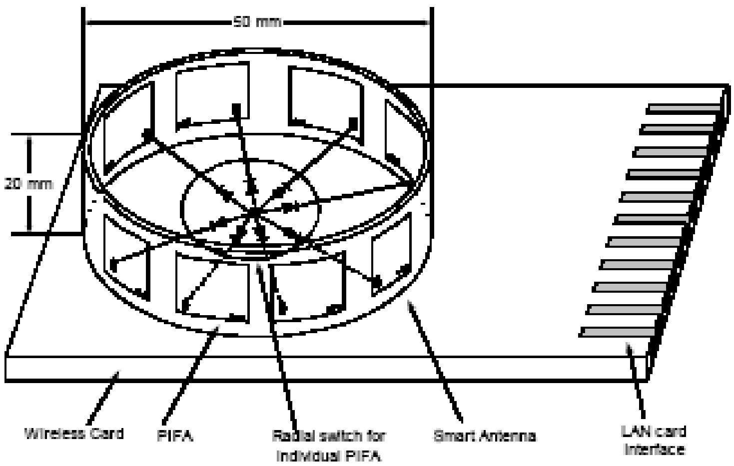


Figure 2.3-S : Eight element PIFA antenna.

2.3.15 A two-ring circular phased-array antenna for mobile satellite communications

An L-band antenna array was developed for possible use in Australian geostationary mobile-satellite-communications system Mobilesat. It can be mounted on top of a vehicle e.g.. A detailed description is given in [4].

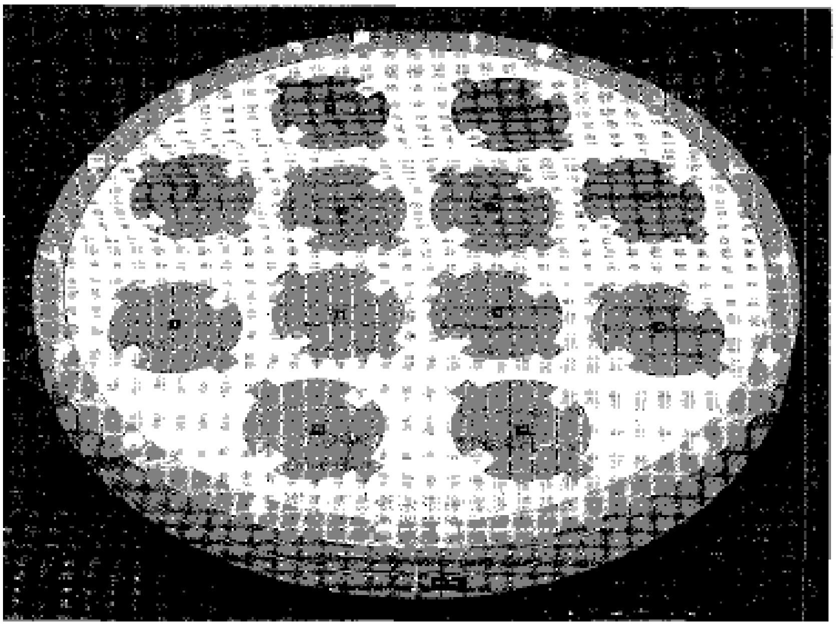


Figure 2.3-T : Photograph of the assembled array antenna

2.3.16 Palm-Sized Pilot Model of Satellite Broadcasting service has been developed

At MBCO (mobile broadcast corporation), Tokyo, Japan, a pilot model for palm sized broadcast terminals has been completed. The terminal will enable mobile users to enjoy audio, video and download service. The terminal is operated in S-band and an example can be seen in the following figure

Figure 2.3-U : Terminal with S-band reception

For further information refer to

http://www.mbco.co.jp/english/03_news/news_archive/030520.html

2.3.17 *Former reviews*

Former reviews can be found online:

- http://www.wtec.org/loyola/satcom/f2_18
- http://www.wtec.org/loyola/satcom/

as well as in chapter 2.3.9.

2.4 Conclusion

The review collected mainly information regarding user terminal arrays from USA and Japan. One part of terminals is developed for use on airplanes with respect to military applications or to establish commercial multimedia services. Smaller terminals are foreseen for wireless communication scenarios to link the single user to a communication environment. This seems to be a focal point of Japanese development, whereas most of the airborne user terminals are related to US companies. Little information could also be obtained from Australian or Canadian developments.

3 References

[1] **Contiguous paraboloid arrays for mobile satellite communications,** *Strickland, P.C.;* Antennas and Propagation Society International Symposium, 2002. IEEE, Volume: 4, 16-21 June 2002 Pages: 724 - 727 vol.4

[2] **Sector-mode beamforming of a 2.4-GHz electronically steerable passive array radiator antenna for a wireless ad hoc network,** *Jun Cheng; Hashiguchi, M.; Iigusa, K.; Ohira, T.;* Antennas and Propagation Society International Symposium, 2002. IEEE, Volume: 1, 16-21 June 2002 Pages:122 - 125 vol.1

[3] **Seven-element ground skirt monopole ESPAR antenna design from a genetic algorithm and the finite element method,** *Schlub, R.; Junwei Lu; Ohira, T.;* Antennas and Propagation, IEEE Transactions on, Volume: 51, Issue: 11, Nov. 2003 Pages:3033 - 3039

[4] **A two-ring circular phased-array antenna for mobile satellite communications,** *Bialkowski, M.E.; Karmakar, N.C.;* Antennas and Propagation Magazine, IEEE, Volume: 41, Issue: 3 , June 1999 Pages:14 - 23

[5] **Smart mobile wireless LAN card antenna,** *Karmakar, N.C.;* Antennas and Propagation Society International Symposium, 2003. IEEE , Volume: 2, 22-27 June 2003 Pages:30 - 33 vol.2

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