MINIATURE ANTENNAS AND RELATED COMPONENTS

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ABSTRACT

Netherlands' research on miniature antennas and related components in the period 1988-1991 is summarized. Wideband dual-polarized waveguide antenna elements in S- and X-band were realized. The height and width of the dielectric-filled waveguides are less than half the free space wavelength. A small cluster of 5 S-band miniature waveguide antennas is part of a hybrid reflector antenna with limited beam switching capabilities. Multipath fading reduction with this reflector antenna is reported based on the Netherlands angle diversity experiment along a terrestrial radiolink.
The microstrip antenna research is focused on design and optimization aspects of an active phased array for an airborne C-band SAR with respect to cross-polar, bandwidth and calibration requirements.

Keywords: waveguide antennas, microstrip antennas, hybrid reflector, angle diversity, multipath fading reduction, phased array

1. INTRODUCTION

In the Netherlands the following institutes are active in antenna research:
- Christiaan Huygens Laboratory (CHL)
- Hollandse Signaal Apparaten (HSA)
- PTT Research Dr. Neher Laboratories (DNL)
- TNO Physics and Electronics Laboratory (FEL)
- Eindhoven University of Technology (EUT)
- Delft University of Technology (DUT)

This paper gives an overview of antenna involvements of Delft University with the mentioned "non-university" institutes. Cooperations with HSA and DNL exist on miniature waveguide antennas (section 2); with CHL polarization characteristics of microstrip antennas are discussed and with FEL a partnership exists in the so-called PHARUS project (section 3).

During this workshop EUT presents a paper by A.B. Smolders which is entitled "Efficient analysis of small antennas embedded in a substrate using a spectral domain moment method".

2. MINIATURE WAVEGUIDE ANTENNAS

The antenna group of Delft University has developed an elementary antenna design approach which has proven to be successful in broad banding miniature waveguide antenna elements with low cross-polar characteristics. The cross section dimensions of the elements are always less than half the free space wavelength λ_o.
The improved results were obtained by means of
- performance prediction of selected coax-waveguide transitions and of open ended waveguides filled with dielectric
- polarization-dependent reflection and transmission structures in the waveguides
- impedance matching at the open end of the waveguide by using an airgap

- simplified models for the radiation characteristics based on line sources.

In the following paragraphs some highlights on miniature waveguide antennas and their applications are given.

2.1 S-band radiators for polarimetric radar

In the period 1987-1992 specific research deals with the design and realization of a two dual polarized 3.315 GHz antenna feeds for the Delft Atmospheric Research Radar. The new aspect in this feed design is the extension of the dielectric filling outside the square waveguide. Because of this extension the feed has a higher gain and so the radiation pattern becomes more narrow. Starting from the concept of line sources a three-dimensional array theory model has been used to perform the calculations of the radiation pattern of the dielectric rod outside the waveguide.

The prototype feed has the following measured characteristics

- center frequency 3.315 GHz
- dual polarization
- cross section dimensions 34.2 mm x 34.2 km (0.4 λ_0 x 0.4 λ_0)
- extension up to 50 mm maximum increase of 5 dB in gain
- VSWR < 1.1 over 540 MHz bandwidth
- mutual coupling between the polarization probes ~ 50 dB.

The E-plane pattern is affected by the thickness of the waveguide walls and the minimization of the walls at the end of the waveguide are under investigation. A final design will be ready in 1993.

2.2 X-band radiators

For the X-band solid state FM-CW weather surveillance radar Solidar at Delft University a cluster of 4 miniature waveguide feeds have been designed. The relative dielectric constant was increased to 5 instead of 2.55 as applied in the S-band radiators. Wideband matching (VSWR < 1.5) over 1 GHz bandwidth was obtained for both polarizations.

The cross section is 9 mm x 9 mm (0.28 λ_0 x 0.28 λ_0). No dielectric extension was used in order to obtain a uniform phase front in the aperture of the 1.20 meter parabolic dish. This requirement was also of interest for the ground based scatterometer to do remote sensing research in the preparation phase of ERS-1 (European Remote Sensing satellite).

3. ANGLE DIVERSITY USING HYBRID REFLECTOR ANTENNAS (D. Beaufort, L. van der Hock)

In the COST 213 project the major Netherlands contribution consisted of the design and application of 4 GHz square miniature waveguide radiators. A cluster of 5 radiators were used in a focal feed parabolic reflector. An experiment was set up in order to verify the angle-diversity improvement capabilities of this hybrid reflector antenna on a terrestrial radiolink by biasing these beams in elevation.

The angle diversity experiment is reported here.

