Design considerations for large SAR array antennas

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INTRODUCTION

Future space-borne SAR systems should feature wider bandwidth, scanning capability in azimuth and elevation, and above all they should provide full polarisation information because polarimetry is one of the most promising tools for the interpretation of radar signatures. Within the context of these considerations, a couple of years ago TNO-FEL conducted a case-study for a C-band space-borne SAR antenna. In the remainder of this paper we will discuss the design considerations, the strong and weak points of the final design and ideas about reducing the costs of SAR array antennas.

The specifications for the SAR antenna sub-array that were used are stated in table 1 [1].

Table 1: SAR antenna sub-array specifications

Number of ports per subarray	2 (one per polarisation)
Frequency	5300 MHz
Bandwidth	100 MHz (operational) ± 25 MHz (margin)
Scan volume	± 15^0 (elevation) ± 2^0 (azimuth)
Polarisation	Dual polarisation H and V
Co to cross polarisation for each scan direction for each port	> 20 dB (25 dB goal)
Complex ratio of copolarisations for each scan direction after calibration on boresight within	Modulus ± 0.3 dB Phase ± 3^0
Input reflection coefficient "S_{ii}" for each port	< -15 dB
Isolation "$S_{I,I+1}$" between 2 ports of sub-array	> 30 dB
Maximum value of "active" reflection coefficient over scan volume for each port	< -12.5 dB (< -15 dB goal)
Absolute copolarisation gain variations over range of polarisation states	± 0.4 dB (± 0.3 dB goal)
Ohmic line losses in sub-array	< 1 dB/m
Aperture efficiency	> 85 % (>90 % goal)

CHOICE OF RADIATOR

The radiating element is chosen to be a square open-ended waveguide radiator. Although for the required bandwidth of 2.3 % also a (stacked) microstrip patch radiator could have been used, we still have chosen for the waveguide radiator. The reasons are the long standing experience of TNO with this kind of radiator, its simplicity, the absence of dielectrics and its structural self-supporting properties, see figure 1.

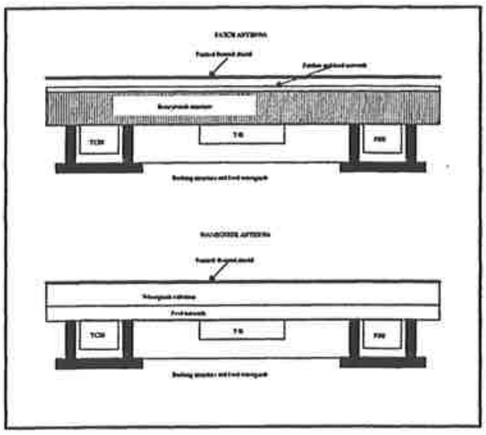

Fig. 1: Cross section of a patch antenna tile and waveguide antenna tile

ANTENNA ANALYSIS TOOL

The basic analysis tool employed is based on the infinite array antenna concept. Every radiating element is considered to be embedded in a planar array, in which the so-called unit cell is infinitely repeated into two directions, see figure 2.

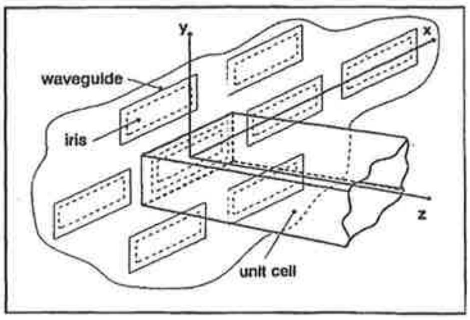

Fig. 2: Array configuration

A uniform amplitude excitation and linear phase taper is assumed. The radiators are waveguides of rectangular or square cross section. Centered irises can be placed in the waveguide aperture. Because of the assumption of infiniteness of the structure, edge effects are neglected and due to the periodicity of the configuration, coupling effects are the same for each of the elements, so permitting the assumption of unit cells into which each element individually radiates (Floquet's theorem). The problem has to be solved now for a single unit cell only. The geometry of the unit cell is depicted in figure 3.

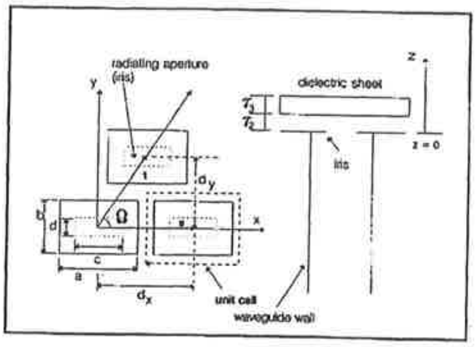

Fig. 3: Geometry of array and unit cell

In front of the waveguide apertures one or more dielectric sheets can be placed. Irises and dielectric sheets serve the purpose of Wide Angle Impedance Matching.

