

PAMIR – a wideband phased array SAR/MTI system

J.H.G. Ender and A.R. Brenner

Abstract: Air- and spaceborne imaging radar systems in forthcoming surveillance and reconnaissance tasks have to meet increasingly severe demands. The next generation of top-level synthetic aperture radar (SAR) systems will comprise, among others, high resolution and long-range imaging capabilities, highly sensitive ground moving target indication and a multitude of sophisticated operational modes. The variety of tasks can be fulfilled only by the use of a reconfigurable phased array antenna together with a comprehensive wideband system design and a multichannel capability. At FGAN a new experimental X-band radar has been conceived, which will possess in its final upgrade an electronically steerable phased array consisting of 16 autonomous and reconfigurable subapertures, five independent receive channels, and a total signal bandwidth of about 1.8 GHz. The sensor is called PAMIR (Phased Array Multifunctional Imaging Radar). It is envisaged to demonstrate SAR imaging at a very high resolution and for a long range. The fine resolution will also be achieved with inverse SAR (ISAR) imaging of ground moving objects. Furthermore, the number of receive channels will allow ground-moving target indication (GMTI) by space-time adaptive processing and single-pass interferometric SAR (IfSAR) with a very high 3-D resolution. In its current stage of extension PAMIR is operable with one receive channel and a mechanically steerable antenna array. The system design and the intended capabilities of PAMIR are described. Ground-based and airborne experimental results concerning high-resolution SAR and ISAR imaging are also presented.

1 Introduction

Air- and spaceborne imaging radar systems in forthcoming surveillance and reconnaissance tasks have to meet increasingly severe demands. The next generation of top-level SAR systems will comprise, among others, high resolution and long-range imaging capabilities, highly sensitive ground moving target indication and a multitude of sophisticated operational modes. The realisation of these and forthcoming radar tasks demands the solution of many technological and methodological problems. The aspired spatial resolution requires the management of transmission and reception bandwidths of about 1.8 GHz. The antenna has to be realised as an electronically steerable and reconfigurable phased array antenna with a finely quantised true time delay feed network and multiple receive channels. The wideband multichannel data acquisition results in very high data rates and volumes. With respect to image resolution and dynamic range, thorough calibration procedures and precise measurements of the carrier motion are indispensable. Furthermore, the wideband and wide-angle scenario requires a thorough modelling of the image formation process with respect to motion compensation and focusing. Space-time resource management through

the use of waveform diversity, sub-apertures, multiple channels and multistatic configurations requires the development of new methods and algorithms for space-time array processing.

With the objective of estimating the achievable performance of such demanding radar systems, FGAN-FHR has decided to build up a new experimental radar platform: PAMIR, the Phased Array Multifunctional Imaging Radar. The most important design parameters of PAMIR are listed in Table 1. PAMIR, which is the follow-up system of AER (see [1]), was designed to meet the growing demands for future reconnaissance systems (like SOSTAR) with respect to flexibility and multimode operation. The system will serve as an experimental airborne X-band platform for different tasks. SAR imaging will be demonstrated at a very high resolution and for a long range (1 dm at 30 km; 1 ft at 100 km). The fine resolution will also be achieved with ISAR imaging of ground-moving targets. A particular research topic is the conception of a broadband phased array with wide scan capabilities ($\pm 45^\circ$). Moreover, five parallel receiving channels will allow array processing techniques like ground-moving target indication (GMTI) via space-time adaptive processing (STAP), electronic counter-counter-measures (ECCM), and interferometric SAR (IfSAR) with a very high 3-D resolution. Furthermore, it is intended to use PAMIR as a ground-based system to demonstrate wideband array processing techniques (angular superresolution, anti-jamming, ISAR for airborne targets). Since the frequency band of the predecessor system AER-II is contained in that of PAMIR, it will also be possible to use both systems for bistatic SAR experiments. In this paper some important aspects of the system design of the experimental platform PAMIR and first high-resolution radar imaging results are presented.

© IEE, 2003

IEE Proceedings online no. 20030445

DOI: 10.1049/ip-rsn:20030445

Paper first received 27th January and in revised form 20th February 2003

The authors are with Forschungsgesellschaft für Angewandte Naturwissenschaften (FGAN) e.V., Forschungsinstitut für Hochfrequenzphysik und Radartechnik (FHR), Neuenahr Str. 20, D-53343 Wachtberg, Germany

Table 1: Basic system parameters of PAMIR

Carrier	Transall C-160
Centre frequency	9.45 GHz
Bandwidth	1820 MHz
Resolution	0.1 m × 0.1 m
Range	100 km
Channels	5 parallel rec. channels
Main antenna	active phased array, 256 T/R modules connected to the radiator columns
Transmit power	1280 W peak
Noise equivalent σ_0 at maximum range	-40 dB
Azimuth scan	$\pm 45^\circ$
Polarisations	VV (Vivaldi) HH (horn)
Basic operational modes:	squinted stripmap SAR spotlight sliding spotlight scan MTI (STAP) IfSAR ISAR

2 System design

2.1 Advanced radar modes

Forthcoming surveillance and reconnaissance demands various stripmap and spotlight SAR modes at different resolutions as well as a large area MTI coverage including clutter rejection, detection and repositioning of ground-moving targets. Besides these tasks, it will be possible to concentrate on targets of special interest; in SAR operation a spotlight illumination with ultimate resolution will be applicable to a small scene chosen arbitrarily within the accessible sector. It should be possible to direct the antenna beam during an appropriate time period to moving targets (e.g. vehicles, ships, helicopters, antennas) to enable the extraction of signatures and to image them via the ISAR technique.