3.1 The angle diversity experiment

In July 1988, a field test started to evaluate performance improvement obtained by limited beam switching on a digital microwave link. The experiment comprised the measurement of both propagation and transmission related parameters. In Lopik, a 140 Mbit/s Pseudo Random Bit Sequence was modulated and transmitted to Loon op Zand, where the signal was received by the Hybrid Reflector Antenna described above. The basic transmission and system parameters are listed in table 1.

The length of the radio hop Lopik - Loon op Zand is 44.6 km. At both ends the antennas are installed on radio towers, about 80 m above sea level. The path profile is given in figure 1.

The path is predominantly flat grassland, with a few rivers crossing it. From the path characteristics and the location of the hop (in a coastal region) it is concluded that both surface reflections and surface ducts may relatively often occur.

channel center frequency	3810 MHz
channel width	40 MHz
polarization	horizontal
modulation	16 QAM
system capacity	140 Mbit/s
nominal input level center feed	-37.6 dBm
input level for BER = 10^{-3}	-76.9 dBm

Table 1: *System and transmission parameters of the angle diversity experiment*

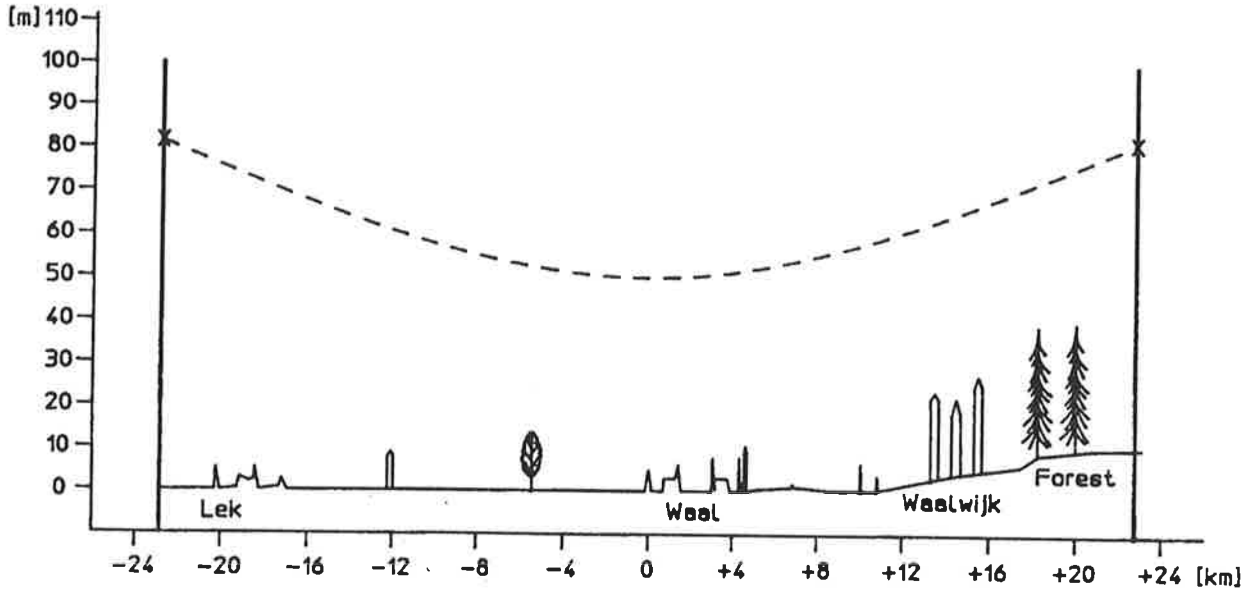

Figure 1: *Path profile of the experimental hop Lopik - Loon op Zand*

3.2 Theoretical performance evaluation

In an earlier contribution to COST 223, a Performance Prediction Model (PPM) for angle diversity was presented, which was developed at PTT Research. This model was designed to predict outage time improvement (outage time being defined as the total number of seconds during which the Bit Error Ratio exceeds 10^{-3}) by limited beam switching on the Lopik - Loon op Zand hop.
According to the PPM, outage time would be reduced by a factor of 24 by switching between the center beam and one diversity beam of the Hybrid Reflector Array. Since the angles-of-arrival are supposed to be symmetrically distributed around the Line-of-Sight (LOS), the improvement factor would not depend on which of the two diversity beams was applied. The improvement factor would mainly be limited by the following two characteristics of the diversity feed pattern:

- the strong signal attenuation for angles-of-arrival at or near the main feed boresight (which is aimed at LOS), which relatively often leads to signal levels below system threshold;
- the symmetry of the main lobe and first side lobe of the diversity feed for angles-of-arrival at or near LOS, which reduces the discrimination of multiple rays by this feed

Using the PPM, a theoretical optimum was determined for the diversity feed pattern, which could be obtained from the given patterns by:

- supplying -20 dB (1 %) of the incident power on the main feed to the signal received by the diversity feed, and:
- pointing downwards the entire reflector by 0.35 degrees.

