WAVEGUIDE PHASED ARRAY ANTENNA ANALYSIS AND SYNTHESIS

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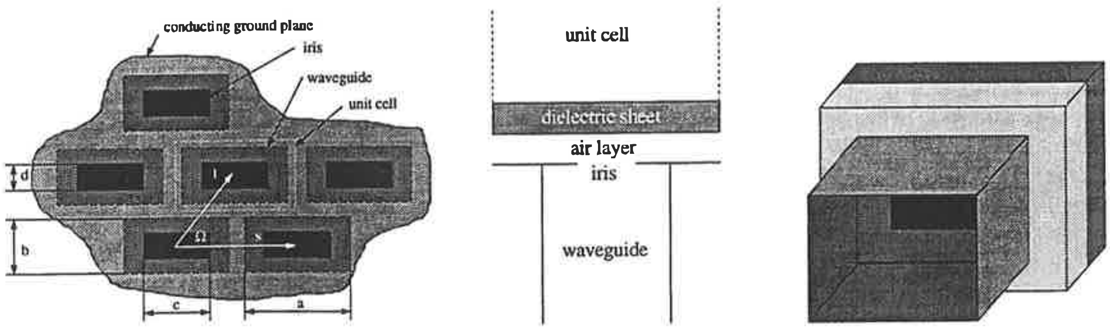
ABSTRACT

Results of two software packages for analysis and synthesis of waveguide phased array antennas are shown. The antennas consist of arrays of open-ended waveguides where irises can be placed in the waveguide apertures and multiple dielectric sheets in front of the apertures in order to accomplish a wide band wide scan angle impedance match. One of the packages is restricted to the use of infinitely thin aperture irises, but has the advantage of fast calculation times. The other package, which has been completed recently, is very versatile and allows multiple (finite thickness) obstacles in the waveguides, but at the cost of longer computation times. The validity of the new software package is demonstrated and a design strategy, using both packages, is discussed. With the newly developed software we expect to have a better control over scan blindness effects.

1. INTRODUCTION

Because the requirements for (synthetic aperture) radar antennas are becoming more stringent, the design of those antennas has to be carried out by accurate modelling and not by experimental methods. Experimental design of advanced phased array antennas is a very time consuming and therefore costly process which does not guarantee an optimum solution. Good theoretical solutions are needed to make the antenna design simple, accurate and efficient and that allow the optimisation of the various antenna dimensions and parameters and the tolerances in a simple way. At TNO-FEL the emphasis in the development of phased array simulation tools has been on open-ended waveguide phased array antennas, because at the moment no radiating element other than the waveguide type can accomplish comparable extreme large bandwidth characteristics when the beam is scanned over a large angular range. (See for example (Ref. 1), for the design of a 20 percent bandwidth X-band antenna with a 60 degrees half-angle scan cone).

In 1994 we finished our first simulation tool that allowed the design of waveguide phased array antennas with internal and external matching structure (Refs. 2,3). Figure 1 shows the geometry for a triangular lattice ($\Omega \neq 90^0$). The presence of infinitely thin irises in the waveguide apertures (internal matching structure) is allowed as well as the presence of a dielectric sheet in front of and parallel to the array aperture (external matching structure). Irises and dielectric sheet serve as Wide Angle Impedance Matching structure (Refs. 4,5).



a b c

Figure 1: *Waveguide phased array antenna unit cell*
a. top view, b. side view, c. perspective view

The array is assumed to be of infinite dimensions, facilitating calculations that - by virtue of periodicity - have to be performed for a unit cell only. The electromagnetic fields in the different domains (waveguide, iris, air gap, dielectric sheet) are decomposed into modes that are transferred to the aperture (iris) plane and matched using a Mode Matching technique, where a Chebyshev polynomial development of the fields in the infinitely thin iris is applied (Ref. 3). The infinite array assumption is valid for the internal elements of arrays consisting of more than roughly 100 elements (Refs. 4,5). By applying the Fourier integral relationship between waveguide (fundamental) mode reflection coefficients and mutual coupling coefficients, centre element behaviour of a medium-sized finite array can be approximated (Ref. 6).