An interesting operation in between stripmap and spotlight is offered by a ‘sliding spotlight’ mode: by steering the look direction for the antenna, the centre of the footprint moves with a fixed velocity along a line on the ground. In this way, the illumination time of an earth fixed point can be chosen arbitrarily to achieve a desired azimuth resolution. A resolution finer than that of the stripmap mode has to be paid for by a limited azimuthal extension of the SAR image; the compromise between resolution and image width can be matched to the demands of each scene.

For the MTI mode, the aperture is partitioned into along-track sub-apertures. The technique of space–time adaptive processing (STAP) is applied suppressing the clutter returns followed by a position estimator based on the sub-aperture signals (see [2]). The same configuration allows MTI and SAR imaging including jammer suppression (see [3] and [4]) and azimuth ambiguity suppression (see [5]).

Partitioning the aperture into across-track subarrays, single-pass interferometry and tomography (see [6]) will be possible promising detailed three-dimensional analysis of man-made objects at fine range–azimuth resolution.

Some examples of establishing advanced operation modes by means of the described space–time–direction–frequency diversity are sketched in Fig. 1. The left-hand side of each diagram shows the frequency allocation along the fast time axis (range direction) covering the transmit and receive periods; on the right-hand side the instan-

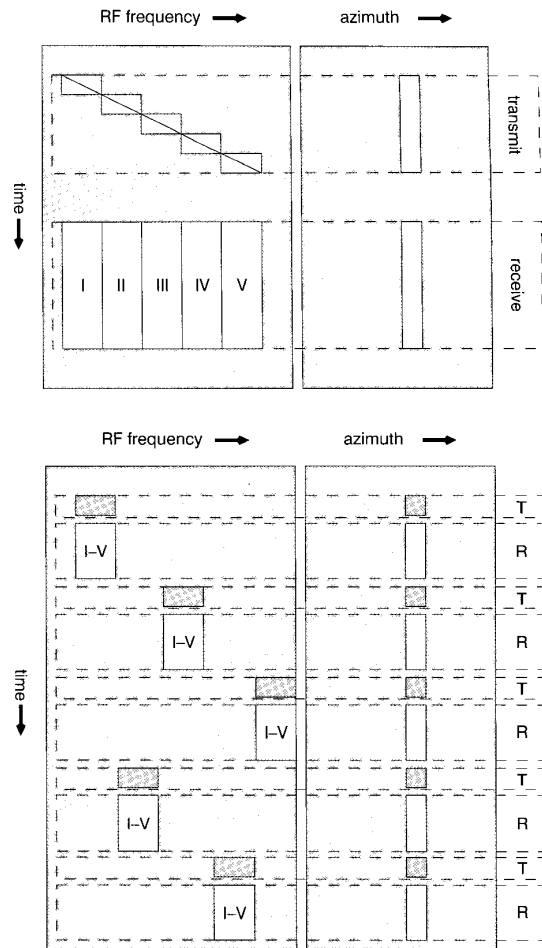


Fig. 1 Two operation modes of PAMIR

- a VHR single pulse SAR
- b Synthetic bandwidth

taneous direction of the phased array beam is depicted along the same time axis.

Fig. 1a shows an example of frequency diversity: a very high range (VHR) resolution SAR mode. The transmitted pulse is composed of five consecutive chirps, while the receiving bandwidth is split up among the five channels. This method (‘concurrent subbands’) is useful if a high PRF is needed.

In Fig. 1b a different VHR mode is sketched: the frequency band is scattered over several pulses (‘synthetic bandwidth method’). To avoid range ambiguities the centre frequencies are chosen in such a way that in the sequence of the centre frequencies two adjacent subbands will never be neighbouring, e.g. in the cycle 1–3–5–2–4 of centre frequencies. The signal-theoretical implications of the synthetic bandwidth approach are treated in [7]. This method is applied to SAR and ISAR imaging.

2.2 Phased array antenna

Bandwidths of more than 2 GHz in the X-band are common features of today’s radiating elements, T/R-modules and other RF components. The principal task in the construction of a wideband phased array is the need for true time delays (TTDs) to guarantee the aspired range

resolution of 10 cm also at large squint angles. Signal-theoretical aspects of this problem are investigated in [8]. For the PAMIR antenna, the finest TTD quantisation has to be of the order of 1 to 2 cm, and the largest delay should be 2.70 m.

According to the experimental nature of the system aspired to, the phased array antenna will be built up as a reconfigurable arrangement of 16 autonomous subarrays ('panels'). This modular approach makes it possible to juxtapose the panels to form a 4.18 m long linear antenna (with superior MTI properties), or to stack them to form a 2-D array (e.g. for multi-baseline IfSAR in spotlight operation).