This will lead to an increased incident signal level on the diversity feed. On the other hand, the slope of the diversity feed pattern around the LOS decreases, so that reduction of selective fading would be somewhat less effective (but, according to the model, still sufficient).

3.3 The experimental set-up

The experimental set-up of the angle diversity field test is shown in figure 2. Equipment was connected to each of the three feeds. In the following, the equipment connected to the center feed will be mentioned "the main channel"; similarly, there is an "upper feed channel" and a "lower feed channel".
Since the main beam is aimed at the Line-of-Sight, the main channel represents an unprotected radio relay system. Performance improvement by angle diversity should therefore be related to the performance of this channel.
The main channel is basically a commercial receiver / demodulator. However, after down-conversion of the frequency from RF (3810 MHz) to IF (140 MHz), one half of the signal power is split off to determine the amplitude spectrum: with narrow band (5 MHz) filters the signal level is measured at 7 frequencies within the radio channel. The other half of the IF-signal is fed into the demodulator which is ended by an error counter for BER-performance evaluation.
The following main channel parameters are measured:

- the Bit Error Ratio during the past second;
- the amplitude spectrum (7 values per sample; sampling rate 5 Hz);
- the AGC-voltage (sampling rate 5 Hz).

For the experiment only two demodulating receivers were available. It was decided to connect the second receiver to the lower feed (the main lobe of which is aiming at elevation angles *above* the LOS, due to the reflector!), because some greater variety in fades and fading types was expected, Hence, the lower feed channel is almost similar to the main channel, except for the amplitude spectrum measurement: equipment for this measurement was added to the lower channel after one year. Until then, a 3 dB attenuator was inserted between the receiver and demodulator in order to obtain a Flat Fade Margin equal to the main channel FFM.
The following lower feed channel parameters are measured:

- the Bit Error Ratio;
- since June 1989: the amplitude spectrum (sampling rate 5 Hz);
- the AGC-voltage (1 Hz; since June 1989: 5 Hz).

On the upper feed (corresponding to the *lower* beam), only the incident power within the radio channel bandwidth was recorded. The lowest detectable level was -76 dBm, which is about 1 dB above system threshold.

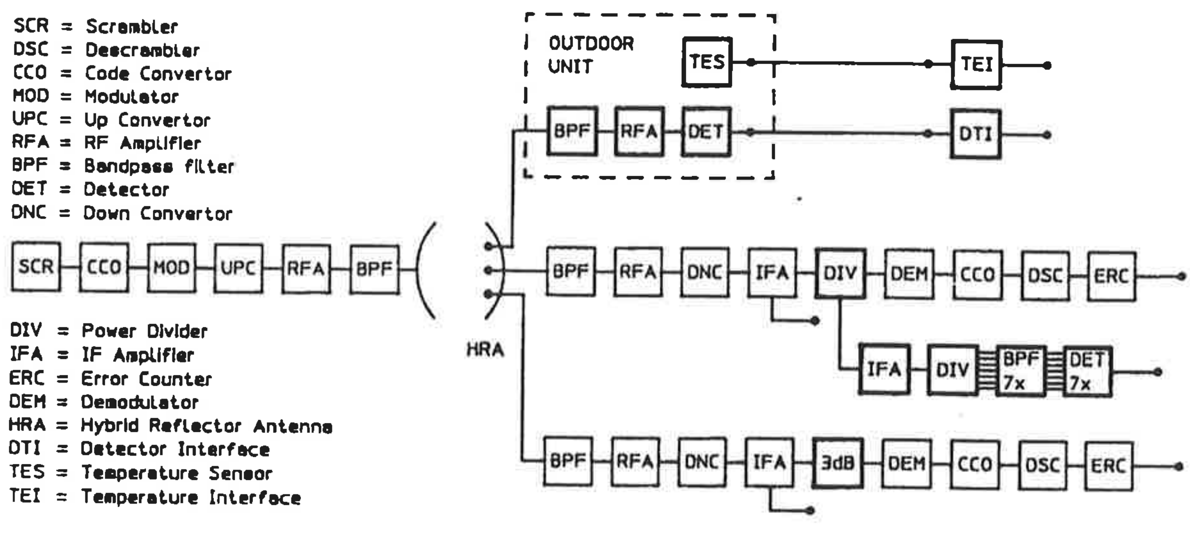

Figure 2: *The experimental set-up of the angle diversity experiment*

3.4 Results of the original set-up

From July 1988 until September 1989 the experiment was conducted using the antenna configuration and the experimental set-up described above. During this period the main channel was in outage during 1042 seconds. Switching to the lower feed would reduce the outage time to 105 seconds. Hence, the measured outage time improvement factor is 10, which is somewhat worse than the predicted value of 24.