This is demonstrated in figure 2 (code-to-code validation), where the approximated finite array coupling coefficients, using infinite array data, for a 23x23 waveguide array are shown together with the results obtained with a code developed for finite array antennas (Ref. 7). A fairly good match is visible. Comparison with measurements have shown an improvement with respect to applying infinite array results directly (Ref. 6).

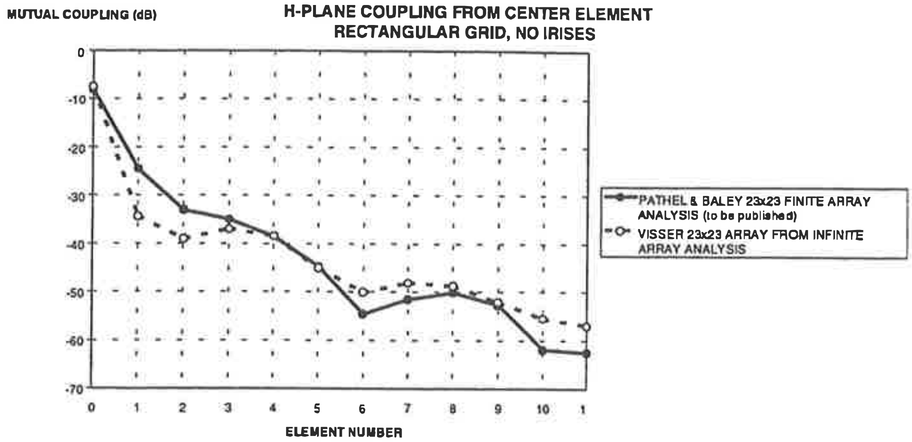


Figure 2: *Code-to-code validation finite waveguide phased array antenna*

The simulation tool discussed is restricted to the use of infinitely thin aperture irises. Recent research developments, however, indicate that wide angle impedance matching can be improved by applying a thick aperture iris or multiple irises in the waveguide (Ref. 8). For that reason and because we want to be able - for a specific waveguide phased array antenna - to apply filters in the waveguide radiators, we have developed a more versatile simulation tool, capable of analysing waveguide filter structures and infinite waveguide phased array antennas allowing the presence of multiple obstacles in the waveguide and multiple dielectric sheets in front of the aperture. Again calculations are based on an infinite array approach (unit cell calculations only).

2. ANALYSIS METHOD

Instead of decomposing the electromagnetic fields in the different domains into modes and transferring them to the aperture plane, we decompose the fields at local junction interfaces and apply Mode Matching techniques to obtain the Generalised Scattering Matrix (GSM) for that junction. A GSM is a scattering matrix that contains, besides the fundamental mode scattering coefficients higher order mode coefficients. The number of scattering coefficients is infinite in principle, but by applying a justified truncation, a finite dimension GSM will result. This method has been used with success by a number of researchers for waveguide structures (Refs. 9-15). In addition to constructing GSM's for waveguide discontinuities, we also construct a GSM for the junction of a waveguide radiating into a free space unit cell and the GSM of a dielectric step in the unit cell. The overall GSM of a waveguide structure or infinite waveguide phased array unit cell (see figure 3) is obtained by cascading GSM's of junctions and GSM's of finite length transmission lines. We have specifically chosen not to use transmission matrices, although that would speed up the computation time due to lack of matrix inverse operations (Refs. 14,22). The reason for this choice is that we want to avoid numerical instability caused by positive exponents exp(+jγd), where γ is the propagation constant and d is the distance between two discontinuities. By cascading directly, the exponents will be negative.

