Executive Summary

SIREV

Development of a Functional Model

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1 Introduction

Adverse weather conditions affect both flight safety and the operational use of airborne platforms. This problem becomes most evident during takeoff, landing and taxiing, but also reliable collision warning in airspace gains increasing importance. In all these cases it would be highly desirable to provide the pilot with visual information about the surrounding environment independent of any weather condition. A weather independent imaging system will also substantially increase the situation awareness of the crew without recourse to any external electronic guidance system. Available radar systems, like the synthetic aperture radar (SAR), have proofed as a valuable tool where weather independent imaging is required, but, inherent to the underlying principle, these systems suffer from a visualisation gap with respect to the forward looking direction.

SIREV (Sector Imaging Radar for Enhanced Vision) is an innovative radar system which has the potential to supply high quality radar images of a sector in front of the aircraft (Figure 1). Besides a map of the earth's surface in flight direction, the image can be further processed to supply additional information about the topography and objects in the field of view. The sensor can be used in almost every kind of weather condition and due to its active illumination the operation is independent of daylight. SIREV is suitable for aircrafts as well as helicopters and allows the pilot even at very low visibility conditions to roll, to take off, to approach the targeted area, to detect obstacles, and to land safely.

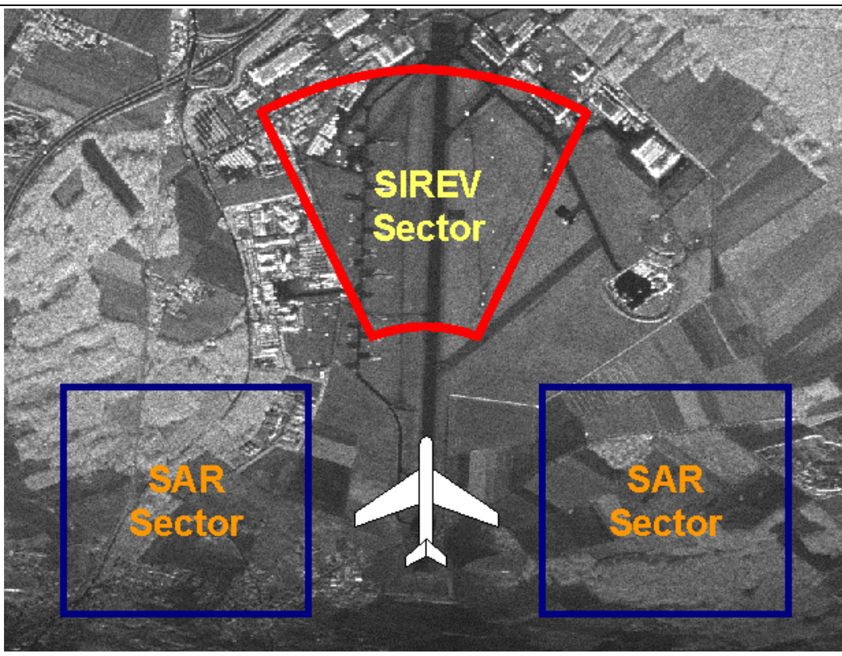

Figure 1: SIREV is an innovative radar system with forward looking capabilities.

2 Project Team

The project was carried out by STN ATLAS and DLR in co-operation with Universität Karlsruhe and Aerosensing. DLR provided the project co-ordination, the concept development, the design of algorithms and all data processing while the antenna system was developed by Universität Karlsruhe. The radar system hardware of Aerosensing was used and the required modifications for the SIREV-experiment were done by this company, too. The involved engineers and scientists are listed below:

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  Dipl.-Ing. R. Spielbauer

3 SIREV Concept and System Description

3.1 General Design Considerations

The principal idea of the SIREV concept is to keep the radar hardware including front-end and antenna comparatively simple and to implement the processing of the radar raw data and the image formation as a software in a separate digital computer. The digital signal processing is cost-efficient, more flexible and can easily be adapted to new requirements. For example, the use of hardware phase shifters may be avoided by digital beam forming, which is carried out in software during the image processing. This concept allows a better suppression of side lobes, a high update rate for the image formation and an accurate coherent signal processing. Different modes of operation are feasible as well, such as a conventional SAR mode, a squint SAR mode and interferometry. It is also possible to take into account different technical solutions as for example conform antennas or varying designs of the radar hardware. The adaptability and flexibility of the SIREV concept is demonstrated in Section 4, where a very cost-efficient functional model for SIREV has been built up using the hardware of an existing radar system.