It showed that simultaneous outage of the main and lower channel occurred only when the lower feed signal level was below threshold. In other words: during outage of the main channel the lower feed always sufficiently eliminates dispersion and hence simultaneous outage only occurs if the lower channel flat fade margin is exceeded. Assuming that this fact also holds for the upper feed, the outage time reduction by switching between the center and upper feed can be estimated from the incident power at the upper feed. During outage of the main channel, the upper feed incident power was below detection threshold for 3.7% of the time (the threshold of the detector was about 1 dB above system threshold). Hence, the estimated outage time reduction factor by switching between main feed and upper feed amounts to *at least* 27.

Selecting each second the best out of *three* feeds adds little to the obtained improvement; the estimated improvement factor for this case is equal to 32. Since this type of switching requires a much more complicated switching algorithm, it must be concluded that a three-beam system is not useful for practical purposes.

3.5 Adaptation of the antenna patterns

According to the Performance Prediction Model, higher improvement should be obtainable when the entire antenna was turned down by about 0.35° and when -20 dB from the main feed signal was added to the diversity feed signal.
However, changing the elevation angle of the antenna is undesirable, because then the main channel would no longer represent an unprotected radio relay link. Hence, it was decided to only supply some of the main feed power to the lower channel. For this purpose a power combiner as shown in figure 3 was used.

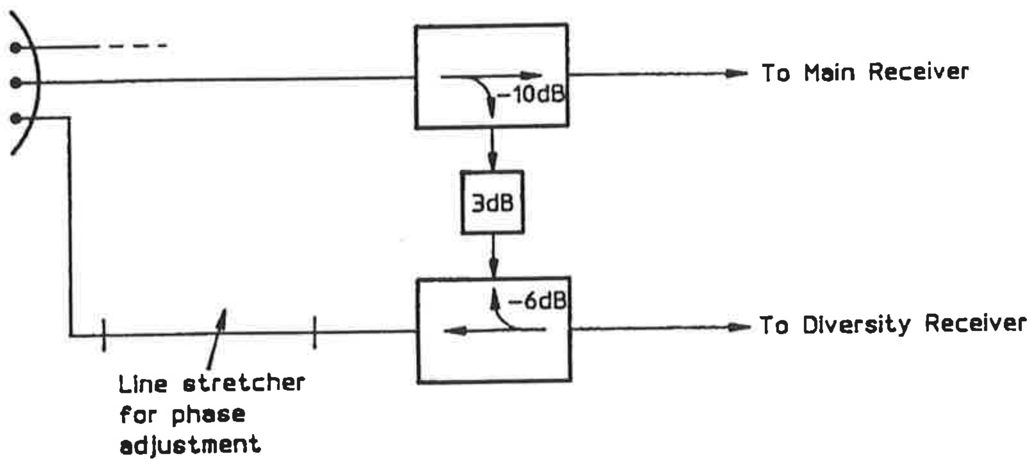

Figure 3: *Fixed power combiner to adapt the lower feed co-polar pattern*

After installation of this combiner, the co-polar patterns of both the main feed and the lower feed were measured on the radio hop. The results can be found in figure 4: surprisingly, the first side lobe of the lower feed pattern had disappeared. Later it was found that the antenna measurements were probably disturbed by strong surface reflections on the path.
Since the PPM still predicted a very high improvement factor for the antenna patterns in figure 4 (about 67), it was decided to continue the field test with the new antenna patterns.