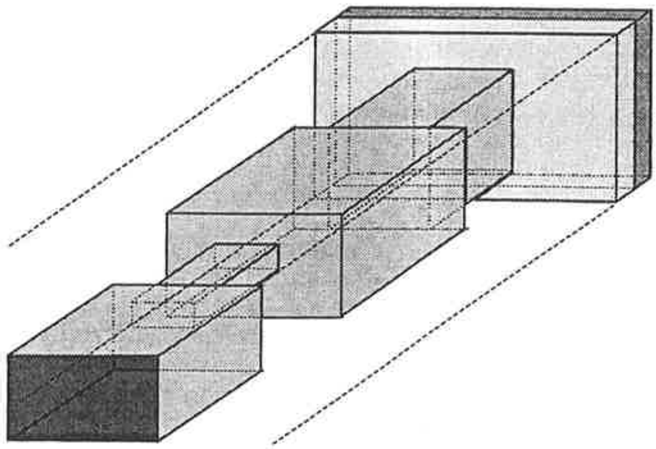


Figure 3: *Example of multiple discontinuity unit cell*

One has to be careful in the truncation of the infinite series of waveguide and free space Floquet modes in order to avoid the relative convergence phenomenon (Refs. 16,17). For the waveguide discontinuities the guideline is used whereby the ratio of the number of modes on both sides of a junction is set approximately equal to the ratio of waveguide dimensions. In this way, the highest cut-off wave number of the modes selected is about the same on both sides of the junction. It is this last observation that will be of use in selecting the number of Floquet modes in free space (Refs. 8,18). Instead of applying numerical experiments on the number of Floquet modes, leading to GSM's of very large dimensions, we will use the cut-off wave number criterion: First the number of modes in the waveguide structure is determined. Then the highest waveguide cut-off wave number is determined . Finally the cut-off wave numbers of the Floquet modes for a given direction of scan are computed and only those that are less than or equal to the maximum waveguide cut-off wave number are used in the simulation.
Simulation of a waveguide structure can be made more efficient by applying a mode preselection scheme, thus using only those modes that are excited at a waveguide junction, avoiding filling up GSM's with non used modes. For an incident dominant mode, we distinguish the junctions shown in figure 4. The theory reveals that only certain waveguide modes are excited at these junctions as stated in table 1.

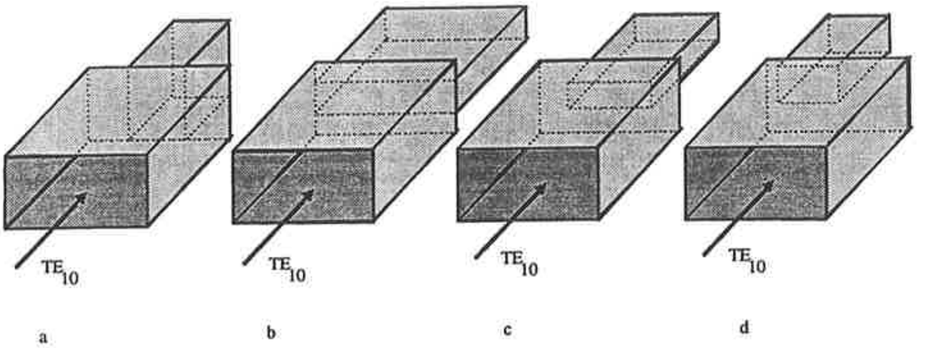


Figure 4: *Waveguide step discontinuities*

a) symmetric inductive step

b) symmetric capacitive step

c) symmetric dual step

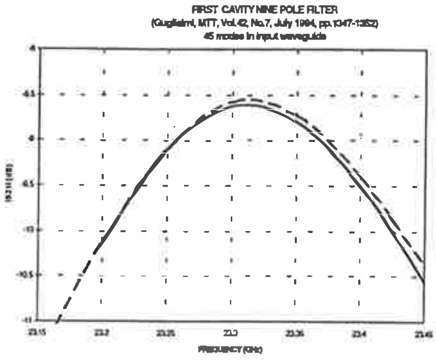
d) unsymmetric dual step

Table 1: *Mode preselection criteria for an incident TE_{10}-mode*

waveguide step	**excited modes**	**restrictions**
symmetric inductive	TE_{m0}	m odd
symmetric capacitive	TE_{1n}, TM_{1n}	none
symmetric dual	TE_{mn}, TM_{mn}	m odd, n even
unsymmetric	TE_{mn}, TM_{mn}	none

