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Application Article

SAR Experiments Using a Conformal Antenna Array Radar Demonstrator

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Conformal antenna arrays have been studied for several years but only few examples of applications in modern radar or communication systems may be found up to date due to technological difficulties. The objective of the "Electronic Radar with Conformal Array Antenna" (ERAKO) demonstrator system which has been developed at the Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR) is to demonstrate the feasibility of an active electronically scanned antenna for conformal integration into small and medium sized airborne platforms. For practical trials the antenna has been adapted for operation with the Phased Array Multifunctional Imaging Radar (PAMIR) system developed at the institute. The antenna in combination with the PAMIR front-end needed to undergo a special calibration procedure for beam forming and imaging post-processing. The present paper describes the design and development of the conformal antenna array of the demonstrator system, its connection to the PAMIR system and results of recently conducted synthetic aperture radar (SAR) experiments.

1. Introduction

Conformal antenna arrays integrated into the surface of a nonplanar part of modern aircrafts, vehicles, or ships are of great interest for certain applications where planar arrays or reflector antennas have definite drawbacks. Some of the potential advantages are improved aerodynamics, increased payload, large field of view (LFOV), and low observability [1]. Despite these advantages, the usage of conformal array technology in commercial applications is still comparably rare. Electromagnetic modelling of nonplanar antenna arrays is a much more complex task than for their planar counterparts because analytical refinement and array periodicity cannot generally be used to simplify the physical relations. Also, the technology needed for fabrication, assembly, and feeding of flush mounted antenna elements on single or double curved surfaces is still comparably complex and costly.

The objective of the "Electronic Radar with Conformal Array Antenna" (ERAKO) demonstrator system which has been developed at Fraunhofer FHR is the development of a single curved antenna array using existing multilayer technology [2, 3]. The system is based on a wing or fin type elliptical profile with a strong degree of curvature and designed to demonstrate multifunction radar. Possible modes of operation include detection, acquisition, and tracking of multiple targets as well as synthetic aperture radar (SAR). For an overview over important system parameters of the demonstrator's antenna array see Table 1.

2. Conformal Antenna Array

The aperture of the ERAKO Antenna array is single curved in the horizontal plane (xy-plane) and planar along the z-axis. For the geometry of the conformal antenna array, an elliptical cross-section with a large axial ratio ($a/b = 4$) and a strong degree of curvature at the tip has been chosen. This configuration may be seen as an approximation for an antenna mounted circumferentially to the wing or fin of an aircraft.

The antenna aperture is subdivided into 30 linear sub-arrays oriented along the z-axis. Each sub-array consists of several planar dielectric and conducting layers. Four

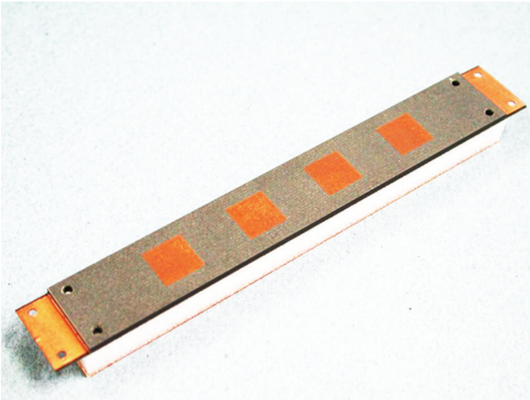

Figure 1: Subarray consisting of four patch antenna elements with common feed.

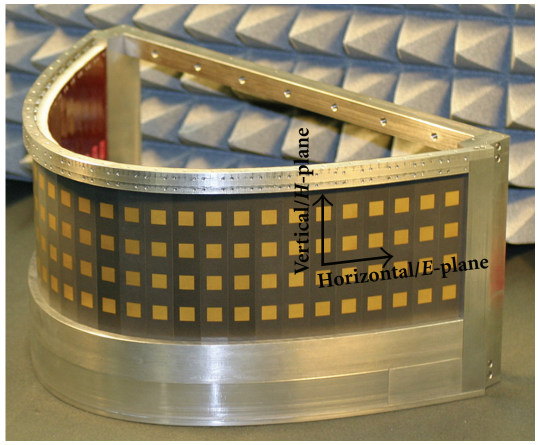

Figure 2: ERAKO antenna front-end showing the 30 sub-array columns. The polarization of the antenna elements is indicated.