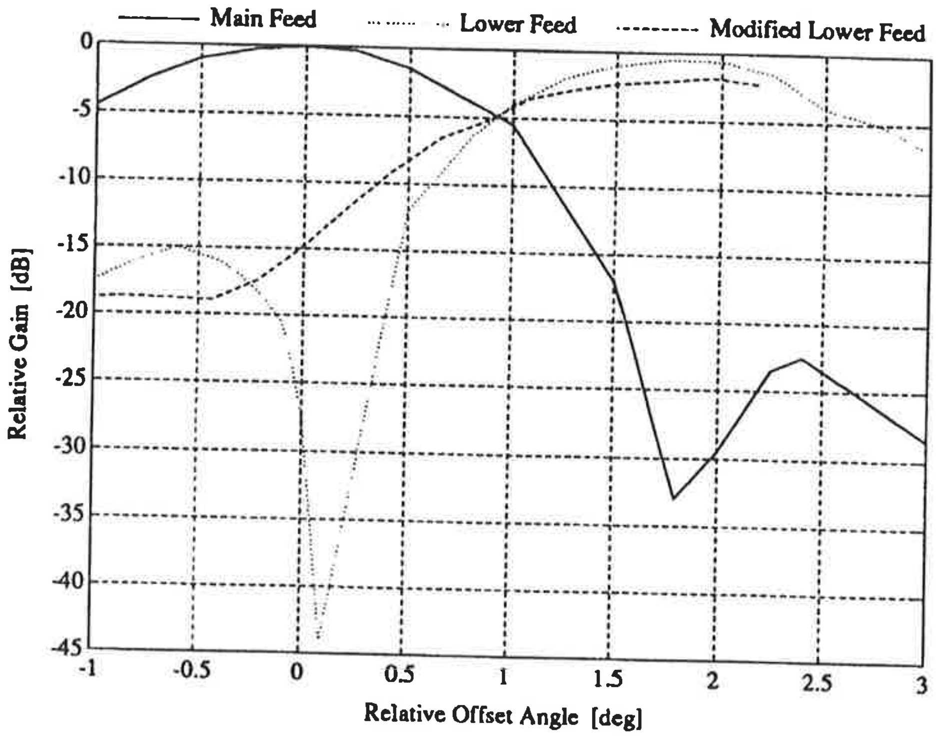

Figure 4: *Measured co-polar patterns of the main feed and lower feed before and after installation of the fixed power combiner*

3.6 Results with the modified diversity beam

The new antenna patterns were tested from September 1989 until April 1990. The result turned out to be dramatic: outage time was reduced only from 740 to 488 seconds, an improvement of 1.5.
Since the main change by the modification was the disappearance of the first side lobe of the diversity feed, the conclusion may be drawn that this side lobe was responsible for the improvement obtained during the first part of the experiment.
An important implication of this conclusion is that on the test hop, during multipath fading most of the signal components ("rays") have an angle-of-arrival *below* the Line-of-Sight. This also explains why the upper feed (which is the lower beam!) reduced multipath fading more effectively.

3.7 Conclusions

With angle diversity reasonable fading reduction can be obtained. To optimize the improvement, the radio hop involved should be carefully considered. On the experimental hop Lopik - Loon op Zand, surface ducts and reflections probably dominate the fading phenomena, leading to angles-of-arrival predominantly below the Line-of-Sight. Probably for that reason the upper feed (= lower beam) reduces fading most effectively.

The Hybrid Reflector Array discussed in this paper can be mounted in standard parabolic reflectors, which allows for a rather easy implementation of angle diversity in the existing networks. Practical application of angle diversity is however hampered by the lack of reliable performance prediction methods. Hence, a strong need exists to develop such a method on very short terms.

4. MICROSTRIP ANTENNAS

In the Netherlands an airborne C-band SAR is under development under the project name PHARUS which is an acronym for PHased ARray Universal Sar. It will be a multi-function radar with the capability of full polarimetric remote sensing measurements (Ref. 1). PHARUS is a joined project of TNO Physics and Electronics Laboratory, the Laboratory for Telecommunication and Remote Sensing Technology of Delft University and the National Aerospace Laboratory NLR.
The antenna system will consist of an array of microstrip antenna elements. Some major aspects in the antenna system design are elucidated.

4.1 PHARUS antenna fundamentals (M.H.A. Paquay)

At the moment, one of the dominant projects in antenna research at TNO Physics and Electronics Laboratory is a microstrip antenna array for an airborne C-band Synthetic Aperture Radar (SAR).
The active antenna will have a modular set-up. The microstrip radiator is integrated with the Transmit/Receive (T/R) module. This module contains a solid state Power Amplifier (25 W peak), two Low Noise Amplifiers, two vector modulators, some switches and control logic. In the transmit mode, a switch selects the horizontal or vertical polarization but the module receives both polarizations simultaneously. The idea behind the modular set-up is that each module can be replaced by a spare one, just by removing 4 screws.