Each panel can be steered electronically in azimuth. Each panel is composed of 16 radiating columns, T/R modules with 6 bit phase shifters and 6 bit attenuators, a TTD network, beamformers, a power unit and a digital interface. An embedded mini-computer controls the subarray and communicates with the other panels and the main steering computer through full-duplex 10/100 Mbit/s ethernet.

Phases, amplitudes and delay values can be stored in a large RAM for a variety of antenna patterns; the loading of the microwave actuators from the RAM to start a new direction is performed in parallel. The TTD switching is planned to be done by a tree structured microwave network (see Fig. 2).

The following types of radiators have been identified to cope with high bandwidth requirements: open waveguides, Vivaldi and sector horn antennas. To build up a column of about 15 cm height, eight waveguides (Vivaldi antennas) are combined passively, while the sector horn antennas can be designed to fill the vertical aperture completely. A commercial T/R module is connected to each column providing a transmit power of approximately 5 W per module. As an example, in Fig. 3 a Vivaldi antenna array consisting of five radiating columns is shown.

2.3 Broadband waveform generation and signal acquisition

The total bandwidth of about 1.8 GHz is managed by using one of the following three principles:

(a) The transmit pulse is generated over the total bandwidth and the five receiving channels are tuned to five subbands covering the bandwidth in parallel. This method (concurrent subbands) is appropriate if a high quality very

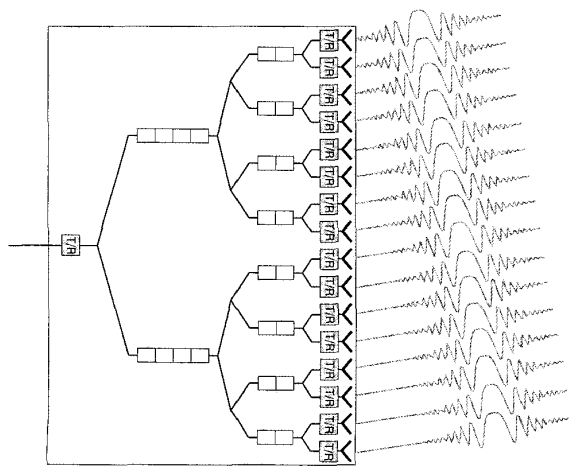


Fig. 2 True time delay network for broadband beam steering

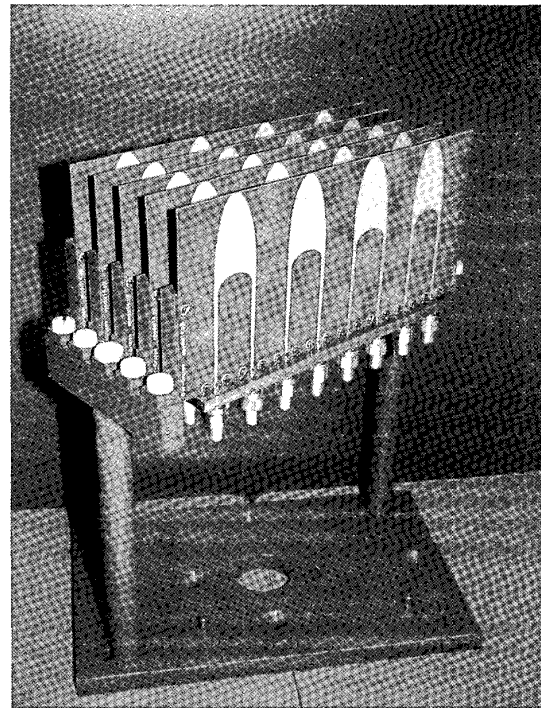


Fig. 3 Vivaldi antenna array consisting of five radiating columns

high resolution (VHR) mode is applied for high PRF demands.

(b) Again, the transmit pulse covers the total bandwidth; during the receive period, a de-ramping signal is generated which can be used by each individual channel. This method (de-ramping mode) can be applied if only a short swath is needed (e.g. for ISAR) and makes it possible to use the entirety of the channels in parallel for spatial processing (interferometric ISAR, ISAR with multi-aperture clutter suppression, ISAR with jammer suppression).

(c) The bandwidth is split over a couple of pulses (see Fig. 4) and the concatenation of the subbands is done in a postprocessing step. This method (synthetic bandwidth) is applied if the PRF demands are not too stringent. The advantages are the availability of all channels for spatial diversity, a high quality of the transmitted signal and the receiving signal acquisition, as well as a lower instantaneous bandwidth for the phased array antenna allowing for correction of the phase-shifter settings from pulse to pulse.

The waveform generation itself is achieved by a two-channel arbitrary waveform generator working at 1 GHz clock frequency producing 10 bit quantised I- and Q-signals. These signals are quadrature modulated to an intermediate frequency producing a bandwidth up to 380 MHz. The generation of waveforms with full bandwidth is performed by use of a switchable bank of five LO sources with a frequency separation of 360 MHz each. In this way, chirps of 1.82 GHz bandwidth can be generated using the stepped chirp principle.