3.2 SIREV Principle

In order to explain the *SIREV* principle it is reasonable to have first a look at the synthetic aperture radar (SAR) which forms the basis of the *SIREV* technique. The main objective of every imaging radar is to obtain a high spatial resolution in both image dimensions, i.e., range and azimuth. In range, the pulse compression technique allows us to achieve a high spatial resolution while minimizing the requirements on the peak transmit power. In azimuth, a high resolution can only be obtained by means of a narrow antenna diagram. Since beam width and antenna length follow an inverse relationship, improved resolution in azimuth requires an extension of the aperture size. In SAR systems such extended apertures are generated by a spatio-temporal sampling process which takes advantage of the relative movement between an airborne platform and the illuminated targets on the ground. The basic idea behind this approach is to synthesise an extended virtual antenna, thereby realizing an effective aperture perpendicular to the flight path which by far exceeds the dimension of the physical antenna. The major drawback of this technique is, however, that it can only be operated in a side looking imaging mode (Figure 2, top).

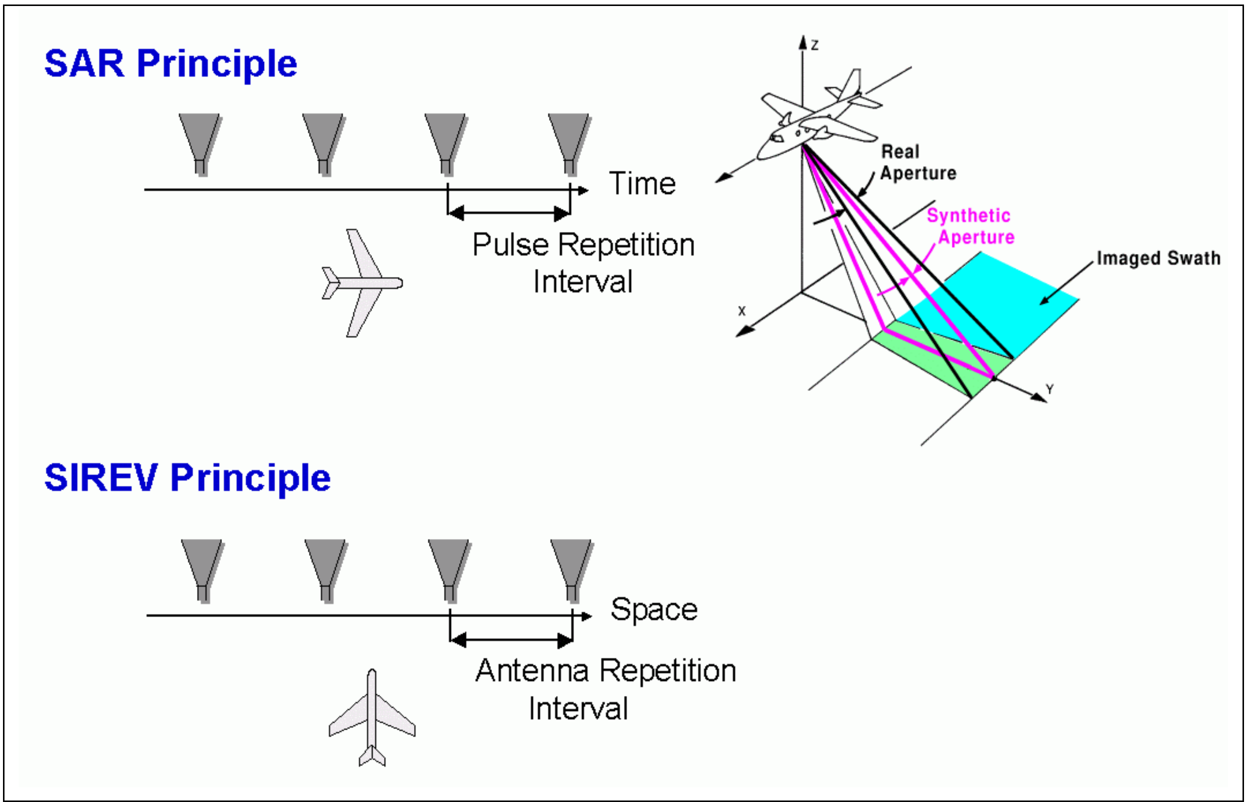


Figure 2: Comparison of the SAR and the SIREV principle.