3. RESULTS

We start to demonstrate the validity of the new developed simulation tool by comparing analysis results with results from the open literature for waveguide (filter) structures. Then results for a triangular lattice open ended waveguide phased array antenna with internal and external matching structure will be compared with results obtained with a different, independently developed and validated computer program. For all structures an incident TE_{10}-mode is assumed and for all analysed structures convergence checks have been performed, so that numbers of modes, when mentioned, can be regarded as slightly overdone. The program we developed is called GAWAIN (Gsm Analysis of Waveguides and Arrays of Infinite Number), named after a knight of the round table.
We start with a nine-pole (inductive iris) waveguide filter (Ref. 19). Figure 5 shows the transmission coefficient for the first cavity, the first two cavities and the transmission and reflection coefficients for the complete filter. The simulation results are compared with the results from computer program WIND (Ref. 19). In figure 5c, only the WIND levels are shown, because WIND results are obtained manually from (Ref. 19). The agreement of our simulations with the WIND results are quit good for the first two cavities of the filter. The levels and frequencies for the complete filter agree good with the WIND results. A better match is expected when the filter is re-analysed with a smaller frequency resolution (in figure 5.c a 2.5 MHz resolution is applied).



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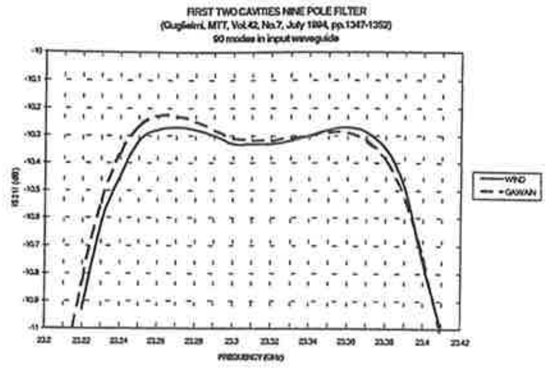

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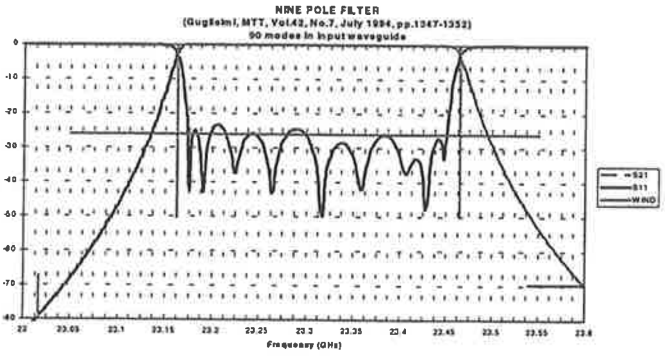


c

Figure 5: *Simulation results nine-pole waveguide filter (Ref. 19)*
a. first cavity, b. first two cavities, c. complete filter

Next we show the reflection coefficient for a resonant iris as function of scan angle (Ref. 14) in figure 6 and the reflection coefficient amplitude and phase for an H-plane step discontinuity (Ref. 20) in figure 7. Finally the reflection coefficient for an unsymmetrical finite thickness iris as function of frequency is shown in figure 8 (Ref. 14). Note that, according to table 1, in this last waveguide structure all TE- and TM-modes are excited.