Table 1: ERAKO system parameter overview.

Design/center frequency	9.4 GHz
Rel. 10 dB-bandwidth	>15%
Mutual coupling	<-20 dB
Polarization	Horizontal
Sub-array gain	12 dBi
Scanning range (1st segment)	$\pm 90^{\circ}$

horizontally polarized microstrip patch antenna elements designed at a centre frequency of 9.4 GHz are coupled to an underlying feed network via slots in the ground plane and each sub-array is connected to a common coaxial connector via its fixed parallel feed network. A single sub-array column is shown in Figure 1 and has a size of $107 \times 16 \times 10$ mm including a conducting copper foil on a foam layer on the backside used to shield the feed network and prevent backward radiation.

Figure 2 shows the antenna aperture with the sub-arrays arranged in a facetted way and attached to a metallic case. Out of these sub-arrays, 24 are connected to a conformal combined feed and calibration network and may be actively operated. The outer three columns at each side of the antenna are terminated and serve as dummies for reducing array edge effects. The aperture dimensions are $330 \times 200 \times 165$ mm, and the minimum radius of curvature is 83 mm.

The scattering parameters of the embedded antenna elements have been obtained using an Agilent E8364B network analyzer. As an example, the comparison of the element matching and mutual coupling between neighbouring antenna elements for one of the centre sub-arrays (columns) and one of the side elements including the calibration network is shown in Figure 3. It can be seen that, with and without a protecting radome, the 10 dB-bandwidth of the antenna elements well exceeds 1 GHz (>10%). Compared to the isolated antenna design, the resonance frequency is slightly shifted and reflection coefficient levels are slightly increased due to multiple imperfect transitions between different lines inside the calibration network. Mutual coupling between neighbouring columns is low, the coupling between two neighbouring columns (S_{12}) does not exceed -20 dB, and -25 dB between elements further apart (S_{13}) over the full frequency range.

For array beamforming, the embedded element patterns of all the columns in the antenna aperture have been measured in an anechoic chamber at FHR over the frequency range of interest. The mutually normalized embedded element patterns of one of the centre sub-array columns (number 15) and two of the side columns (#4 and #27) in the azimuth plane (E-plane) measured during Tx operation at the centre frequency (9.45 GHz) are shown in Figure 4 for the co-(horizontal) polarization. The embedded element far field patterns show the broad diagrams typical for patch antenna elements with a maximum gain of approximately 12 dBi for the central column and exhibit some ripples due to the facetted aperture design, mutual coupling effects, and the radome influence. The level of cross-polarization isolation is below -20 dB over most part of the azimuth angle range (not shown in the figure). The element pattern of the central element exhibits a wide and almost symmetric shape, which is due to its prominent position and orientation. At the same time, the element patterns of the side elements show their maxima at different angles and are rather distorted. The different maxima positions are due to their rotated orientation dictated by the curved aperture. The distorted shapes can be explained by considering the mounting of the conformal array on the radar system's front-end, as can be observed in Figure 6. The strong decay of the element patterns on one side is due to the shadowing of the front-end, whereas the gradual decay on the opposite side is due to the shadowing of the conformal array itself. In the latter case, a strong ripple is observed which is because of the interference of several contributions of wave propagating around the aperture and radiating at many different positions. To obtain optimum radiation performance from the antenna, different methods suited for pattern synthesis of conformal antenna arrays have been tested and applied [4].

