

INTRODUCTION

1.1 THE DEFINITION OF A CONFORMAL ANTENNA

A conformal antenna is an antenna that conforms to something; in our case, it conforms to a prescribed shape. The shape can be some part of an airplane, high-speed train, or other vehicle. The purpose is to build the antenna so that it becomes integrated with the structure and does not cause extra drag. The purpose can also be that the antenna integration makes the antenna less disturbing, less visible to the human eye; for instance, in an urban environment. A typical additional requirement in modern defense systems is that the antenna not backscatter microwave radiation when illuminated by, for example, an enemy radar transmitter (i.e., it has stealth properties).

The IEEE Standard Definition of Terms for Antennas (IEEE Std 145-1993) gives the following definition:

2.74 conformal antenna [conformal array]. An antenna [an array] that conforms to a surface whose shape is determined by considerations other than electromagnetic; for example, aerodynamic or hydrodynamic.

2.75 conformal array. *See:* conformal antenna.

Strictly speaking, the definition includes also planar arrays if the planar “shape is determined by considerations other than electromagnetic.” This is, however, not common practice. Usually, a conformal antenna is cylindrical, spherical, or some other shape, with the radiating elements mounted on or integrated into the smoothly curved surface. Many

variations exist, though, like approximating the smooth surface by several planar facets. This may be a practical solution in order to simplify the packaging of radiators together with active and passive feeding arrangements.

1.2 WHY CONFORMAL ANTENNAS?

A modern aircraft has many antennas protruding from its structure, for navigation, various communication systems, instrument landing systems, radar altimeter, and so on. There can be as many as 20 different antennas or more (up to 70 antennas on a typical military aircraft has been quoted [Schneider et al. 2001]), causing considerable drag and increased fuel consumption. Integrating these antennas into the aircraft skin is highly desirable [Wingert & Howard 1996]. Preferably, some of the antenna functions should be combined in the same unit if the design can be made broadband enough. The need for conformal antennas is even more pronounced for the large-sized apertures that are necessary for functions like satellite communication and military airborne surveillance radars.

A typical conformal experimental array for leading-wing-edge integration is shown in Figure 1.2. The X-band array is conformal with the approximately elliptical cross section shape of the leading edge of an aircraft wing [Kanno et al. 1996]. Figure 1.3 shows an even more realistically wing-shaped C-band array (cf. [Steyskal 2002]).

Array antennas with radiating elements on the surface of a cylinder, sphere, or cone, and so on, without the shape being dictated by, for example, aerodynamic or similar reasons, are usually also called conformal arrays. The antennas may have their shape determined by a particular electromagnetic requirement such as antenna beam shape and/or angular coverage. To call them conformal array antennas is not strictly according to the IEEE definition cited above, but we follow what is common practice today.

A cylindrical or circular array of elements has a potential of 360° coverage, either with an omnidirectional beam, multiple beams, or a narrow beam that can be steered over

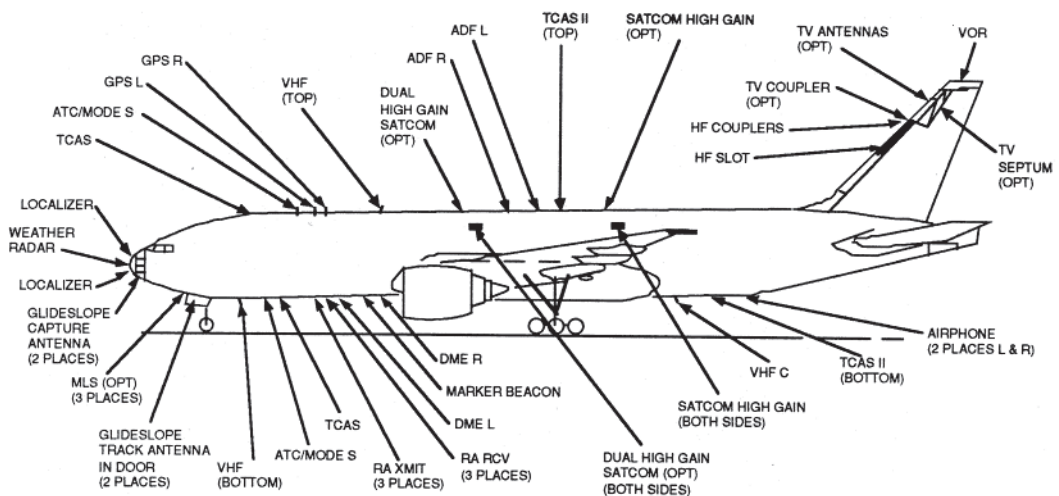


Figure 1.1. At least 20–30 antennas protrude from the skin of a modern aircraft. (From [Hopkins et al. 1997], reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