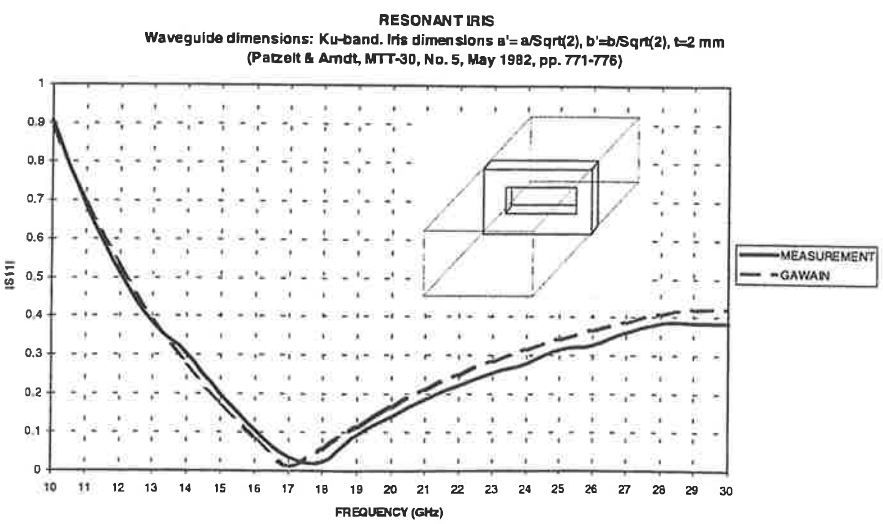


Figure 6: *Reflection coefficient resonant iris of finite width*

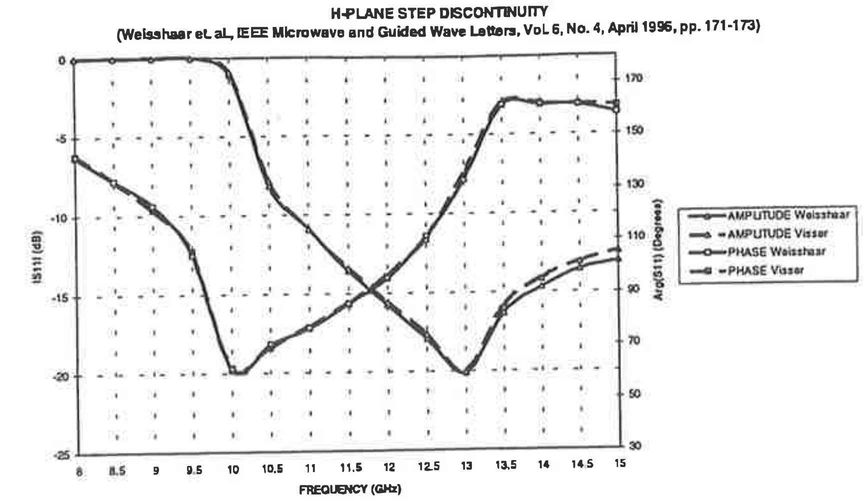


Figure 7: *Reflection coefficient H-plane step discontinuity*

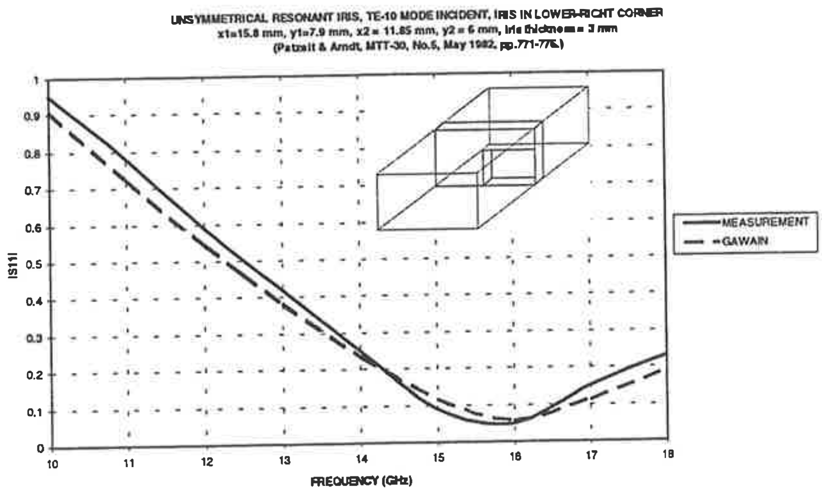
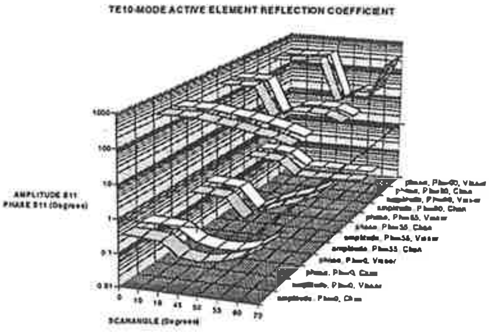


Figure 8: *Reflection coefficient unsymmetric resonant iris with finite thickness*

With the above examples the validity of the program GAWAIN has been proven thoroughly for waveguide structures. What remains is to prove the validity of the simulation tool for waveguide phased array antennas.