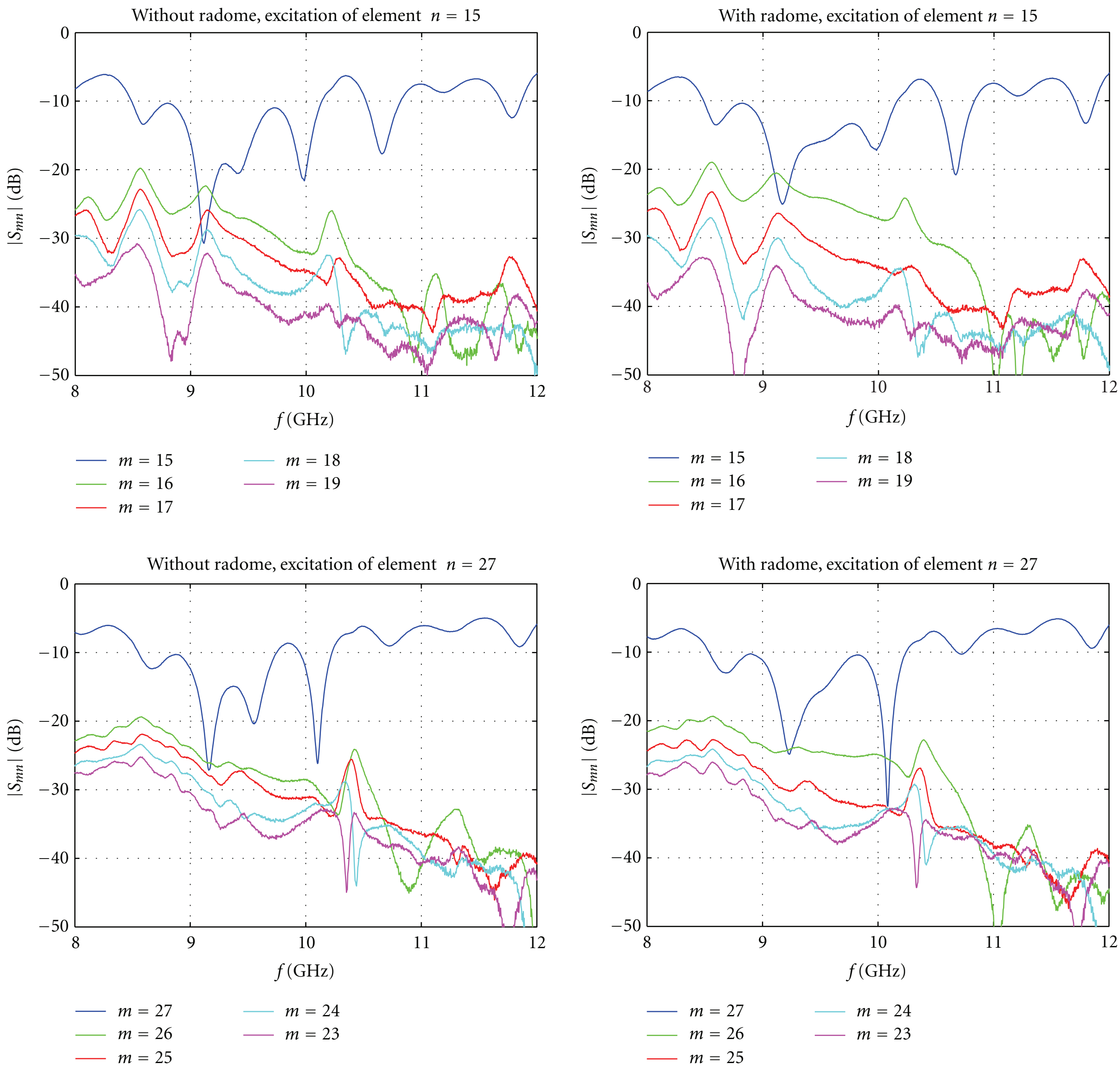

FIGURE 3: S-parameter measurement results for one of the centre elements (#15, top) and one of the side elements (#27, bottom) with (left) and without (right) radome (matching and mutual coupling to neighbouring elements).