The main design parameters for the antenna are a -1 dB gain bandwidth of 100 MHz (2%) and dual linear polarizations with a maximum cross-polarization level of -23 dB. This last requirement turned out to be the most difficult one to realize. Microstrip patch antennas in general do not have very good radiation properties compared to, for example, waveguides. But, on the other hand, they have a greater variety of possible configurations. The research started in cooperation with the Delft University. There, a model (Transmission Line Model (Refs. 2, 3)) was implemented and several experiments were done with some basic configurations. For a single polarized patch with 1 probe, it turned out that the best cross-polar level was reached with the feed at the edge of the path. Unfortunately, the matching is worse at this point. We tried also balanced feeds; that is, 2 feeds in the resonant direction but on the opposite sides and with opposite phases. For dual polarization this gives already four feeds plus two feed networks and the matching problem is even more difficult than the single feed case. And the radiation properties were not even that fantastic as the literature indicated. More and more we realized that the feeds were a disturbing aspect in the whole configuration. The feeds for the vertical polarization disturbed the fields of the horizontal polarization. The solution we found was to excite both feeds simultaneously. For one polarization the feeds are fed in phase, for the other polarization they are fed with opposite phases. The co-polar fields are now in the diagonal planes of the patch. Cavity model analysis shows that the combinations TMxy±TMyx-modes have better cross-polar characteristics than single modes.

Remaining problem was the matching. Quarter wavelength lines on the substrate worked well, but the radiation of these lines disturbed the cross-polarization. For mechanical stability reasons we use a Duroid substrate on a 6 mm thick aluminium ground plane. The solution to our matching problem was to use the coax feed-line through this aluminium as quarter wavelength transformer. First we have done an experiment with airline coax with very good results, the best until now. For stability reasons we use now a 100 Ohm coax line. That does not transform directly to 50 Ohm but that is a minor problem.

Finally the feed network. A ratrace is almost ideal for this application. It has a sum and difference port and these input ports are mutual isolated. Also the output ports to the antenna are mutual isolated. So the feed network does not give extra coupling to the polarizations. Besides that it is possible to have different in- and output impedances which makes it possible to incorporate the final matching from the 100 Ohm coax lines to the 50 Ohm of the rest of the T/R-module. Meanwhile we are working on an internal calibration channel. We make a fifth port to the ratrace which has a certain coupling to the input ports, but which is isolated from the antenna ports. In the transmit mode we can monitor the output of the Power Amplifier, in the receive mode we are able to inject a well known signal to the Low Noise Amplifiers. Fig. 5 gives a schematic overview of the T/R-module plus patch antenna (the construction of the calibration port is slightly different as shown in the figure). This design satisfies all the requirements of PHARUS (Ref. 4).

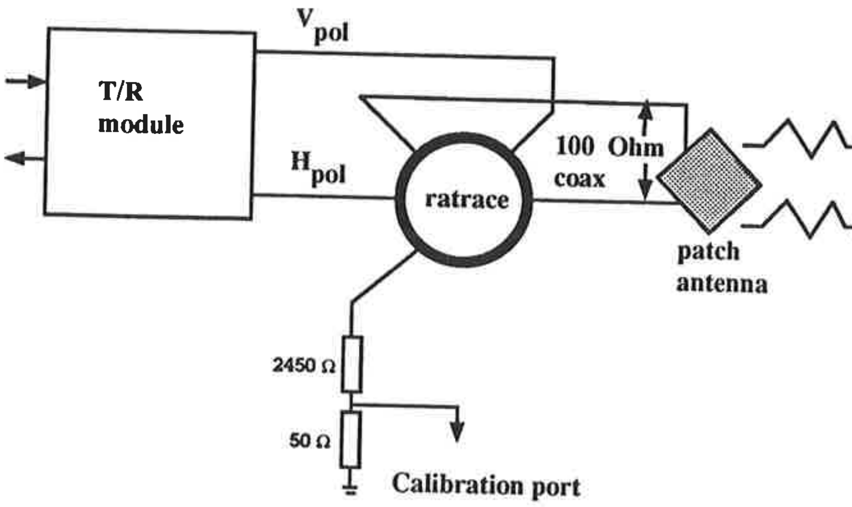

Figure 5: *Schematic overview of the T/R-module plus patch antenna*

Development of microstrip antennas cannot do without theoretical models but there is also a lot of experimental experience needed to get a practical acceptable design. Probably that dual character will stay with this kind of antennas.

4.2 Phased array antenna calibration aspects (M. Tian)

Each active phased array is designed for wanted antenna gain patterns. Since the phase and amplitude of the elements of the phased array are controlled by T/R modules, the synthesized gain patterns are part of the system requirements. Further the antenna pattern is also a function of the T/R module excitation coefficients which show a random perturbation. Therefore, the unique problem of the active antenna calibration arises from the error estimation of the T/R modules.