The calculations for this case study were performed using a Mode Matching method [2], which has been extended over the last couple of years to increase the degrees of freedom in the design of these kind of waveguide antennas [3]. Very recently we have abandoned the Mode Matching method for a very efficient Multimode Network Representation method [4].

Very large array antennas, i.e. antennas consisting of thousands of elements, can be analysed perfectly well by an infinite array theory. For medium sized phased array antennas (a couple of hundreds of elements), finiteness effects have to be included in the array behaviour calculations.
Therefore and because of our sub-array design strategy, to be discussed further on in this paper, we have developed an approximate method for calculating the behaviour of an element in a medium sized array antenna.
Since direct calculation of finite array antenna characteristics is very time consuming for arrays consisting of more than say 10 elements, it is expedient to look for an approximate method.

FINITENESS: APPROXIMATE METHOD

We make use of the fact that the element reflection coefficient and mutual coupling coefficients are related by a Fourier transformation [5]. As a result of our infinite array antenna analysis we obtain the waveguide fundamental mode reflection coefficient in the unit cell. By calculating this reflection coefficient as function of scan angles θ_0 (angle with respect to array normal) and ϕ_0 (angle in the array plane, relative to the horizontal axis) and integrating over all possible scan angles, we obtain the coupling coefficients (for a rectangular grid):

$$S(m,n)=\frac{1}{4\pi^2}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi}\Gamma(\vartheta_0,\varphi_0)e^{jm\psi_x d_x}e^{jn\psi_y d_y}d(\psi_x d_x)d(\psi_y d_y) \tag{1}$$

where:

$$\psi_x = k_0 \sin(\vartheta_0)\cos(\varphi_0) \tag{2a}$$

$$\psi_y = k_0 \sin(\vartheta_0)\sin(\varphi_0) \tag{2b}$$

$$k_0 = \frac{2\pi}{\lambda} \tag{2c}$$

The indices m and n denote the position of an element relative to a central element (m,n) = (0,0).

The coupling coefficients for a finite array antenna, obtained from infinite array data following this procedure give very reasonable results as is shown in [6], where a comparison is made with results obtained from a finite array antenna theory.

With a finite set of thus derived coupling coefficients, we can obtain the approximate reflection coefficient behaviour of an element in a finite array environment:

$$\Gamma(\vartheta_0,\varphi_0)=\sum_{m=-M}^{M}\sum_{n=-N}^{N}S(m,n)e^{-jm\psi_x d_x}e^{-jn\psi_y d_y} \tag{3}$$

with M and N defining the size and number of elements of the array antenna.

The improvement of using the infinite array data to approximate a finite array can be quite extreme in the case of analysing cross polarisation. This is shown in figure 5 for the antenna depicted in figure 4.

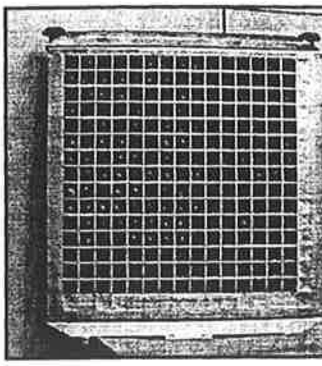

Fig.4: 15x15 square waveguide array antenna. Waveguide aperture: 35.88mm x 35.88mm. Element distances: 38.60mm.

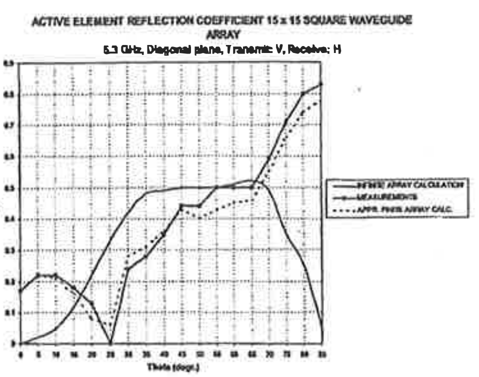

Fig.5: Cross polarisation reflection coefficient vs. scan angle θ_0 for the centre element of the array shown in figure 4. Infinite and approximate finite array simulation results and measurements

ANTENNA SYNTHESIS

Designs are based upon the synthesis of a single element in an infinite array environment. This single element design serves as the basis for the design of a sub-array. Element optimisation parameters follow from table 1. One additional constraint, i.e. the minimum element spacing, follows from the choice of the number of elements per sub-array. The needed scan volume (see table 1) and the avoidance of grating lobes within this volume leads to the choice of a sub-array of 8 x 1 elements, oriented horizontally with an element spacing around 0.7 λ.