3. The ERAKO System

For radar applications, it is foreseen to connect each of the 24 subarrays to a T/R module channel. Because the thermal properties of the electronics may change significantly during operation, a calibration network has been included at the backside of the aperture. Eight sub-arrays are connected to one calibration network. The planar substrates of the sub-arrays and the calibration networks form 90° angles.

For each sub-array port, a small fraction of the transmit power of −30 dB including the phase information is redirected to a calibration port via this network and specially designed vertical directional couplers [5]. Eight sub-array columns are connected to one dedicated calibration port. Using the back-coupled signal deviations between the amplitude and phase relations between the T/R modules may be compensated. The combined feed and calibration network assembled in the ERAKO antenna front-end as seen from below is shown in Figure 5. The backward couplers in three different groups and their connectors and the ports of the dummy elements at the sides of the array can be seen.

These calibration ports are to be used for an on-line calibration procedure for the Transmit-Receive Modules during long-term radar operation. Each of the three ports can be connected to an additional channel of the digital multichannel receiver. The procedure is typically conducted

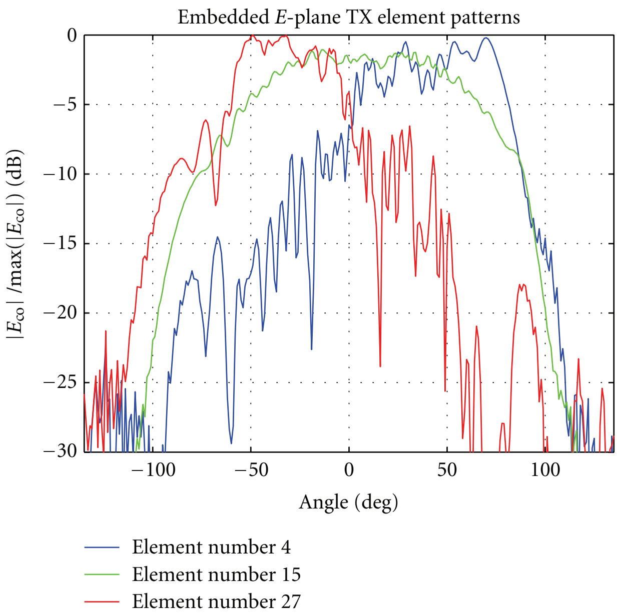

FIGURE 4: Mutually normalized embedded element patterns measured in TX operation of one of the centre elements (#15) and two of the side elements (#4 and #27) of the array aperture at the centre frequency ($f = 9.45$ GHz) for the copolarisation.

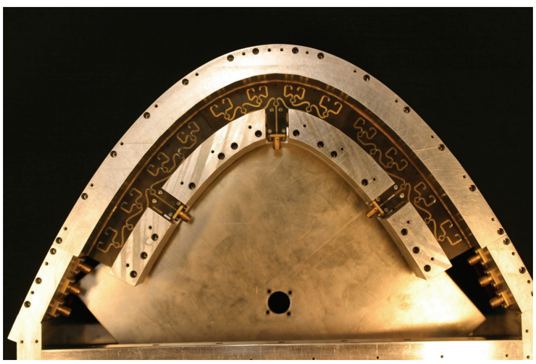

FIGURE 5: Feed and calibration network of the ERAKO antenna array seen from below.

FIGURE 6: PAMIR front-end including ERAKO antenna installed on experimental truck.

such that a signal is transmitted from a single selected channel while all other transmitters are switched off. Inside the feed network, this signal is coupled back into one of the three designated calibration ports, as illustrated in Figure 10. By comparing the actual amplitude and phase shift "received"/detected at the calibration channel to the desired values which have been pre-determined in a similar fashion during an off-line procedure, changes in the behaviour of the active electronic components of the selected channel's transmitter may be detected, which could be caused by temperature drift or ageing. The desired values for steering the array radiation pattern into specific directions are determined using the measurements described in Section 3.2. For bigger antenna arrays, larger numbers of sub-array channels may be combined into one calibration path.