The far field pattern $E(\theta, \varphi)$of the planar antenna array including the T/R module errors is

$$E(\theta,\phi) = \sum_{i=1}^{n} A_i e^{j\beta_1} F_i$$

with (1)

$$F_i = \sum_{m=1}^{M_i} C_{m,i} e^{j(ux_{m,i}+vy_{m,i})} E_{m,i}(\theta,\phi)$$

where

A_i and β_i = the amplitude and phase of the *i*th T/R module respectively,
F_i = the array function,
M_i = number of elements fed by the *i*th T/R module,
$c_{m,i}$ = complex excitation coefficient of the *m*th element fed by the *i*th T/R module,
$x_{m,i}, y_{m,i}$ = coordinates of the *m*th element fed by the *i*th T/R module,
u = $k\sin\theta\cos\phi$,
v = $k\sin\theta\sin\phi$,
k = $2\pi/\lambda_o$ the wavenumber,
$E_{m,i}(\theta,\phi)$ = gain pattern of the individual element.

First, let us consider an example of where the array size equals 32x16. The subarray size, each of which is fed by one T/R module, is 2x2. When a single T/R module has amplitude (in percentage) or phase (in degree) disturbance, the gain degradation (in dB) is shown in Fig. 6.

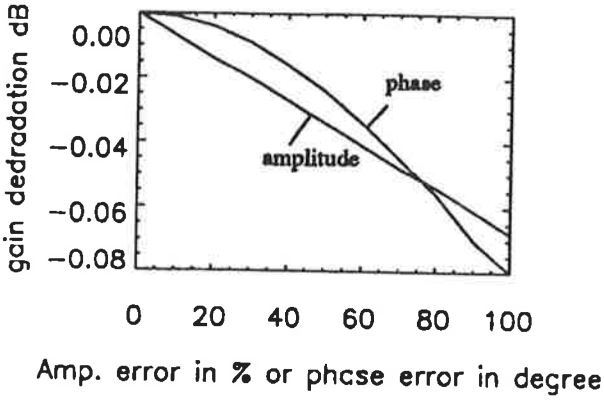

Figure 6: *Pattern degradation vs. amp. and phase disturbance of a single subarray*

The far field power can be expressed as

$$P(\theta,\phi) = E^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} A_i A_j e^{j(\beta_i-\beta_j)} F_i F_j^* \qquad (2)$$

where * denotes the complex conjugate.

The statistical computation has been performed in terms of variance of P as

$$\sigma^2(P) = \overline{(P^2)} - \overline{P}^2 \qquad (3)$$

where the overhead bar denotes the expected value. Fig. 7 shows the uniform and Gaussian probabilistic distributions based on the same example as Fig. 6.

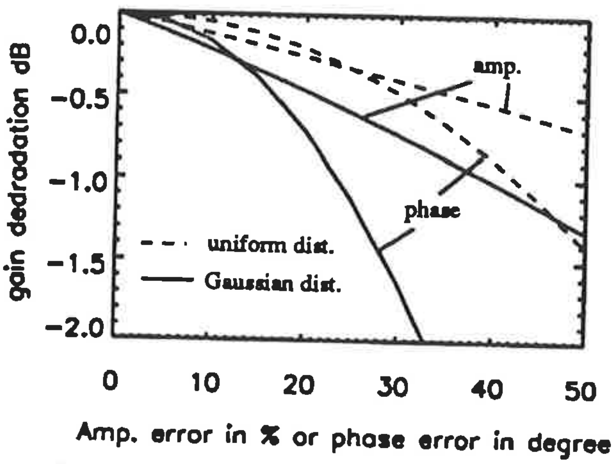

Figure 7: *Probability estimate of pattern degradation vs. T/R random excitation error*

One of the conclusions from above results is that, there is a regular relationship between antenna peak gain and element errors or T/R module failures, i.e. linear vs. amplitude error and exponential vs. phase error. The present results have been verified by successive research work with a statistical error model (Ref. 5). The calculation results for beamwidth and sidelobe as well as error bounds are also reported elsewhere.

4.3 Microstrip antenna with low cross-polarization

The polarization characteristics are of major importance for the performance and the design of microstrip patch antennas (MPA).

A compensation method has been proposed and investigated at Delft University in order to reduce the cross-polar characteristics. This technique, which is applicable for the rectangular MPAs, is explained as follows: The MPA is edge-fed at point P_1 as shown in Fig. 8, the cross-polar component is in general perpendicular to the co-polar component P_1. The second (orthogonal) edge-feeding at P_2 is used in such a way that the co-polar component of P_2 and the cross-polar component of P_1 can have equal amplitude and anti-phase. An overall reduction of cross-polarization may now be obtained.