This task will be accomplished by comparing simulation results for a certain X-band antenna with simulation results obtained with a validated, independently developed program (Refs. 8,21). Since this program has been thoroughly validated, we will use the simulation results of this program as reference. The dimensions of the antenna used for validating GAWAIN are classified, so we restrict ourselves to stating that the antenna is a 30% bandwidth X-band waveguide phased array antenna, capable of scanning in a 120 degrees angle cone. The array consists of open ended waveguides arranged in a triangular lattice where irises are placed in the waveguide apertures and a dielectric sheet is placed in front of the aperture to accomplish a Wide Angle Impedance Match.
Figure 9 shows the fundamental mode reflection coefficient (amplitude and phase) of a unit cell (active element reflection coefficient) as function of scan angle in the principal planes Phi = 0, 45 and 90 degrees (H, D, E) for a fixed frequency. A good match between the simulation results from both computer programs is observed.
In figure 10, the active element reflection coefficient as function of scan angle for different frequencies is shown for a fixed plane Phi. Again the agreement between both simulations is good, thereby proving the validity of GAWAIN for waveguide phased array antennas also.



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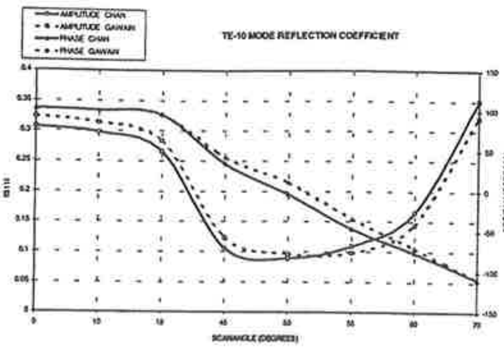

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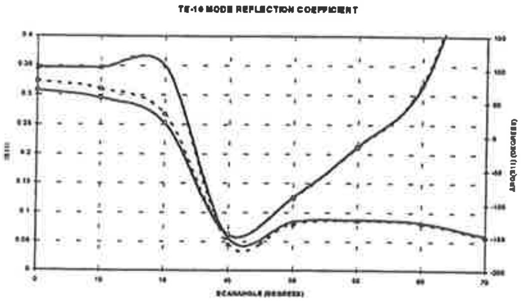

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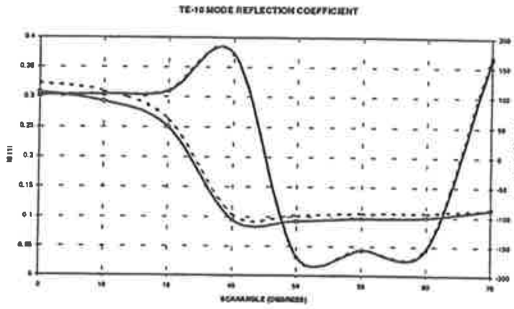

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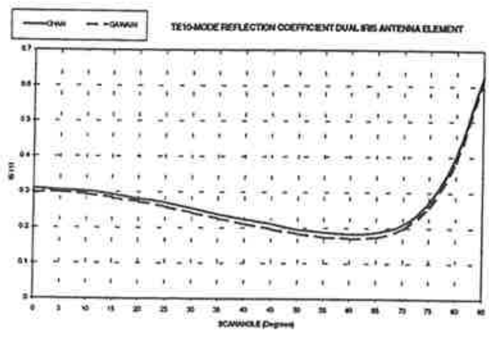
Figure 9: *Active element reflection coefficient vs. scan angle for different scan planes*
a. Overview, b. H-plane, c. D.plane, d. E-plane



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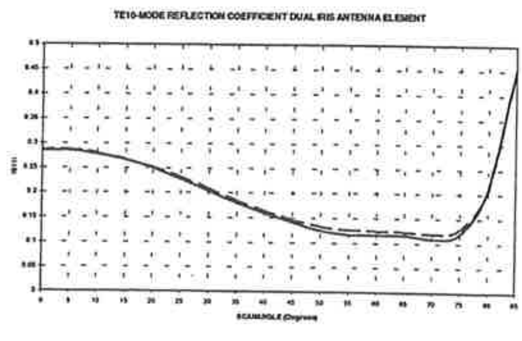