Using this calibration information, corrected phase and amplitude settings may be determined and applied to compensate for the error. For the characterisation of the full array, this step must be repeated sequentially for all 24 active antenna channels. The procedure may be applied in both directions for the transmitting and receiving parts of the electronics. For the operation of the radar system, it is essential to find an appropriate strategy for the time distribution of the calibration signals. Without delaying the target acquisition or tracking this may be done, for example, by including single calibration pulses (or short sequences) in between radar pulse trains every few seconds only.

3.1. Experimental Setup. The Phased Array Multifunctional Imaging Radar (PAMIR) experimental system was originally developed for high resolution long range surveillance with highest flexibility to demonstrate multimode operation [6]. The system serves as airborne sensor for Synthetic Aperture Radar (SAR) imaging with a resolution of up to 10 cm and for detecting moving targets in clutter with a minimum speed of 1 m/s. This multifunctionality can only be achieved with an Active Electronically Scanned Array (AESA) antenna. For this purpose, an experimental radar platform was designed that may be flexibly adopted to changing system requirements.

One of two mockups that were developed for the PAMIR system is a cylindrical aircraft pod containing a linear antenna array with a length of 4.25 m which optimizes the Ground Moving Target Indicator (GMTI) capability of the system for detecting very small target velocities. In addition to the large case used for airborne experiments, there is also a shorter version with a length of approximately 1 m, which can accommodate up to three RF subgroups (in total 48 antenna elements). This case can be installed at the top of an experimental truck vehicle in order to conduct SAR trials. For the experiments in combination with the conformal ERAKO antenna array, these two systems were combined.

The ERAKO antenna was mechanically and electronically connected to two RF subgroups (with 16 channels each) requiring the construction of a special frame structure as support. Since the radar data is measured at a velocity of

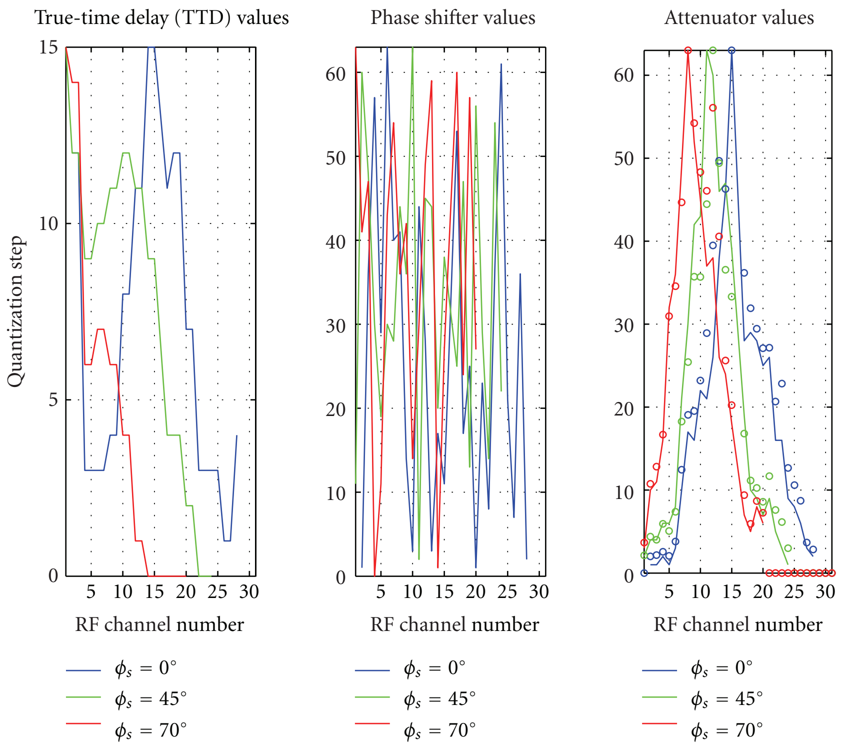

FIGURE 7: Experimentally optimised settings for the true-time delay (TTD), phase shifter, and attenuator settings in RX-operation for three different electronic scan angles. Ideal attenuator values are denoted by circles.

approx. 80 km/h, the ERAKO antenna had to be protected against environmental influences such as wind pressure, rain, or flying insects. The aperture of the antenna has been enclosed in a conformal radome made of glass epoxy. Measurements of reflection and mutual coupling coefficients between the individual antenna elements have shown only a very small influence due to the radome. The PAMIR front-end including the conformal antenna mounted at the top of the truck is shown in Figure 6.