Given a set of antenna design specifications, an antenna can be designed by iteratively using an analysis code. Due to the large number of design parameters and the existence of many local optima in the solution space, this is a very time consuming task. Therefore, an optimisation programme – using the analysis code – has been developed, that allows for automatically generating an antenna design given a set of design specifications as input.

The optimisation method used is an intermixed combination of simulated annealing and the downhill simplex method due to Nelder and Mead [7, 8]. This combination of methods is more suited to continuous optimisation than the method of simulated annealing in itself [7]. The optimisation starts as a simulated annealing method and gradually changes to a downhill simplex method as the 'temperature' is lowered. When the global optimum area is found by simulated annealing, the downhill simplex method rapidly isolates the optimum.

Of all possible configurations, the ones incorporating aperture irises and dielectric sheets or a triangular lattice, although giving better results than those without, were not chosen. Thus, an easier to realise design was obtained and still the design specifications were met, as is shown in figures 6 and 7.

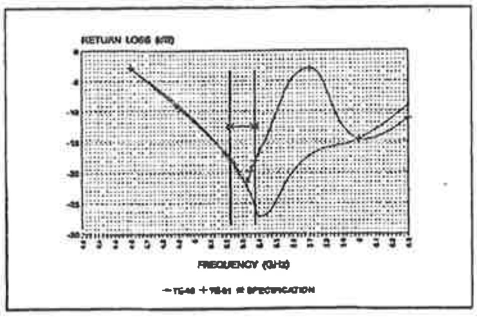

Fig. 6: Worst case return loss over scan volume vs. frequency. Aperture dimensions 35.88 mm x 35.88 mm. Element distances: 39.60 mm x 39.60 mm.

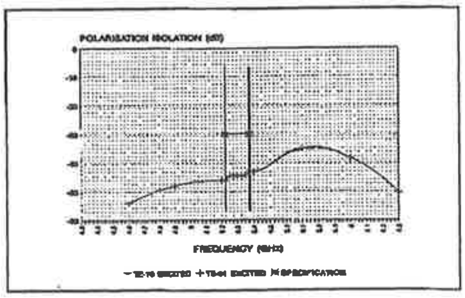

Fig. 7: Worst case polarisation isolation over scan volume vs. frequency.

SUBARRAY DESIGN

With the results of the embedded element optimisation, we can design a sub-array. In order to reduce the costs of the large (ca. 12m x 1m) antenna, phase shifting on element to element basis is not recommended. Due to the limited scan volume, elements can be grouped into 8 x 1 sub-arrays. Figure 8 shows an array composed of 8 x 1 sub-arrays.

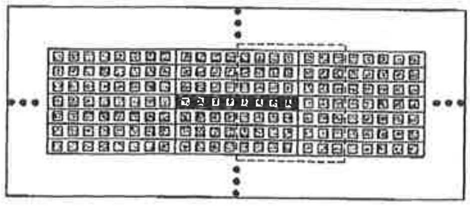

Fig. 8: Centre sub-array in array environment

To calculate the centre sub-array reflection coefficient, three steps need to be performed:

1. Calculate the coupling coefficients for a finite set of elements, using infinite array data;
2. Recalculate the reflection coefficient for element i; i = 1,2, ..., 8, or: sum the coupling coefficients, with appropriate phasings, within a window around each element (shown in the figure is a 7 x 7 window for element #8).
3. Combine the thus obtained element-in-sub-array reflection coefficients to obtain the overall sub-array reflection coefficient.

With this design strategy we have shown [1] that one cannot design a phased array antenna that is scanned on sub-array level, taking into account only the isolated sub-array behaviour, even when this *isolated* sub-array shows no significant mutual coupling influences. The element-to-element coupling may be low, but due to the size of the total array antenna, inclusion of coupling from all surrounding elements and sub-arrays may not be neglected.