In contrast to SAR, the *SIREV* antenna consists of a physically existent linear array of single elements, which is oriented horizontally and perpendicular to the flight direction (Figure 2). The antenna elements may now be switched in sequential order to transmit and receive the radar signals as shown in Figure 3. This monostatic mode with equally located transmit and receive antennas still corresponds to a SAR system, yet we don't have to move a single antenna along a straight trajectory. The disadvantage of the monostatic mode is, that it requires a T/R-module for each antenna element, thereby increasing the complexity and costs of the necessary hardware. A more cost-effective realization may be achieved by using only one transmit antenna, which leads to a bistatic configuration where the receive antennas are spatially separated from the transmit antenna. This configuration can be operated in either a simultaneous or a sequential receive mode. The simultaneous mode makes optimum use of the transmitted signal power by a large effective antenna area whereas the sequential receive mode minimises the hardware requirements. An example for a bistatic spatial arrangement is shown in *Figure 4*. The major disadvantage of the bistatic configuration is, that it reaches only half of the image resolution as compared to the monostatic case. In principle, it is also possible to combine the advantages of the monostatic and bistatic configurations using a small number of transmit antennas.

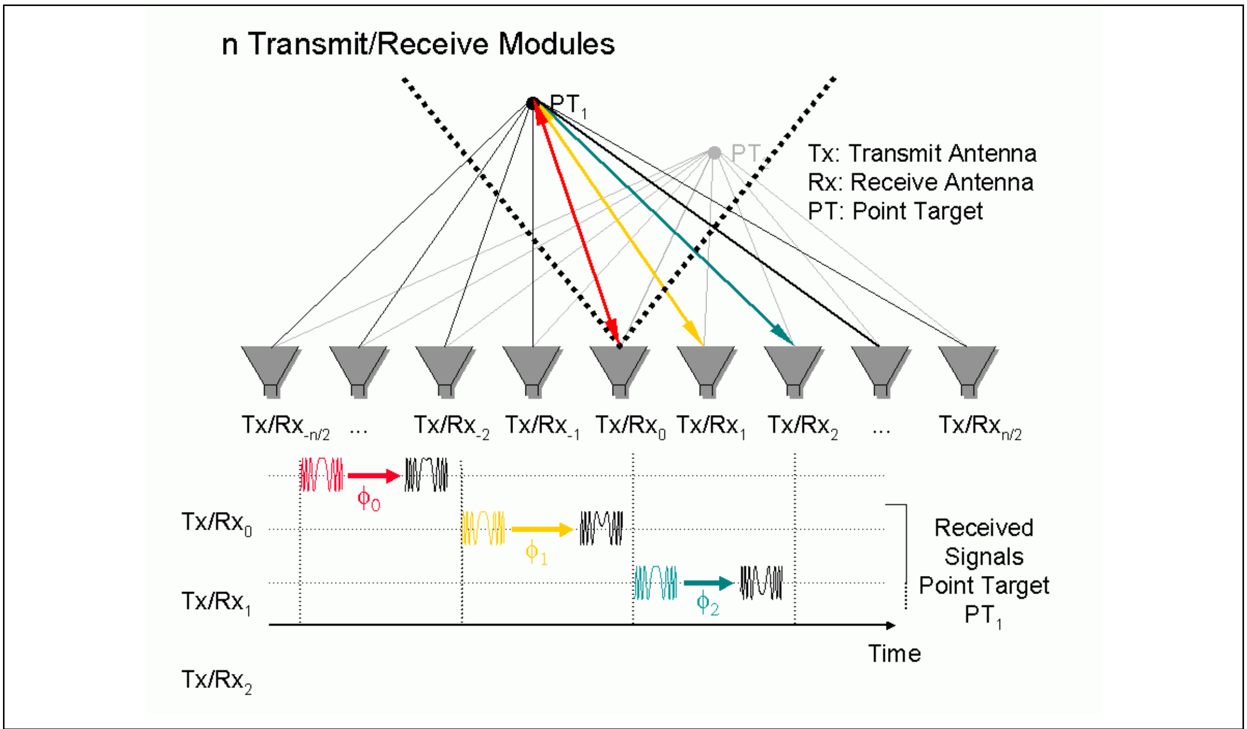


Figure 3: *Monostatic* SIREV mode where each antenna element is used for transmitting and receiving.