3.2. Array Calibration Process. The ERAKO SAR experiments should be conducted at different steering angles in azimuth of the electronically scanned array antenna with respect to the nose-on direction of the antenna. Especially large scanning angles (e.g., 70°) are of great importance because they are not normally available for typical planar phased array antennas and demonstrate some of the advantages of conformal array antennas on curved apertures. The aim of the calibration procedure was to find optimum settings for the electronic components in each channel of the ERAKO system and to produce the desired array far field for each scanning angle. In transmit (TX) mode, the individual channels should operate at maximum output power while in receive (RX) mode the outer elements should amplify the received signals at lower levels than the ones at the centre for low side lobes in the RX radiation pattern. Therefore, the T/R module settings had to be determined separately for the RX and TX case, respectively.

Each channel of the PAMIR electronics includes a phase shifter with a resolution of four bits and amplitude attenuators with a resolution of six bits; all quantisation steps are in linear scale. In addition, there are electronically switchable true time delays (TTD) for two adjacent channels which can be used to stabilise the phase front of the radiation pattern over frequency for wideband signal operation.

The settings of the individual channels of PAMIR in the transmit (TX) and in the receive mode (RX) were determined for each scan angle in an iterative off-line calibration process, based on the measured embedded element patterns and the frequency response of complex transmission parameters. As an example, Figure 7 shows the experimentally optimised settings for the true-time delay (TTD), phase shifter, and attenuator settings in RX operation for three different electronic scan angles (0°, 45°, and 70°). Because of the finite number of quantisation steps and unavoidable non-linearities, small deviations from the ideal attenuator values determined previously in the beamforming process [7] had to be taken into account. In these cases, ideal values are denoted by circles.

Subsequently, the parameters resulting from the calibration procedure were verified in the anechoic chamber where the performance of the antenna array was measured. The resulting normalized array radiation patterns in RX mode measured over frequency at different scanning angles of 0°, 45°, and 70°, respectively, are shown in Figure 8 as an example. The upper images show the variation of the normalised array pattern over frequency and the lower