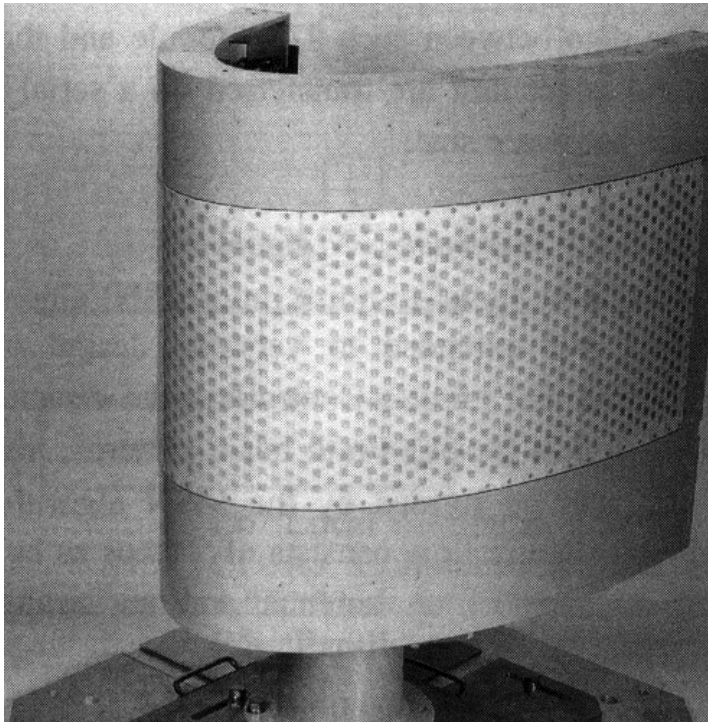


Figure 1.2. Conformal array antenna for aircraft wing integration [Kanno et al. 1996].



Figure 1.3. A microstrip array conformal to a wing profile in the test chamber. See also color insert, Figure 1. (Courtesy of Air Force Research Lab./Antenna Technology Branch, Hanscom AFB, USA.)

360°. A typical application could be as a base station antenna in a mobile communication system. Today, the common solution is three separate antennas, each covering a 120° sector. Instead, one cylindrical array could be used, resulting in a much more compact installation and less cost.

Another example of shape being dictated by coverage is shown in Figure 1.4. This is a satellite-borne conical array (and, hence, the drag problem is certainly not an issue here).

The arguments for and against conformal arrays can be discussed at length. The applications and requirements are quite variable, leading to different conclusions. In spite of this, and to encourage further discussion, we present a summary based on reflections by Guy [1999], Guy et al. [1999], Watkins [2001], and others in Table 1.1.

1.3 HISTORY

The field of phased array antennas was a very active area of research in the years from WW II up to about 1975. During this period, much pioneering work was done also for conformal arrays. However, electronically scanned, phased array antennas did not find widespread use until the necessary means for feeding and steering the array became available. Integrated circuit (IC) technology, including monolithic microwave integrated circuits (MMIC), filled this gap, providing reliable technical solutions with a potential for