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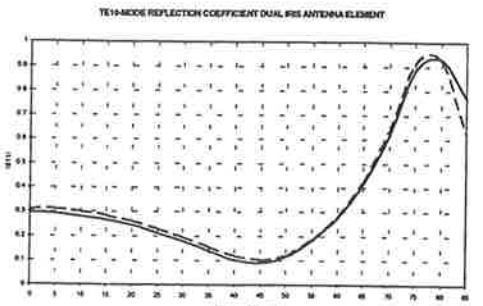

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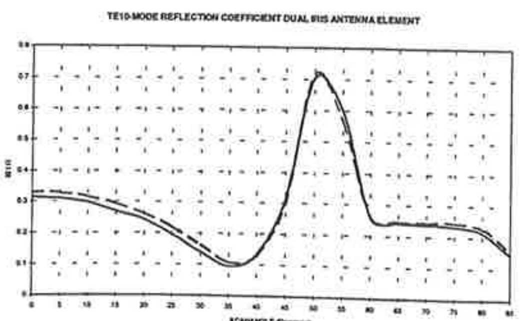

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Figure 10: *Active element reflection coefficient vs. scan angle for different frequencies*
a. f = f0, b. f = f0+1, c. f = f0+2, d. f = f0+3

4. DESIGN STRATEGY

The first analysis program is embedded in an optimisation shell (using downhill simplex and simulating annealing techniques) in order to generate within 24 hours waveguide phased array antenna designs, using a 66 MHz 80486 Personal Computer, given a number of electrical and mechanical constraints. In figure 11, an example is shown where an initial design - obtained in approximately two months by itteratively using the analysis program for a different set of antenna constraints - is re-designed using the optimisation tool.

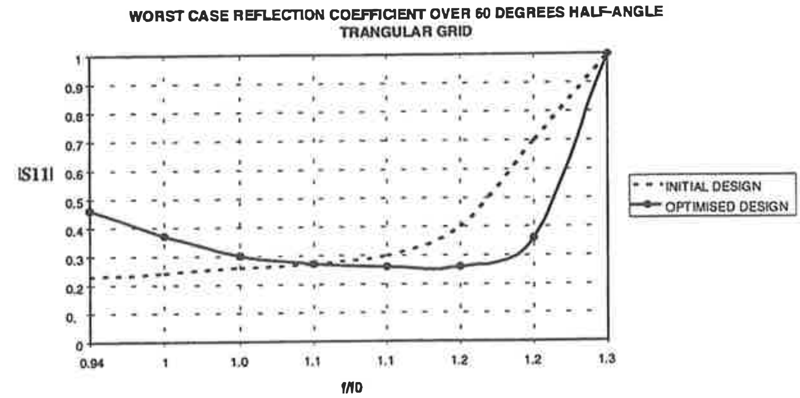

Figure 11: *Result automated antenna synthesis*

The new developed computer program is, due to its versatility, too slow to allow for being completely embedded in an optimisation shell. Only parts of a unit cell can be optimised within acceptable time limits. Therefore it will be advantageous to use the first program (restricted to the use of infinitely thin aperture irises) to synthesise initial antenna designs. The only problem concerned with infinitely thin aperture irises is that they are difficult (though not impossible since the model is valid for a thickness up to .2 mm.) to manufacture. Fortunately, the same iris behaviour can be obtained by increasing the thickness while at the same time enlarging the iris opening to compensate for the thickness (Ref. 8). So after an initial (thin iris) design is synthesised, the design can be fine-tuned by using GAWAIN through optimising the iris (by changing the dimensions or moving it inside the waveguide or adding an additional iris).
Another reason for developing a more versatile simulation tool is that we want to have more degrees of freedom (e.g. the iris width) in the design of waveguide phased array antennas in order to reduce blind scan angle effects.