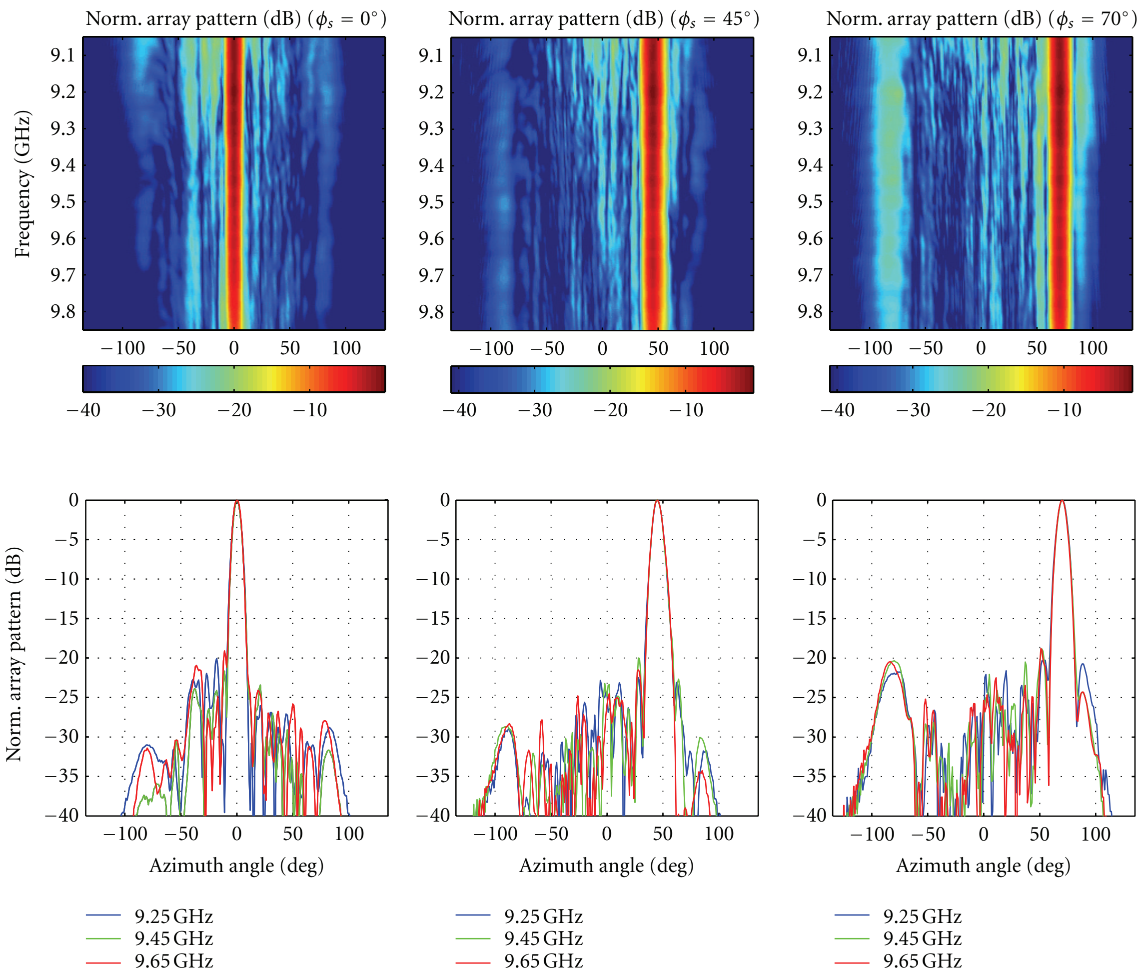

Figure 8: Measured array radiation pattern at scanning angles (0°, 45°, and 70°) in RX operation and its variation over frequency.

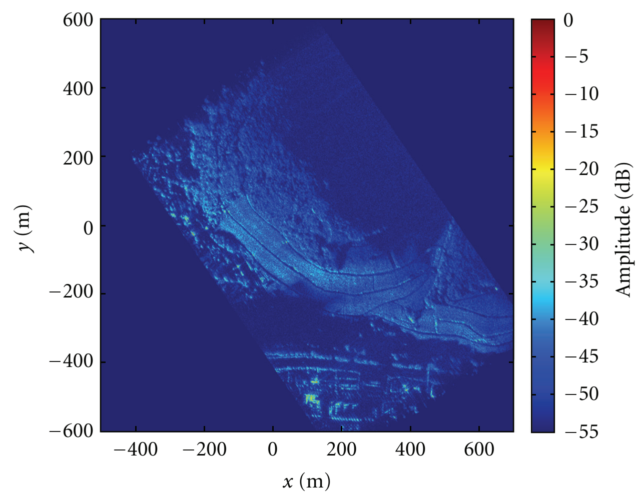

Figure 9: Example of a SAR image with a resolution of 50 cm × 50 cm.

diagrams are selected cross-sections for frequencies 9.25, 9.45, and 9.65 GHz for comparison. It is worthwhile to note that the main beam direction is very stable and the side-lobe level remains below −20 dB for almost all frequencies, even for large scan angles.