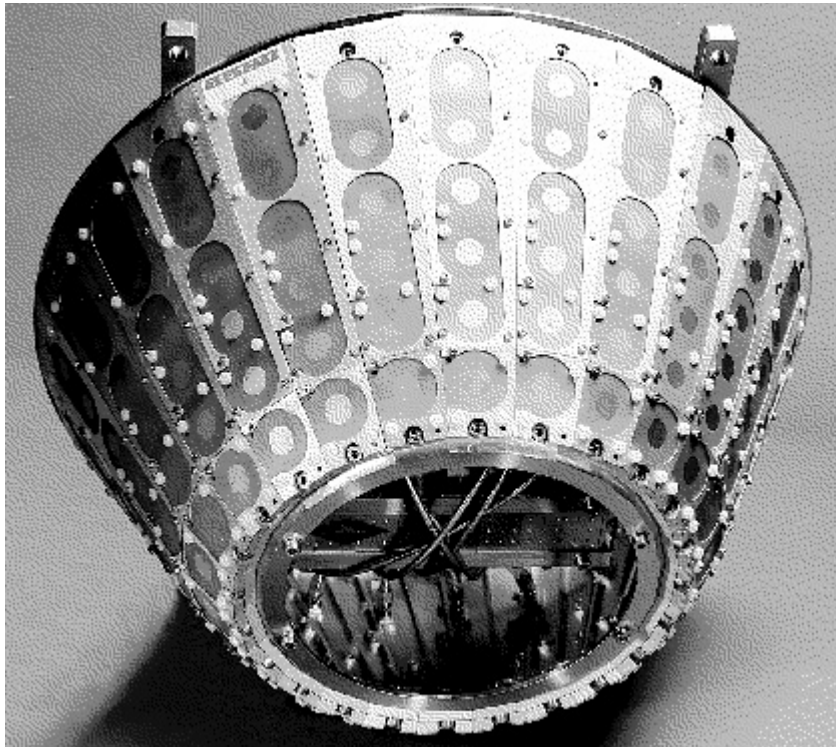


Figure 1.4. A conical conformal array for data communication from a satellite [Vourch et al. 1998, Caille et al. 2002]. See also color insert, Figure 5.

Table 1.1. Planar versus conformal array antennas

Parameter	Planar array	Conformal array
Technology	Mature	Not fully established
Analysis tools	Available	In development
Beam control	Phase only usually sufficient, fixed amplitude	Amplitude and phase, more complicated
Polarization	Single can be used (dual often desired)	Polarization control required, especially if doubly curved
Gain	Drops with increased scan	Controlled, depends on shape
Frequency bandwidth	Typically 20%	Wider than planar is possible
Angular coverage	Limited to roughly $\pm 60^\circ$	Very wide, half sphere
RCS	Large specular RCS	Lower than planar
Installation on platform	Planar shape limits due to swept volume	Structurally integrated, leaves extra space. No drag
Radome	Aberration effects	No conventional radome, no boresight error
Packaging of electronics	Known multilayer solutions	Size restriction if large curvature, facets possible

low cost, even for very complex array antennas. An important factor was also the development of digital processors that can handle the enormously increased rate of information provided by phased array systems. Digital processing techniques made phased array antenna systems cost effective, that is, they provided the customers value for the money spent.

This being true for phased arrays in general, it also holds for conformal array antennas. However, in the area of conformal arrays, electromagnetic models and design know-how needed extra development. During the last 10 to 20 years, numerical techniques, electromagnetic analysis methods, and the understanding of antennas on curved surfaces have improved. Important progress has been made in high-frequency techniques, including analysis of surface wave diffraction and modeling of radiating sources on curved surfaces.

The origin of conformal arrays can be traced at least back to the 1930s when a system of dipole elements arranged on a circle, thus forming a circular array, was analyzed by Chireix [1936]. Later, in the 1950s, several publications on the subject were presented; see, for example, [Knudsen 1953a,b]. The circular array was attractive because of its rotational symmetry. Proper phasing can create a directional beam, which can be scanned 360° in azimuth. The applications were in broadcasting, communication, and later also navigation and direction finding. An advanced, more recent application using a large circular array is the French RIAS experimental radar system [Dorey et al. 1989, Colin 1996].

During the Second World War, HF circular arrays were developed for radio signal intelligence gathering and direction finding in Germany. These so-called Wullenweber¹ arrays (code word for the development project) were quite large with a diameter of about 100 meters. After the war, an experimental Wullenweber array was developed at the University of Illinois (see Figure 1.5). This array had 120 radiating elements in front of a reflecting screen. The diameter was about 300 m; note the size of the buildings in the center [Gething 1966]. Many similar systems were built in other countries during the Cold War.