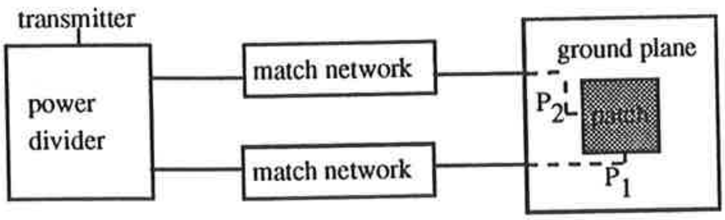

Figure 8: *Experiment set-up for cross-polar compensation*

Based on the transmission model, in combination with the concepts of equivalent slots and of aperture antennas, the radiated field of the compensation probe is computed. The calculation indicates that, the compensation coefficient *d* is a function of the scanning angle. It was verified that, for a given *d*, the cross-polar can be reduced to an absolute minimum at specific angles only. Fig. 9 shows the effect of optimization for three *d* values over the required scan angles.

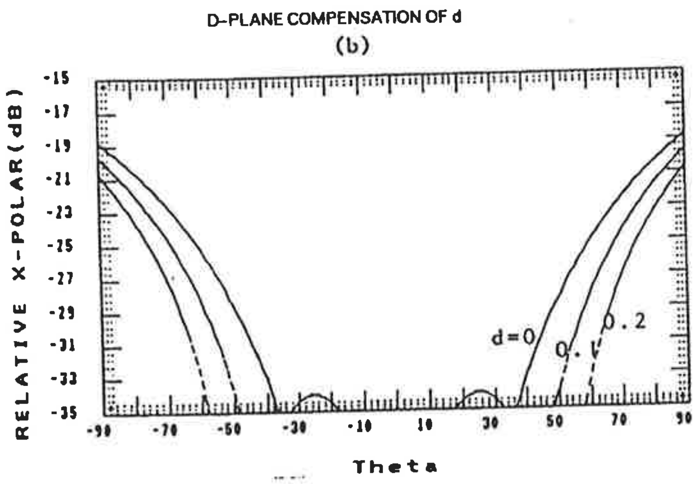

Figure 9: *Cross-polar level with variable compensate values*

This optimization tactics has been demonstrated in measurements with the set-up of Figure 8. TEM-line matching networks have been developed to achieve a wider band impedance matching at each feeding point. The power divider consists of circulators and line stretchers to obtain exactly in-phase and adjustable fractional feeding components at P_1 and P_2.

The problems such as difference in E- and H-plane phase centers and interaction between the polar planes encountered during the experiment were also tackled. The optimum compensation coupling coefficient relative to the main probe is experimentally chosen to be -24 dB with 30° phase delay. Fig. 10 gives one of the results of cross-polar measurements at the center frequency of 5.294 GHz. It is noted that only the diagonal plane is shown because the worse cross-polarization occurs there.

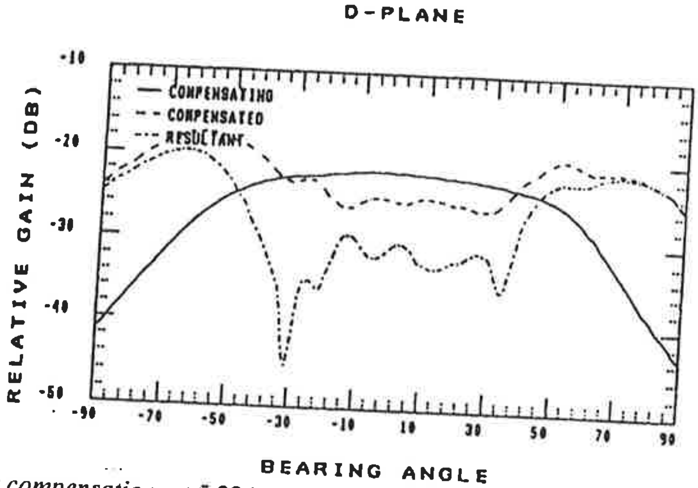

Figure 10: *Cross-polar compensation at 5.294 GHz*

Finally, the primary results of the developed microstrip antenna are indicated in Table 2.

Center Frequency:	5.294 GHz		
Bandwidth:	60 MHz (VSWR ≤ -11 dB)		
Scan Angle Interval:	-41° ~ +41° (3 dB co-polar)		
Cross-polar Characteristics:			
	E-plane	H-plane	Diag. plane
$\text{Frequency}_{center}$	-30 dB	-32 dB	-34 dB
Frequency_{lower}	-36 dB	-27 dB	-31 dB
Frequency_{upper}	-31 dB	-31 dB	-29 dB

Table 2: *Specifications of the microstrip antenna with cross-polar compensation*

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