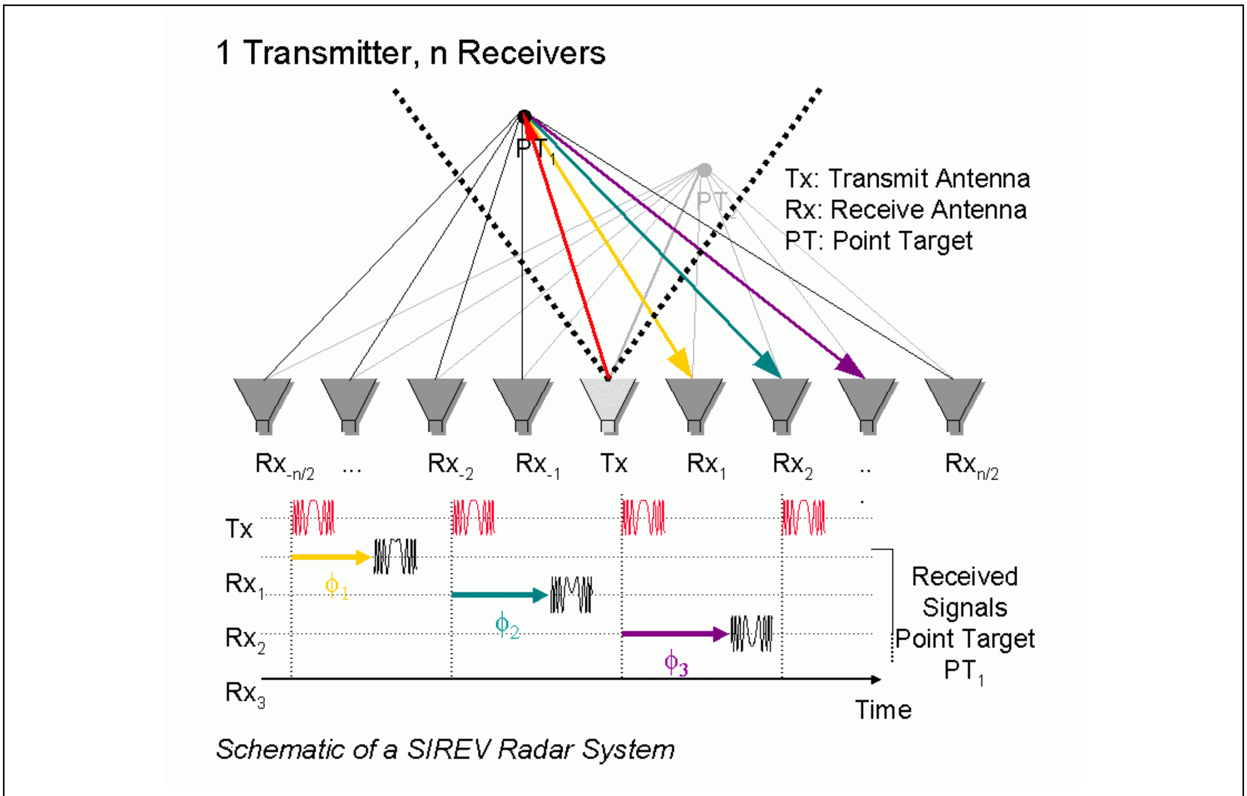


Figure 4: *Bistatic* SIREV mode with one central antenna element for transmitting and n elements for receiving.

3.3 SIREV Processing

In SIREV, azimuth resolution is substantially increased by a joint evaluation of the phases and amplitudes of all received array signals. As an illustration, the transmitted and received radar signals for one point target are shown in the lower parts of Figure 3 and *Figure 4*, respectively. Due to the different antenna positions the phases of the received back scattered signals are different. By inverting the indicated phase delays for each point in the illuminated scene, it is possible to digitally focus the antenna beam to different spatial locations. In mathematical terms, this corresponds to an inverse filter which can be realized by a shift-variant correlation during the digital signal processing. While conceptually simple, this direct focusing approach has the great disadvantage, that it is computationally expensive since the number of required multiplications and additions increases quadratically with the number of antenna array elements. Therefore, a much more efficient focusing technique has been developed for SIREV which is based on an adaptation of the Extended Chirp Scaling (ECS) algorithm[1]. *Figure 5* shows a flowchart of the SIREV ECS algorithm, together with a symbolic signal representation of several point targets on the left and a real raw data example on the right. From the block diagram it becomes apparent, that the SIREV ECS algorithm consists basically of complex multiplications and fast Fourier transforms (FFTs). Therefore, the computational complexity is reduced from $const_1 \cdot N^2$ to $const_2 \cdot N \cdot \log(N)$, N being the number of array elements. It is also possible to introduce a motion compensation in the SIREV ECS algorithm as shown by the grey boxes.

3.4 Estimation of Imaging Quality

In order to obtain a reference for the SIREV image data processing and to get a first impression of the SIREV mapping capabilities a SIREV image simulation was carried out based on X-band data from the Experimental SAR System of DLR (E-SAR). The results of this analysis are shown in Figure 6. From this figure it becomes clear that the imaging quality will be substantially improved for higher frequencies if the antenna length is kept constant.