¹Named for J. Wullenweber, 1488–1537, Lord Mayor of Lübeck

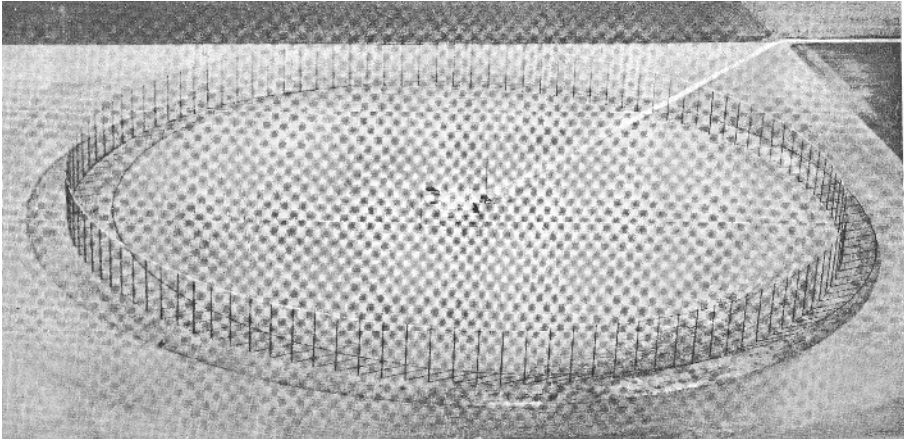


Figure. 1.5. The experimental 300 m diameter Wullenweber antenna at the University of Illinois. (Courtesy P. J. D. Gething, "High-Frequency Direction Finding," *Proceedings of IEE*, January 1966, p. 54.)

Some of these huge antennas may still be operating. See also [IRE PGAP Newsletter Vol. 3, December 1960].

During this period, new, efficient pattern synthesis methods and practical feeding and beam control schemes were investigated by several workers. For an overview see [Davies 1981, 1983]. A very useful approach in this work was based on the concept of phase modes. For the circular array, the excitation can be viewed as a periodic function in azimuth, with period 2π . The excitation can therefore be expressed as a Fourier series. Each term in this series is a phase mode, which can be generated in the practical situation by convenient networks, specifically the Butler matrix. A phase mode has constant amplitude but a linear phase progression from one radiating element to the next, totaling a multiple of 2π over the circumference. The phase mode concept proved to be an efficient tool in pattern synthesis, and will be described in more detail in Chapters 2 and 10. By measuring the phase modes on reception, the signal direction of arrival (DOA) can be determined [Rehmark 1980]. Figure 1.6 shows a direction-finding application using this technique.

With omnidirectional elements, the full circle can be used. However, constructive addition of signals from both the front and the rear part of the circular array is not easily achieved, in particular not over an extended bandwidth. Most circular arrays therefore use directive radiating elements, pointing outward from the center. The Wullenweber antennas have usually a reflective element or screen behind each radiator, making them directive. Element directivity has been analyzed in relation to the phase mode concept and significant improvements compared to omnidirectional elements were demonstrated [Rahim et al. 1981].

In order to increase the directivity and narrow the beam in elevation, several circular arrays placed on top of each other can be used. A good example is the electronically scanned TACAN (tactical navigation) antenna [Christopher 1974, Shestak 1974]. The TACAN antenna can be placed on the ground, radiating a rotating phase-coded signal that helps aircraft to find their position in relation to, for example, an airfield.

Jim Wait did fundamental work on radiation from apertures in metallic circular cylinders; see [Wait 1959]. His work has been continued by many others employing either

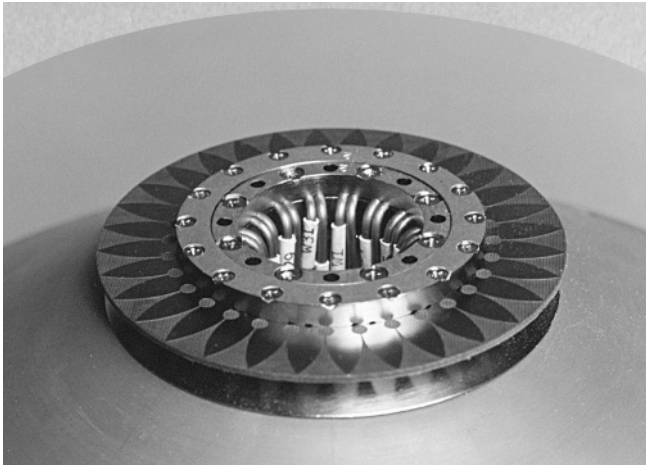


Figure 1.6. Broadband circular array for signal-bearing measurements. See also color insert, Figure 7. (Courtesy of Anaren Inc., Syracuse, NY, USA.)

modal expansion techniques or high-frequency diffraction techniques [Hessel 1970, Pathak et al. 1980]. In particular, mutual coupling is included in the solutions. The methods will be described in Chapter 4.