An important parameter for scanning array antennas is the so-called scan loss. Measurements have shown that this parameter is 1.28 dB with respect to a scanning angle of 0° in case of the RX operation and 0.86 dB for the scanning angles of 45° and 70°, respectively. In the TX case, the values are 0.57 dB and 1.35 dB. These are significantly lower than for an ideal planar array where values of 1.5 dB and 4.7 dB can be expected for the considered scanning angles. This shows clearly the potential superiority of the conformal array over the planar array concerning the scan loss. Despite of the fact that the frequency range of the PAMIR system had to be reduced to match the available bandwidth of the antenna elements, the calibration measurements were performed in the frequency range from 9.05 GHz to 9.85 GHz. However, only a total bandwidth of 380 MHz has been used for the radar experiments.

4. SAR Experiments

The experimental mockup calibrated using the procedure described above was used to conduct several SAR

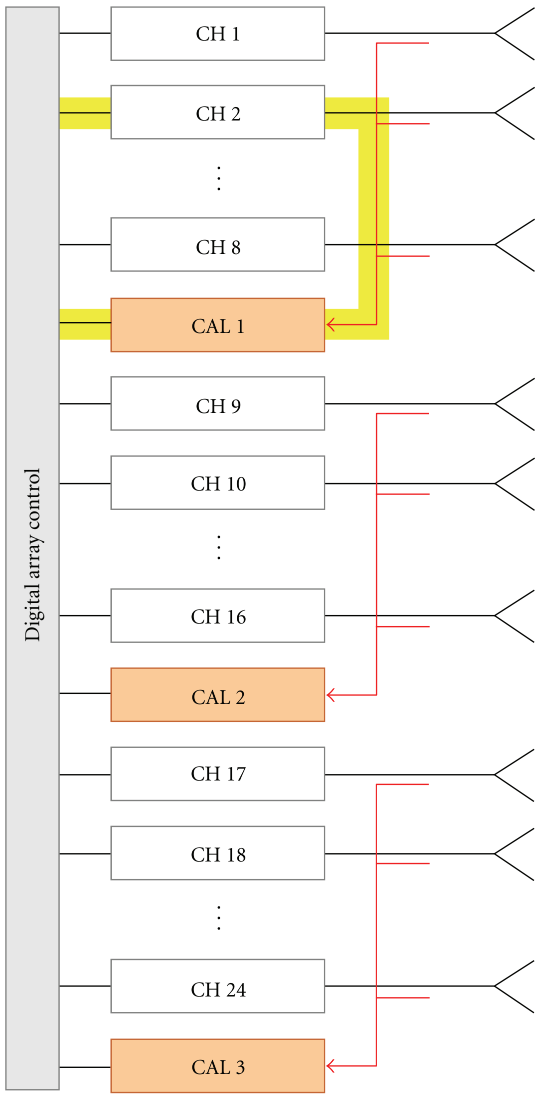

FIGURE 10: In the on-line calibration procedure, a signal is transmitted to a single antenna channel (e.g., CH 2) and fed back to a calibration channel by means of the calibration network to detect changes in the properties of active components.

experiments [8]. The PAMIR system including the ERAKO antenna array was installed on the roof of the experimental truck. Side-looking SAR measurements have successfully been made for different scan directions while driving over a road bridge. An example of a resulting SAR image for a resolution of 50 cm × 50 cm taken at a scan angle of 70° is shown in Figure 9.

5. Conclusions

A conformal antenna array has been connected to the electronics of a wideband multifunctional imaging radar system to perform active radar experiments. For the process of calibration, an iterative off-line method has been developed for finding the settings of the individual channels taking into account the special properties of the curved aperture of the conformal antenna. Subsequently, the optimum settings have been used to form the desired array radiation patterns and several SAR experiments have been conducted with very good results.

With the experiments described above, the feasibility and potential of a conformal antenna array for active radar operation has been shown. They are an interesting alternative to planar arrays on platforms where the antenna shape is dictated by the curvature of the vehicle, for example, small unmanned aerial vehicles (UAVs). While the scope of the present paper only covers the topic of imaging radar, other modes of operation with electronic scanning capability are also possible. Hopefully, such demonstrations will help to increase the number of applications of conformal antenna arrays for radar or communication systems in the future.

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