The waveforms are not limited to linear chirps. Nonlinear chirps with a well formed spectrum can be generated as well as noise-like signals. With a predistortion of the waveforms, unwanted phase and amplitude modulations are compensated. An adaptation of the waveforms to a special radar task is possible, too.

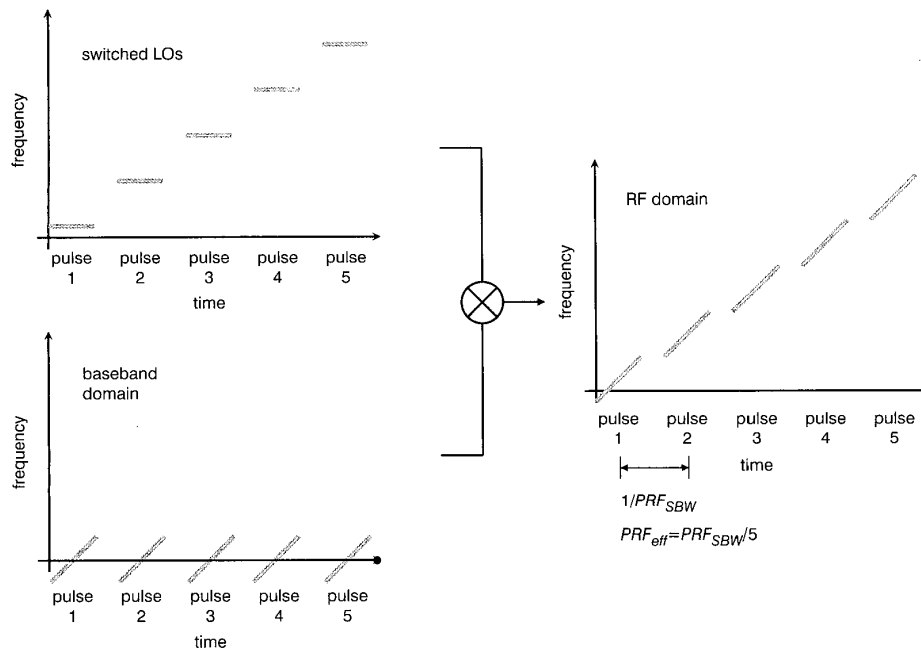


Fig. 4 Allocation of the total bandwidth by means of the synthetic bandwidth technique

The receive branch is composed of five parallel channels with A/D converters working at 400 MHz clock rate and producing 2×8 bit quantised quadrature signals. The data are multiplexed to time-stretch memories and read out with 50 Msample/s. A formatter combines the data from the five channels with auxiliary information (e.g. motion parameters) to a standard data stream, which is routed to a disc array with 200 Gbyte capacity and a continuous data rate of 60 Mbyte/s and also directed to the real time processor, if requested.

3 SAR imaging

3.1 Methods

In realising a wideband and long range SAR sensor the process of image formation is a task of particular importance. Most common SAR processors of recent years are formulated in the wavenumber domain. Their theoretical foundations are based on approximations like the far-field approximation or the range curvature approximation induced by the application of the stationary phase principle. The attainable image quality is sufficient in case of relatively small bandwidths. These approaches benefit from considerable savings in computational effort. As a consequence of the availability of wideband technologies and their increasing usage in SAR applications, the need for non-approximative SAR processing strategies is evident. Wavenumber domain based range-migration methods [9] in case of linear apertures are well suited for this purpose, but not under real-world conditions of curved and nonequidistant sampled apertures. An attractive alternative, however, are time domain based non-approximative SAR processing techniques [10]. They are inherently capable of incorporating nonideal carrier track, propagation effects, nonstandard aperture sampling in the case of using the synthetic bandwidth technique and are not afflicted with the huge memory requirements of the wavenumber domain based algorithms.

The corresponding data model is formulated in the slant range geometry, where the flight path is along the x -axis and the sensor is side-looking into the ρ -direction. At each position ξ the sensor transmits a pulse $s_r(t)$ with

$$s_r(t) = \text{Re} \left\{ e^{j2\pi f_0 t} e^{j\pi a t^2} \text{rect} \left(\frac{t}{T} \right) \right\} \quad (1)$$

where f_0 is the carrier frequency, and T the pulse length. The distance from the sensor to a point in the x - ρ plane is given by

$$R(\xi; x, \rho) = \sqrt{(x - \xi)^2 + \rho^2} \quad (2)$$

In a monostatic configuration, applying the start-stop approximation and without regarding the two-way antenna pattern, the acquired signal $s_r(x, \rho)$ in the spatial domain after quadrature demodulation can be described as

$$s_r(x, \rho) = \iint \sigma(x', \rho') e^{-jk_r R(\xi; x, \rho)} s_r \left(\frac{2(\rho - R(\xi; x, \rho))}{c} \right) dx' d\rho' \quad (3)$$

Here the terrain reflectivity density is denoted by σ , c is the velocity of light, and $k_r = 4\pi f_0/c$. The inversion of this integral equation, that means the estimation of the terrain reflectivity density $\sigma(x', \rho')$ out of the measured data $s_r(x, \rho)$, can be performed by means of a separable matched filter. While the matched filter compression of the pulse can be performed range line by range line in the frequency domain, the impulse response of the matched filter for the azimuthal compression is a two-dimensional space-variant function and will be applied in the time domain. This procedure is well known in other coherent imaging modalities such as ultrasonic imaging, where it is called coherent beamforming. In SAR applications like UWB SAR sometimes the term backprojection is used.