Nose-mounted antennas in missiles or aircraft are protected by a pointed radome. Alternatively, the antenna elements could be put on the radome itself. This possibility has created an interest in conformal arrays on cones [Munger et al. 1974]. The progress in this field has been slow, however. Also, conformal spherical antennas have attracted interest. A well-known example is the dome radar antenna [Bears 1975, Liebman et al. 1975]. This antenna has a passive-transmission-type lens of hemispherical shape. It is fed from its diameter plane by a planar-phase-steered array (Figure 1.7). The lens causes an extra

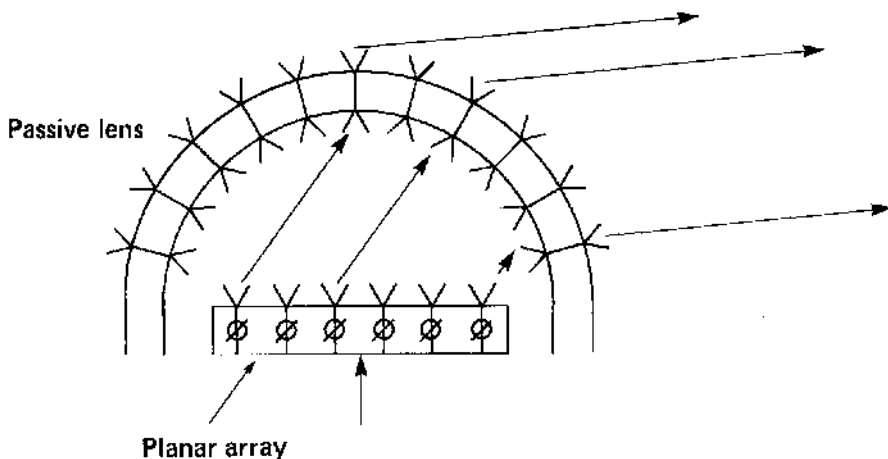


Figure 1.7. The dome array concept using a single planar array and a passive lens for hemispherical coverage.

deflection of the beam so that a scan of more than 90° is achieved. Such a wide coverage would normally require four planar arrays. However, there is a need for polarization control and the lens structure has some bandwidth limitations. It is an advantage that only one steered array is needed for hemispherical coverage, but detailed analysis [Kinsey 2000] indicates that the dome antenna does not offer any cost benefits over traditional solutions using planar arrays. According to Fowler [1998], the invention seems not to have been used in real applications.

Another array with more than hemispherical coverage, in this case for satellite communication from mobile units, is shown in Figure 1.8. This is an active faceted array with integrated transmit and receive electronics.

A great deal of important conformal work was done at the U.S. Naval Electronics Laboratory Center (NELC) in San Diego. The work included development of both cylindrical and conical arrays as well as feeding systems. Most of the activities in this field were closed around 1974. However, many technical results from this active period may be found in the *IEEE Transactions on Antennas and Propagation*, Special issue on conformal antennas (January 1974). Several workshops on conformal antennas were held in the United States, for example, in 1970 and 1975, but the proceedings may be hard to find. Most of the material was later published in scientific journals. At the 1996 Phased Array Symposium in Boston, several interesting conformal designs were presented in a Japanese session [Rai et al. 1996, Kanno et al. 1996]; see Figure 1.2.

An indication of a recent resurgence in the interest in conformal antennas is the series of Conformal Antenna Workshops, held in Europe every second year, starting from 1999. The first was held in Karlsruhe (Germany), the second in The Hague (The