[1] A. Moreira, J. Mittermayer and R. Scheiber: "*Extended Chirp Scaling Algorithm for Air- and Spaceborne SAR Data Processing in Stripmap and ScanSAR Imaging Modes*", IEEE Trans. on Geosci. and Remote Sensing, Vol. 34, No. 5, 1996.

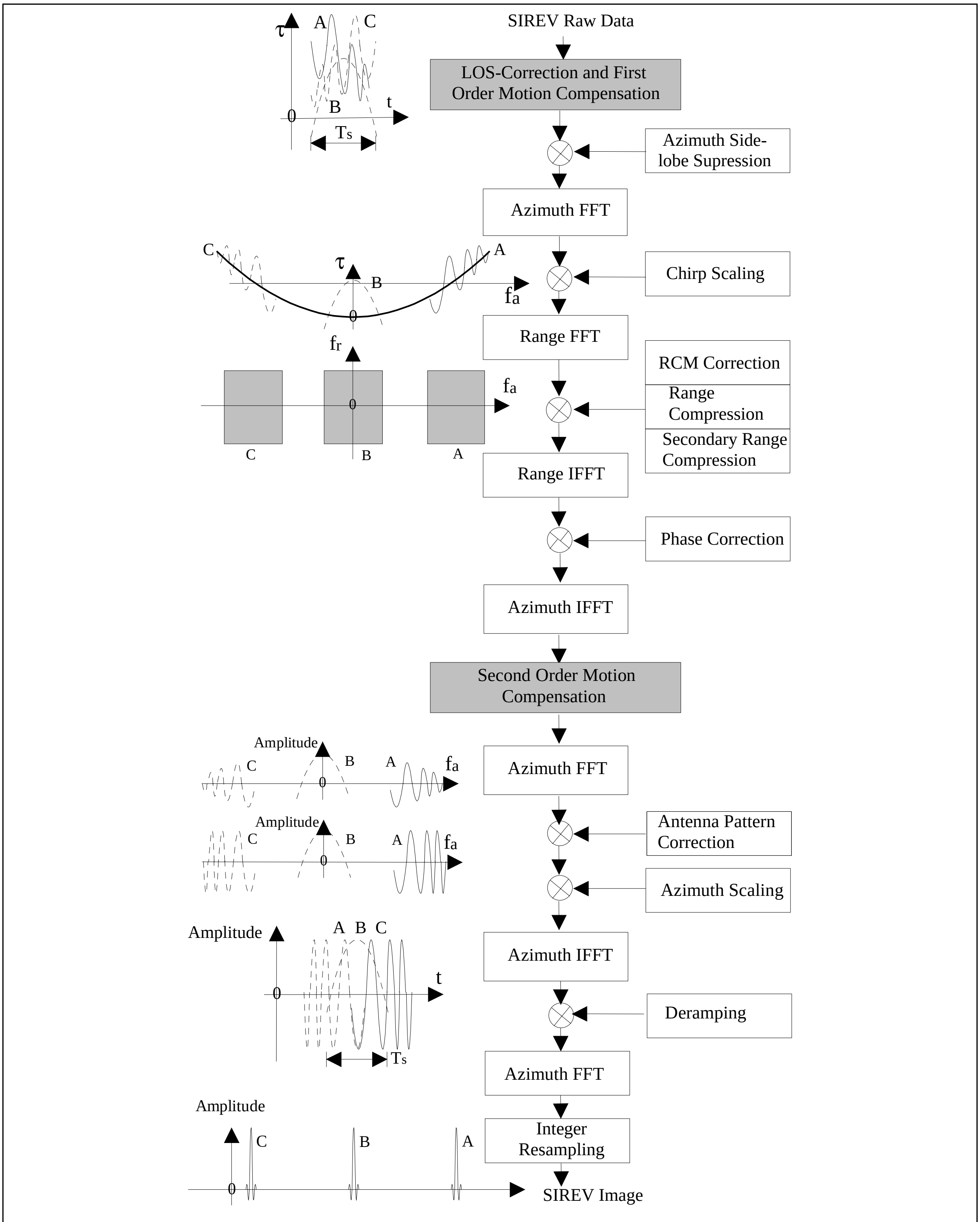


Figure 5: Block diagram of the fast SIREV ECS image processor

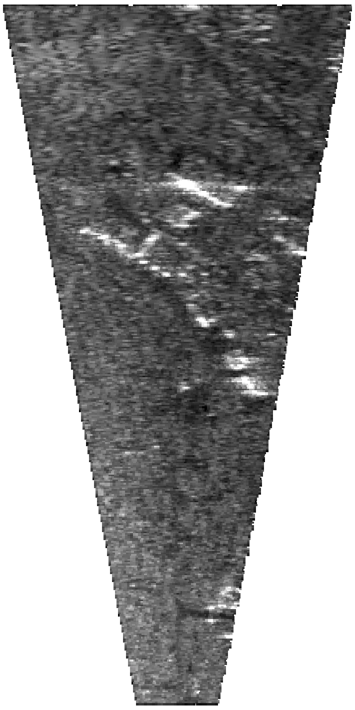
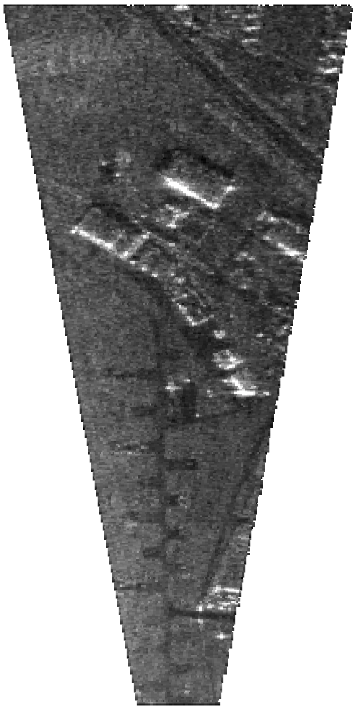
X-Band	Ka-Band	W-Band
		
wavelength: 0.031 m	wavelength: 0.085 m	wavelength: 0.0032 m
height: 200 m		
look angle: 45°		
chirp bandwidth: 100 MHz		
chirp length: 1,5 μs		
azimuth beam width: 24°		
raw data sample: 1012		
valid near range: 396 m		
valid far range: 1698 m		
range resolution: 2.2 m		
Azimuth extension near range: 170 m		
azimuth resolution near: 6 m	azimuth resolution near: 1.6 m	azimuth resolution near: 0.6 m
Azimuth extension far range: 710 m		
azimuth resolution far: 24 m	azimuth resolution far: 6.7 m	azimuth resolution far: 2.5 m

Figure 6: SIREV image simulation for X-Band (left), Ka-Band (middle), and W-Band (right).

4 Development of a Functional Model

4.1 Hardware Setup

4.1.1 Modification of the Existing Radar Hardware

A main goal of the project was to demonstrate the function and feasibility of the *SIREV* principle. Thus, it was preferable to use available hardware even with specifications that are not optimised for this purpose. For example, the entire imaging radar of AeroSensing was used keeping in mind that the volume, weight and power consumption were much higher than really needed for the demonstration. Cost minimisation was also the major reason for building up the functional model in X-Band notwithstanding the degraded image resolution to be expected. A block diagram of the realised radar hardware is shown in Figure 7. As seen on the left, the recourse to an existing radar receiver required also a sequential switching of the receiving antenna elements leading to a poorer signal to noise ratio as compared to a simultaneous reception of the radar echoes by all array elements. The image processing was performed off-line and is not included in the block diagram.