EXCITATION AND FEED NETWORK

For the SAR antenna under consideration, due to the relatively small bandwidth required, we applied a single layer, dual polarised microstrip patch structure to excite the radiator.
It is important to note that the patch structure in itself is not used as an antenna element, but only serves the purpose of exciting the waveguide fundamental modes.
A feed network was designed in microstrip technology. The loss specifications (< 1dB /m) however were not met; the sub-array feed network loss was calculated to be 1.19 dB/m.
Waveguide and feed network could fit in a 3 cm thick layer; the same thickness as would be occupied by a printed antenna with its support structure, see figure 1.

Although we are able now to design broadband waveguide exciters and low-loss feed networks, the fact remains that the costs of large phased array antennas will be dictated mainly by the element exciters and the feed networks. So, in order to reduce the costs we have to take a closer look at these components.

REACTIVELY LOADED ARRAY

One way of reducing the costs is eliminating the number of excited radiators. Ideally, one radiator will be excited; all other elements will we short circuited in a transmission line of appropriate length. This concept, which is very easy to realise in open-ended waveguide technology is known as 'reactively loading' [9]. A reactively loaded array antenna behaves like a fully excited array antenna with the exception that the antenna beam will be broadened. This effect can be compensated for, however, by incorporating 'angle selective surfaces' in the array antenna, see figure 9.

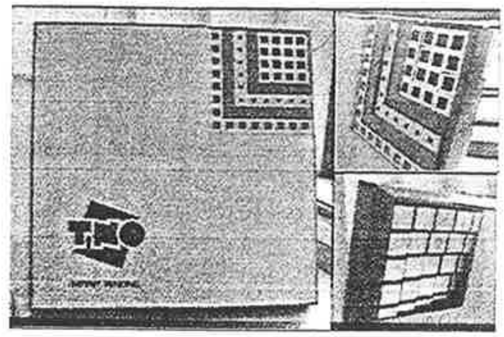

Fig. 9: Reactively loaded open-ended waveguide array antenna with integrated angle selective surfaces

Beam steering can be accomplished by adjusting (switching) waveguide lengths, but this will increase both volume and complexity of the array antenna, making this kind of antenna more suitable for fixed beam antennas.

THE REFLECTARRAY

The reactively loaded array is less expensive than the fully excited array since it has only one active element and beam steering is done by carefully adjusting the waveguide lengths. However also this antenna is voluminous. Yet another option for a SAR antenna is referred to as the reflectarray. A reflectarray is an antenna system that combines the simplicity of the reflector type antenna with the performance versatility of the array type. The antenna system consists of a feed and a reflector. The reflector is characterised by a surface impedance that can be synthesised to produce a variety of radiation patterns. This reflector can be planar or conformal depending on its application, where on its surface (mostly a grounded dielectric) antenna elements are placed in a geometrical order. The reflectarray principle is depicted in figure 10.

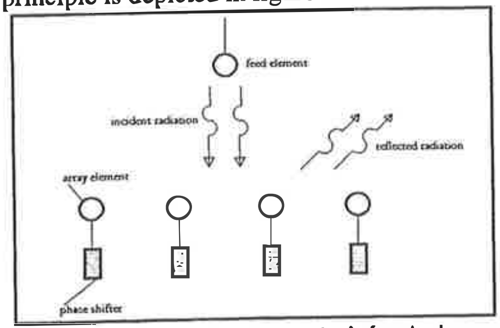

Fig. 10: Reflectarray concept. A feed element is placed above an array of reflecting elements that are attached to phase shifters by which the reflected or reradiated field can be steered.

This antenna system has essentially no limitation in its dimensions and has much less distortion in its planar shape, whereas the geometrical shape of a large reflector to create the needed high gain and low side lobes, is much harder to implement without distortion. Up till now the reflectarray has been rather underrated, but as a cheap and versatile antenna system it can be used in several applications showing good performance. In a great number of these microwave applications a highly directive antenna with a main beam scanned to a certain angle is required. To achieve this a certain aperture illumination with progressive phase shifting is used. The two primary ways to do this are by the use of reflectors and arrays. The reflector antenna uses its geometry to create the desired phase across the aperture, while the array employs distinct elements fed with progressive phasing. The advantage of the reflector antennas is the fact that they typically exhibit large bandwidth and low loss. The main disadvantage of the reflector is the geometrical costraint it imposes on the design. The most popular reflector, the parabolic reflector for example also exhibits inherently high cross-polarisation levels.