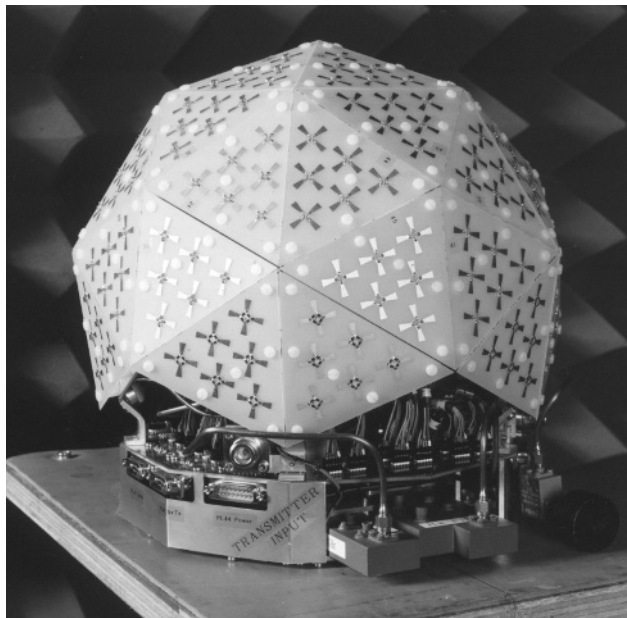


Figure 1.8. A faceted active array antenna with six dual polarized dipole elements in each facet. See also Figure 8.4 and color insert, Figure 6. (Courtesy of Roke Manor Research Ltd., Roke Manor, Romsey, Hampshire, UK.)

Netherlands), the third in Bonn (Germany), and the fourth in Stockholm (Sweden) in 2005.

A paper in *Space/Aeronautics* magazine in 1967 [Thomas 1967] presented a very optimistic view of the development of conformal arrays for nose radar systems in aircraft; see Figure 1.9. Obviously, the development did not proceed quickly, mainly because of the limitations discussed previously. However, the conformal nose-mounted array has many advantages, especially an increased field of view compared to the traditional $\pm 60^\circ$ coverage of planar antennas.

A vision of a future “smart skin” conformal antenna is shown in Figure 1.10. This antenna constitutes a complete RF system, including not only the radiating elements but also feed networks, amplifiers, control electronics, power distribution, cooling, filters, and so on, all in a multilayer design that can be tailored to various structural shapes [Josefsson 1999, Baratault et al. 1993].

1.4 METAL RADOMES

What do radomes have to do with conformal array antennas? Radomes are usually thought of as dielectric shell structures protecting an antenna installation. If made of metal, a dense array of openings (slots) can provide the necessary transmission properties within a restricted range of frequencies. The result is a conformal frequency-selective structure (FSS). It is not an antenna, of course, but viewed from the outside it exhibits all the radiating characteristics of a curved antenna array of radiating elements, just like a conformal antenna. Hence, the (exterior) analysis problem of the structure has much in common with the analysis of conformal arrays. Pelton and Munk [1974] describe a conical metal radome that could be used in a high-speed aircraft or missile application.

A doubly curved FSS acting as a frequency and polarization filter is shown in Figure 1.11. Here we have a spherical array with two layers of rectangular slots in a copper sheet on a dielectric carrier [Stanek and Johansson 1995].

1.5 SONAR ARRAYS

The activities related to sonar arrays are often overlooked by the antenna community. These acoustic arrays used for underwater sensors are analogous to radar or communica-

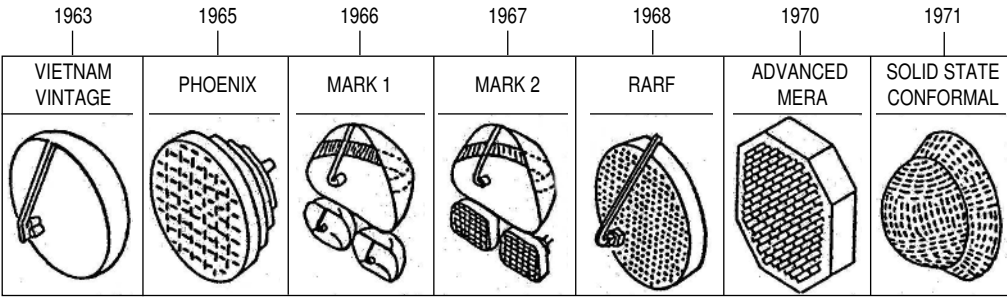


Figure 1.9. Predicted nose radar development as of 1967 [Thomas 1967].