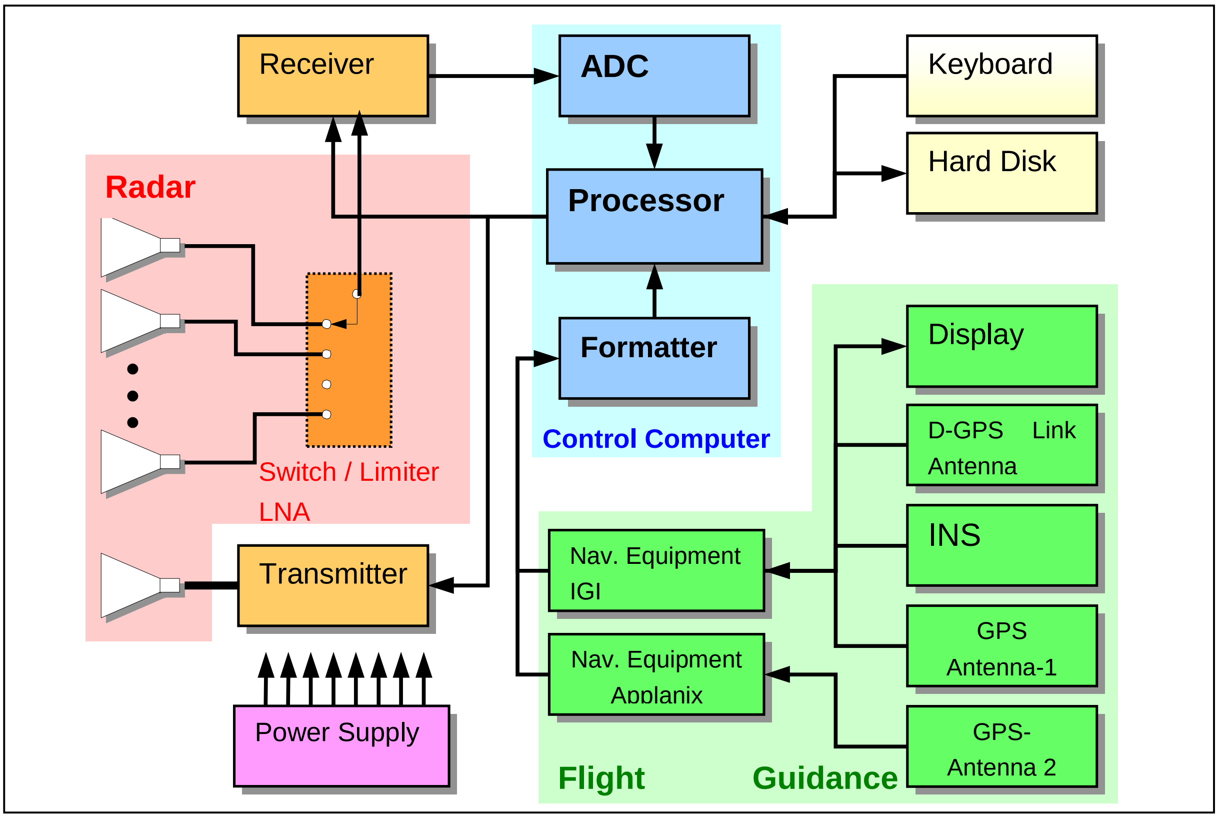


Figure 7: Block diagram of the radar hardware

4.1.2 The Antenna System

In SIREV, an active antenna replaces the passive antenna of a conventional airborne SAR system. This allows the use of digital beam-forming (DBF) on-receive-only without replacing the radar systems receiver. The antenna system consists of one high power horn antenna used for transmission and 56 receiving subarrays. The operating frequency and bandwidth are 9.55GHz and 400MHz, respectively. The receiving elements are horizontally polarized aperture coupled microstrip patch antennas. The overall antenna length is 3m. For every transmitted pulse the output of the receiving antenna is connected to one of the subarrays, thus effectively one out of 56 subarrays can be selected through a digital control signal to be the active receiving element. The receiving signals are additionally amplified using low noise amplifiers (LNA). In order to achieve high efficiency in combination with a compact design and to reduce the noise figure, the active RF-circuits (switches and LNAs) are integrated on the feeding network of the receiving antennas. To get high compatibility to different SAR systems, the DC circuits consisting of voltage converters, control signal decoding circuits, heating elements and thermal sensors are integrated into the antenna. Figure 8 shows a view of the RF side with the 56 2×2 patch subarrays without the radome of the complete antenna system. At one end all the connectors except the RF input for the transmitting antenna are placed. The attachment of the whole antenna system to the skids of the helicopter is shown in Figure 9.

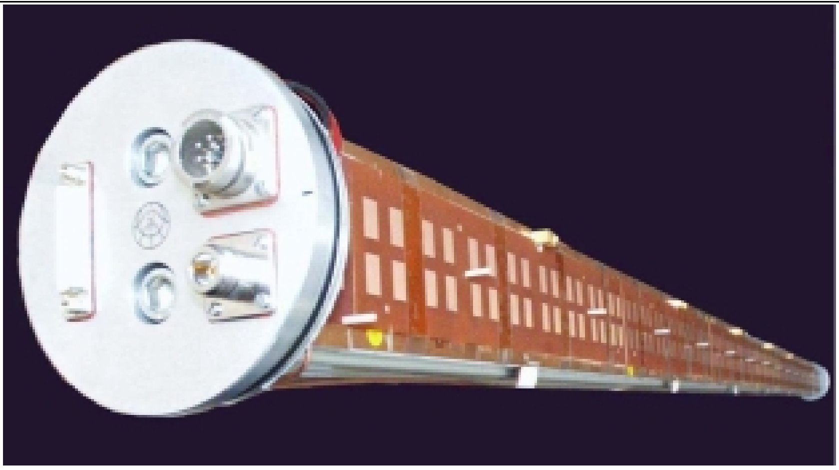


Figure 8: The seven RF-units placed on the front side of the antenna system.