The computational load of the time domain processing is very high. However, by exploiting the fact that the range lines can be processed independently with no need for interprocess communication, the corresponding algorithm

can be parallelised very efficiently. Accordingly, real-time SAR processing in the time domain could be performed with the use of a bank of dedicated circuits or a massively parallel processor architecture. If real-time processing is not obligatory the most cost-efficient solution is to realise a distributed processor running on an already existing workstation cluster [11, 12].

3.2 Results

In a first assessment accomplished within a ground-based car trial the first extension stage of PAMIR was operated in a van driving over a high bridge, looking sideways onto a rural scene consisting of a vineyard with vine rows and closely spaced bending wires and a forest area. A trihedral corner reflector was situated in the scene as well. At this stage the sensor possessed a fixed two-horn antenna with a peak transmit power of 8 W and was utilised in the stripmap mode [13–15]. The synthetic aperture stretched across an angle of about 25°. Prior to the SAR processing, an autofocus procedure based on the data corresponding to the trihedral corner reflector was applied.

First, the SAR data were processed with a spatial resolution of $1\text{ m} \times 1\text{ m}$, which is the resolution limit achievable with the predecessor system AER-II (see Fig. 5). Fig. 6 shows the same scene but now processed with the finest possible resolution. The -3 dB resolution of the trihedral's impulse response amounts to $5\text{ cm} \times 8\text{ cm}$ and therefore achieves the theoretical limit. In comparison to the low-resolution image in Fig. 5, the high-resolution image offers many additional details.

In its actual extension stage PAMIR possesses a mechanically steerable antenna array with 24 sector horn antenna elements and a transmit peak power of 120 W. With this configuration, in August 2002, a first flight campaign was conducted acquiring a wide variety of SAR data. Flights were over urban as well as rural areas, and the sensor was operated and field-tested in various imaging modes such as stripmap-, sliding-spotlight- and spotlight-SAR. Despite of the lack of motion data, which

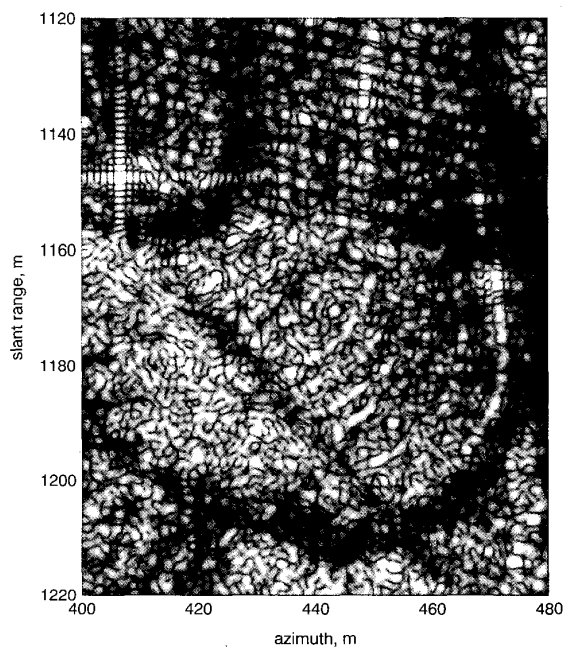


Fig. 5 SAR image of a vineyard (resolution $1\text{ m} \times 1\text{ m}$)

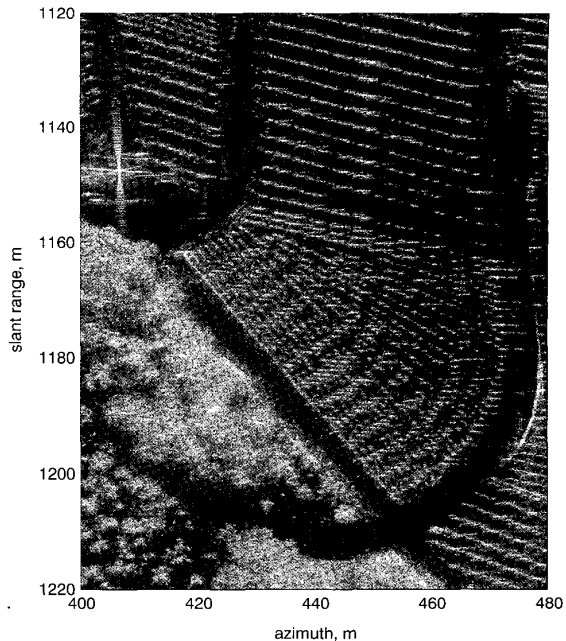


Fig. 6 SAR image of a vineyard (subdecimetre resolution)

was caused by a malfunction of the motion sensors, for near-range acquisition up to 10 km a spatial resolution in the subdecimetre regime could already be attained. For these purposes, a motion compensation based on autofocus techniques was applied. The image generation itself was performed by the above-mentioned time-domain SAR processor.