5. SCAN BLINDNESS

For a certain waveguide phased array antenna, we see in figure 12a that at certain angles in the active element pattern, mutual coupling contributions are causing a destructive interference, resulting in a reflection coefficient of unity. (When the waveguide element is isolated in a ground plane with no other elements present, this distortion will not occur, thus validating that the effect is due to mutual coupling). When in a phased array antenna the beam is steered to the angle where the unity active element reflection coefficient occurs, all transmitted power will be reflected and the antenna is said to be blind for that direction. Scan blindness, although related to, is a different phenomenon than the occurrence of grating lobes. A grating lobe (second main lobe) exists in visible space whenever the elements in an array are spaced further apart than half a wavelength. In figure 12b the position of the grating lobe is indicated for the antenna under consideration at the frequency under consideration.

A misunderstanding is that scan blindness occurs at the same or nearly the same position as the grating lobe. The misunderstanding is caused by the fact that whenever a waveguide antenna is analysed with omission of higher order modes, the maximum reflection coefficient will be found at the position of the grating lobe. Therefore such a one-mode solution is also referred to as 'grating lobe series' [23]. When the antenna is analysed with incorporation of higher order modes, the scan blindness can be found to occur much closer to broadside, the separation between blind scan angle and grating lobe depending on the different antenna parameters. This effect is clearly visible in figure 12. Figure 12 also reveals that by careful designing a waveguide phased array antenna -known to have a blind scan angle due to a prescribed lattice configuration - blindness effects can, although not removed, be reduced. (The results shown in figure 12 are obtained with the 'old' simulation tool). The blindness area can be made smaller and the blindness position can be shifted. One has to be aware, however, that improving the antenna characteristics at the frequency where blindness occurs is compensated for by a worsening at other frequencies.

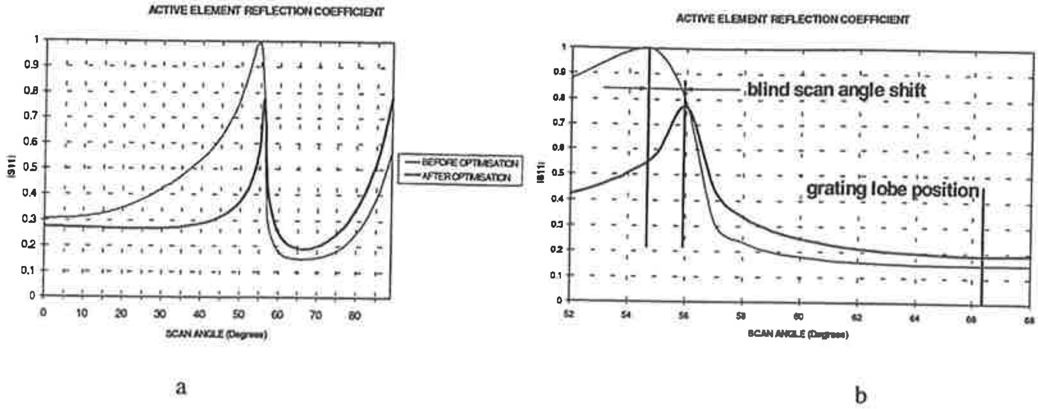

Figure 12: *Scan blindness*
a. reflection coefficient vs. scan angle, b. detail

Although it is widely accepted and understood that scan blindness and the occurrence of grating lobes are directly related to one another, the precise nature of this relationship is not fully understood yet. The assumption that the blindness is caused for by surface waves propagating along the dielectric sheet is not acceptable since resonance effects have also been observed without the presence of dielectrics in planar arrays [23]. A more likely assumption is that blindness effects are caused for by leaky waves which exist in the array structure [24]. Element pattern nulls (unity reflection coefficients) are due to the destructive interference between the direct radiation from the excited waveguide and the component radiated by the leaky wave.

We expect that by the development of GAWAIN, thus having gained more degrees of freedom in the design of waveguide phased array antennas, we are better able to control scan blindness behaviour.

6. CONCLUSIONS

In addition to an existing analysis and synthesis software tool for waveguide phased array antennas at TNO-FEL, a new, more versatile software tool for simulation of waveguide structures and waveguide phased array antennas has been developed. The validity of the new tool is proven thoroughly and a waveguide phased array antenna design strategy using the best of both TNO-FEL in house developed computer programs is outlined. It is expected that with the newly developed software we will be able better than before to control scan blindness effects in waveguide phased array antennas.

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