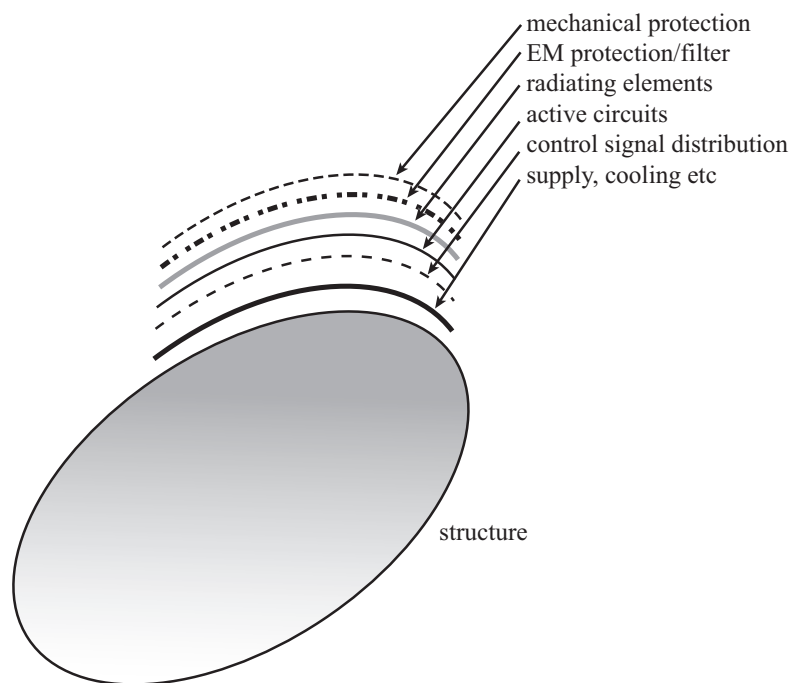


Figure 1.10. Vision of a smart-skin antenna.

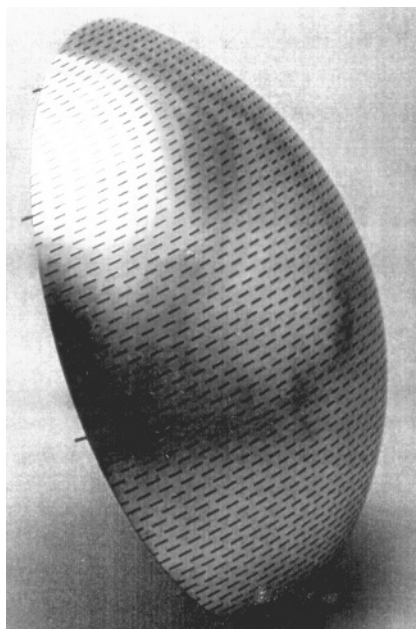


Figure 1.11. A spherical frequency-selective structure of resonant slots. See also color insert, Figure 8. (Courtesy of Ericsson Microwave Systems AB, Göteborg, Sweden.)

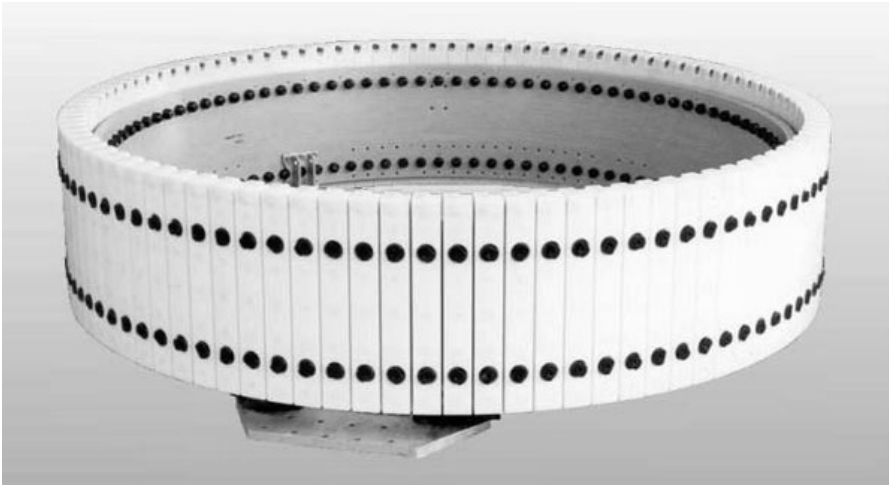


Figure 1.12. A cylindrical passive hydrophone array. See also color insert, Figure 10. (Courtesy of Atlas Elektronik GmbH, Submarine Systems, Bremen, Germany.)

tion arrays. The techniques for signal processing and beam forming are similar [Ziehm 1964, Stergiopoulos and Dhanantwari 1998, Gaulladet and de Moustier 2000]. The wave propagation is radically different, however, with sonic waves propagating almost six orders of magnitude more slowly than electromagnetic waves. The time scale is therefore radically different. The wavelengths used are about the same, and acoustic sensor arrays have an almost “electrical” appearance (Figure 1.12).

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