To illustrate the necessity of using non-approximative image formation algorithms in the wideband and wide-angle scenario, PAMIR data after range compression are shown in Fig. 7. The Figure shows a small cutout

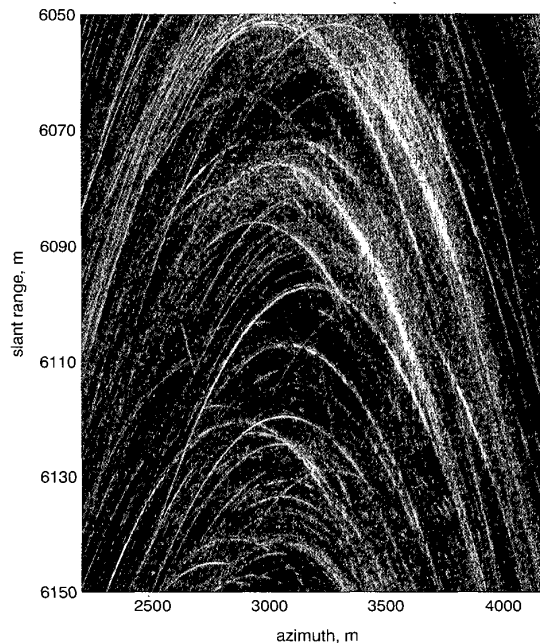


Fig. 7 Wideband and wide angle SAR data corresponding to an urban area

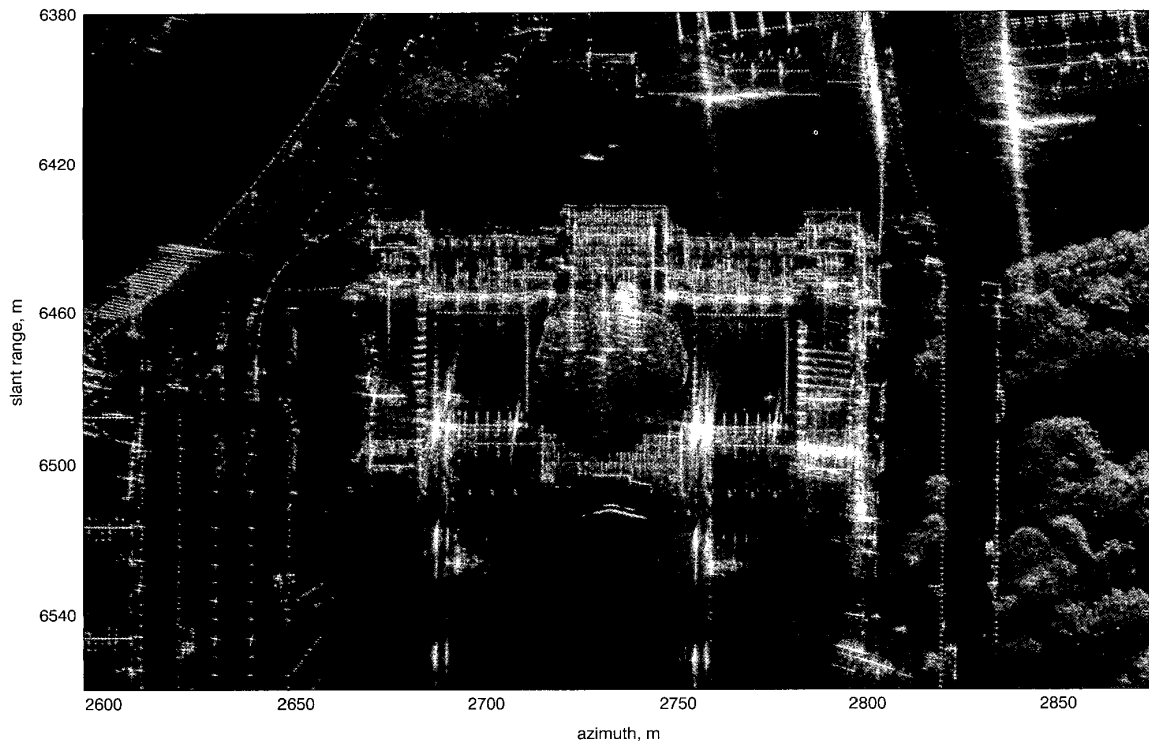


Fig. 8 SAR image of the Reichstag building in Berlin

from the entire data record which was acquired in the sliding-mode scanning an urban area. It can be recognised that the processing algorithm has to deal with a distinct range curvature stretching across hundreds of range cells.

A SAR image of an urban area is shown in Fig. 8. The data were acquired in the sliding spotlight mode with a ratio of the antenna footprint velocity to the carrier velocity of 0.2 and an average distance of about 7 km. The Reichstag building in Berlin, which is the seat of the German Federal Parliament, is situated in the middle of the scene. In the upper left, a part of the River Spree can be recognised and to the right the park Tiergarten adjoins the Reichstag. The dynamic range of the image amounts to more than 65 dB, reflecting the very different scattering properties of the scene (e.g. water, vegetation, metallic objects). As a typical overlay effect, the folding of the rear facade of the Reichstag building onto the roof terrace can be observed, as well as ghost artefacts caused by multipath propagation.