The most commonly applied reflectarray consists of microstrip antenna elements. The microstrip patch reflectarray was first introduced by [10] lateron [11], [12] and [13] also worked on this type of reflectarray. The microstrip patch reflectarray is inexpensive, easy to install and manufacture, has almost no limitations to the conformal properties of the mounting surface and it possesses high power capabilities. Moreover microstip patch arrays are low-profile antennas that are capable of low cross-polarisation levels but typically have small bandwidth and fairly large losses at microwave frequencies. Combining some of the more attractive features of reflectors and arrays, resulting in the reflectarray, is beneficial. Apart from the microstrip patch reflectarray it is also possible to use other antenna elements on the reflector. Waveguides [14], dipoles or even Fresnel zones [15] on the reflector area can be utilised.

To aim the main beam of the antenna to a desired direction in space one has to apply progressive phase shifting in one or both principal directions of the reflector. The microstrip patch reflectarray is most flexible when it comes to applying phase shifting. It is possible to create phase delay by attaching microstrip transmission lines or stubs (see figure 11) to the side of the patch that is perpendicular to the scan plane [16]. Electronically scanning the beam can be done by applying PIN diodes in the stubs [16]. Switching the diode shorts the stub at a certain distance form the patch edge, creating the desired path length traveled by the electromagnetic wave. Yet another way of creating phase delay is by rotating the patches [17], see figure 11. Also this can provide active scanning, when micromachined motors are attached to each patch. It is also possible to give some variation to the resonance length of the patches. In this way the phase of the reflected field is affected [12] which is mainly due to the high-Q nature of the patch element. This can also be done with printed (crossed) dipoles or resonant printed rings. They can all be seen as FSS-based (Frequency Selective Surface) but active scanning of the main beam is not possible.

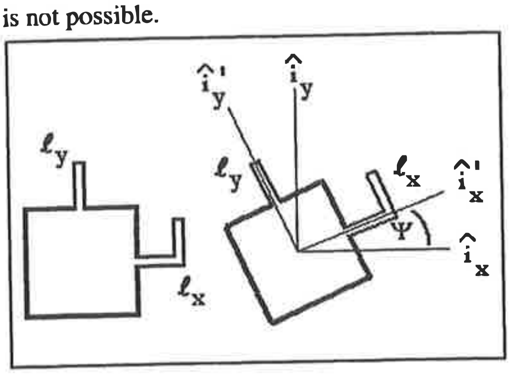

Fig. 11: Circularly polarised reflectarray patch element. Left, reference element. Right, ψ-degrees rotated element creating a 2ψ-degrees phase shift in the reradiated field in relation to the reference patch. The stubs with lengths ℓ_x and ℓ_y are attached to influence polarisation of the reradiated field.

For certain applications the microstrip reflectarray antenna system has good potential to replace antennas like the active phased array antenna and reflector antennas like the parabolic dish. It is important to mention that in general reflectarrays, as is the case with the usual reflectors, suffer from efficiency decrease due to feed spillover and amplitude tapering. Moreover, the electromagnetic performance of a microstrip reflectarray will allways be less than that of the traditional reflector antenna (dielectric losses, phase errors). That is why the primary advantages of the microstrip reflectarray are in dimensions, weight, surface conformability, fabrication ease and cost. Microstrip reflectarrays have multiple polarisation capabilities. An important electromagnetical advantage of the microstrip reflectarray is the improved cross-polarisation performance. This is due to the polarisation selectivity of the used elements on the reflector surface and the possibility of rearranging the elements to cancel cross-polarisation. A disadvantage of the reflectarray antenna however, is its bandwidth. The bandwidth of a reflectarray is larger than that of a flat reflector but is much less than the bandwidth of a parabolic reflector. This can be slightly improved by techniques to enlarge the bandwidth of the individual radiating elements on the reflector, but it will never be as large as the bandwidth of the dish antenna. In comparison with an active phased array antenna, the reflectarray is less lossy because of the absence of a complex feeding network, which also explains the flatness of microstrip reflectarrays.

All in all efficiencies of 70% and bandwidths of 12% have been reported. On average sidelobe levels are 25 dB down and cross-polarisation levels of –30 dB have been reported.
The microstrip reflectarray answers to most of the requirements of the SAR-antenna system. Especially the high polarisation requirements will be met. With the other advantages of the antenna being low-profile, low cost and conformability, it is a good option to replace the phased array antenna. With the use of a planar or conformal *phased array feed antenna* the need of individually adjusting each element in the reflectarray to scan the beam can be avoided, making the system even simpler and easier to install.

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