4 ISAR imaging

4.1 Methods

ISAR imaging of ground-moving targets is a challenging task, since the moving target echoes have to compete with the clutter background. The resolution has to be as fine as possible, because the targets of interest have relatively small geometrical extension. Since the target motion is unknown, autofocussing methods have to be applied extensively.

The relative motion of the target to the radar platform is composed of the translational motion and the rotational motion with respect to the line of sight. The rotational motion provides the basis for imaging, whereas the translational motion has to be compensated. So, ISAR

imaging is implemented in two main steps: first, the compensation of translational motion (motion compensation), and secondly, the actual imaging due to the rotational motion.

The ISAR image formation with a system like PAMIR has some additional aspects: along-track multiphase centres allow the rejection of clutter returns by STAP filters; the accurate angular estimation of GMTs allow tracks to be established with high accuracy; and the synthetic bandwidth method requires additional effort.

The ISAR processing of PAMIR data is still in development. Nevertheless, some main building blocks have been implemented. The first task is to get an initial estimate of the track. For this purpose, for one of the frequency bands the data are processed in the following way: After transformation to the range–frequency domain and multiplication by the signal reference function, the phase referring to a reference point is compensated. This point may be earth-fixed and close to the target or, better, attached to a rough estimate of the path of the target, delivered by a tracking algorithm based on the range and angle history. Now the data are Fourier transformed in the azimuth domain for consecutive segments and an inverse range-FFT is applied. Since this procedure already has focusing properties, the result is a ‘film’ of preliminary object images in the corrected range–Doppler domain, which may be blurred but provide enough SCNR to establish a second tracker in this domain. The estimated path is fitted by a parametrised model which allows correction of the errors of the first track. The motion compensation is refined by this better estimate and extended to all subbands. The last focusing is performed by use of the polar-reformatting technique. The first results show that in most cases even an additional fine-tracking of the individual scatterers will be necessary to achieve images with the uppermost resolution.

4.2 Results

For the purpose of ISAR imaging, PAMIR was used as a fixed radar platform. In a first experiment the paraboloidal reflector (diameter=34 m) of the tracking and imaging radar (TIRA) system on the premises of FGAN was observed. The antenna is placed in the interior of a large spherical radome (see Fig. 9, left); it was rotated around the azimuth axis at a high angular speed. Using a PRF of 15 kHz with the synthetic bandwidth technique, it was possible to sample each of the subbands with non-ambiguous Doppler frequency. By means of a processing technique consisting of subband combination and polar reformatting, a sequence of 116 ISAR images of the paraboloid at decimetre resolution (see Fig. 9, right) covering a whole rotation is achieved; so it was possible to process the images into a video animation showing the rotating antenna and exhibiting interesting dynamical multipath effects. Though the distance to the object was only a few hundred metres, it is clear that such imaging of a rotating antenna covered by a radome should be possible with no additional effort at the same resolution from an arbitrary distance, provided the radiated power is strong enough to yield the same SNR.

In a second trial, the truck-mounted PAMIR looked from a hill down onto a curved street. Again, the synthetic bandwidth technique was applied to record the echoes from cars driving along the street in both directions. Now the tasks to be fulfilled by the ISAR processing were more difficult. The motion parameters of the cars were estimated

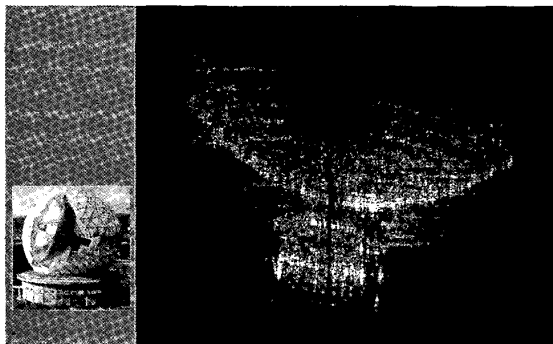


Fig. 9 ISAR image of the rotating TIRA antenna
Left: artist's view of paraboloid and radome
Right: ISAR image

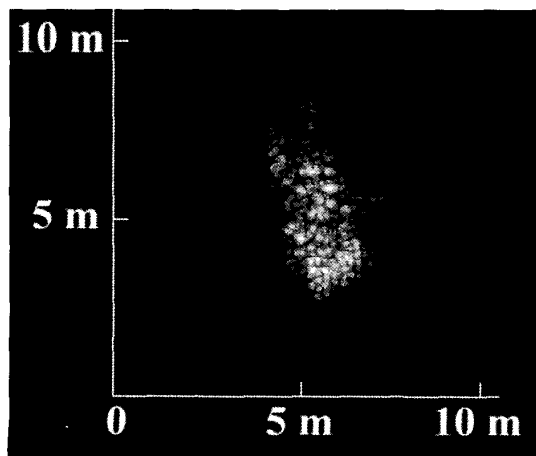


Fig. 10 ISAR image of a small private car

without making use of any information concerning the run of the curve. By means of motion compensation and autofocusing, images of the moving vehicles were obtained. As an example, Fig. 10 shows an ISAR image of a small private car.

ISAR image formation for ground-moving vehicles is still a field for further scientific investigations. The data obtained during the described preliminary experiments will serve as a basis for the comparison of different imaging algorithms.

5 Summary

Theoretical and experimental research at FGAN-FHR in the field of multichannel SAR/MTI during the last decade has given the impulse to tackle a challenging project: the design and realisation of an experimental phased array SAR/MTI system capable of managing a bandwidth of 1.82 GHz in a very flexible way and fulfilling sophisticated radar operations.

PAMIR, the Phased Array Multifunctional Imaging Radar, will be realised in different stages of extension. The first one, equipped with a non-steerable low-power antenna, was used in a ground-based car trial in the beginning of 2002. In SAR and ISAR experiments encouraging results with respect to high-resolution imaging were obtained. With the aid of autofocus methods subdecimetre resolution was demonstrated.

In a flight campaign in August 2002, PAMIR was provided with a mechanically steerable antenna with a transmit peak power of 120 W. The sensor was operated and field-tested in various imaging modes like stripmap-, sliding-spotlight- and spotlight-SAR as well as ISAR. The evaluation of the corresponding SAR images proves the sensors capabilities with respect to spatial resolution, range and image dynamic.

During the next few years, PAMIR will be upgraded with a multichannel capability and different realisations of a reconfigurable high-power phased array antenna. We plan to perform sophisticated radar experiments and expect a substantial database for further scientific work. We will especially investigate the limits of achievable resolution in far range, the focusing properties for ground-moving target—ISAR, IfSAR with a very high 3-D resolution, bistatic SAR imaging, limits of airborne MTI sensitivity and the phased array broadband performance.

6 Acknowledgment

The authors would like to thank all colleagues who have contributed to the realisation of the PAMIR system and the TIRA team giving experimental support. Concerning the flight campaign, they also appreciate the support and the assistance of WTD 61, Manching. This work is funded by the German Federal Ministry of Defense (BMVg) and the Federal Office of Defense Technology and Procurement (BWB).

7 References

- 1 ENDER, J.H.G., BERENS, P., BRENNER, A.R., RÖSSING, L., and SKUPIN, U.: 'Multichannel SAR/MTI system development at FGAN: From AER to PAMIR'. Proceedings of IGARSS'02, Toronto, Canada, 2002, pp. 1679–1701
- 2 ENDER, J.H.G.: 'Space-time processing for multichannel synthetic aperture radar', *Electron. Commun. Eng. J.*, 1999, 11, (1), pp. 29–38
- 3 KLEMM, R.: 'Principles of space-time adaptive processing' (IEE, London, UK, 2002, 2nd edn.)

- 4 ENDER, J.H.G.: 'Antijamming adaptive filtering for SAR imaging'. Proceedings of Int. Radar Symp. DGON, Munich, Germany, 1998, pp. 1403-1413
- 5 ENDER, J.H.G.: 'Linear and non-linear techniques for multichannel SAR image generation'. Proceedings of EUSAR2000, Munich, Germany, 2000, pp. 173-176
- 6 RÖSSING, L., and ENDER, J.H.G.: 'Multi-antenna SAR tomography using superresolution techniques', *Frequenz*, 2001, **55**, (3-4), pp. 123-128
- 7 BERENS, P.: 'SAR with ultra-high range resolution using synthetic bandwidth'. Proceedings of IGARSS'99, Hamburg, Germany, 1999, pp. 1752-1754
- 8 BERENS, P., and ENDER, J.H.G.: 'Signal theoretical aspects of high resolution SAR with phased arrays'. Proceedings of EUSAR2000, Munich, Germany, 2000, pp. 349-352
- 9 CAFFORIO, C., PRATI, C., and ROCCA, F.: 'SAR data focusing using seismic migration techniques', *IEEE Trans. Aerosp. Electron. Syst.*, 1991, **27**, (2), pp. 194-207
- 10 DESAI, M.D., and JENKINS, W.K.: 'Convolutional backprojection image reconstruction for spotlight mode synthetic aperture radar', *IEEE Trans. Image Process.*, 1992, **1**, (4), pp. 505-517
- 11 BRENNER, A.R., KÜRSCH, J., and NOLL, T.G.: 'Distributed large-scale simulation of MR imaging', *Magn. Reson. Mater. Phys. Biol. Med.*, 1997, **5**, pp. 129-138
- 12 BRENNER, A.R.: 'Distributed SAR processing in the time domain'. Proceedings of EUSAR2002, Cologne, Germany, 2002, pp. 573-576
- 13 BRENNER, A.R., and ENDER, J.H.G.: 'First experimental results achieved with the new very wideband SAR system PAMIR'. Proceedings of EUSAR2002, Cologne, Germany, 2002, pp. 81-86
- 14 ENDER, J.H.G., and BRENNER, A.R.: 'PAMIR—a wideband phased array SAR/MTI system'. Proceedings of EUSAR2002, 2002, Cologne, Germany, pp. 157-162
- 15 ENDER, J.H.G., and BRENNER, A.R.: 'High-resolution radar imaging by means of a versatile radar platform', *Frequenz*, 2002, **56**, (9-10), pp. 188-197