Figure 9: Antenna system attached to the skids of the helicopter.

4.2 Results

In the following, the imaging results obtained from two flights in the vicinity of Oberpfaffenhofen will be summarised. The first scene contained a large corner reflector as the main scattering element and data from this recording were used to calibrate the system. The second raw data set was obtained during a flight across the river ‘Lech’. The recording parameters of the two flights are given in *Table 1*.

	recorded scene	
	corner reflector “Rottenried”	river “Lech”
center frequency	9.55 GHz	
chirp bandwidth	100 MHz	
antenna length	2.85 m	
number of receive antenna elements	56 (equally distributed)	
PRF	14792.9 Hz	
chirp duration	1.3 µs	1.3 µs
average helicopter forward velocity	28 m/s	21 m/s
average helicopter altitude	1056 m	927 m
average ground level	556 m	645 m

Table 1: Recording parameters for the two test flights

4.2.1 Demonstration of Successful Focusing

In order to test the integrity of the recorded raw data set the response to the large corner reflector, which is shown in Figure 10 on the left, was investigated first. A detailed analysis of the recorded signals revealed that some preprocessing steps are necessary before a successful focusing of the radar data can be achieved. This preprocessing steps concerned mainly different signal delays caused by different wiring lengths of individual array elements within the SIREV antenna. After an appropriate compensation of the signal delays, successful focusing has been demonstrated as shown by the exemplary impulse response in Figure 10 on the right. During the processing of this image no azimuth side lobe suppression had been used in order to allow a detailed point target analysis. This analysis revealed that the conformance with the theoretical optimum obtained from a simulated point target response is very good.

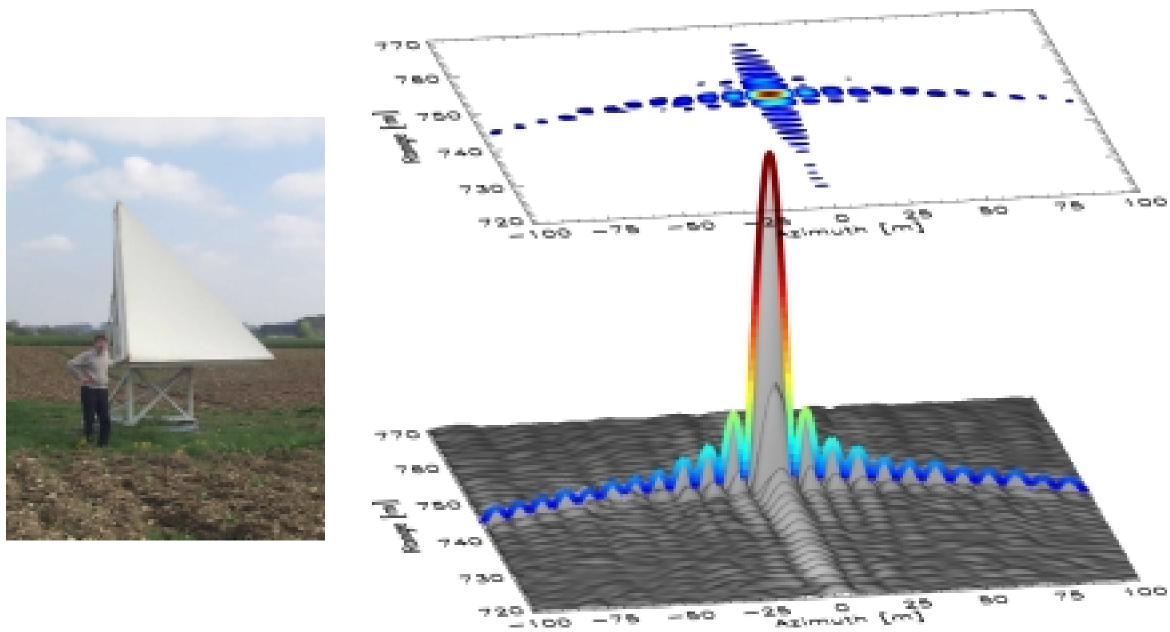


Figure 10: Corner reflector (left) and the measured response (right).

In order to demonstrate that the focusing is both time- and space invariant, a sequence of 10.000 image frames corresponding to a flight period of 37,9 seconds has been processed. A visualisation of the azimuth profiles of the corner reflector responses is shown in Figure 11 on the right as a 3-D surface plot. From the figure it becomes evident, that the focusing remains stable over the investigated time interval and that azimuth and elevation independent raw data compression has been achieved.

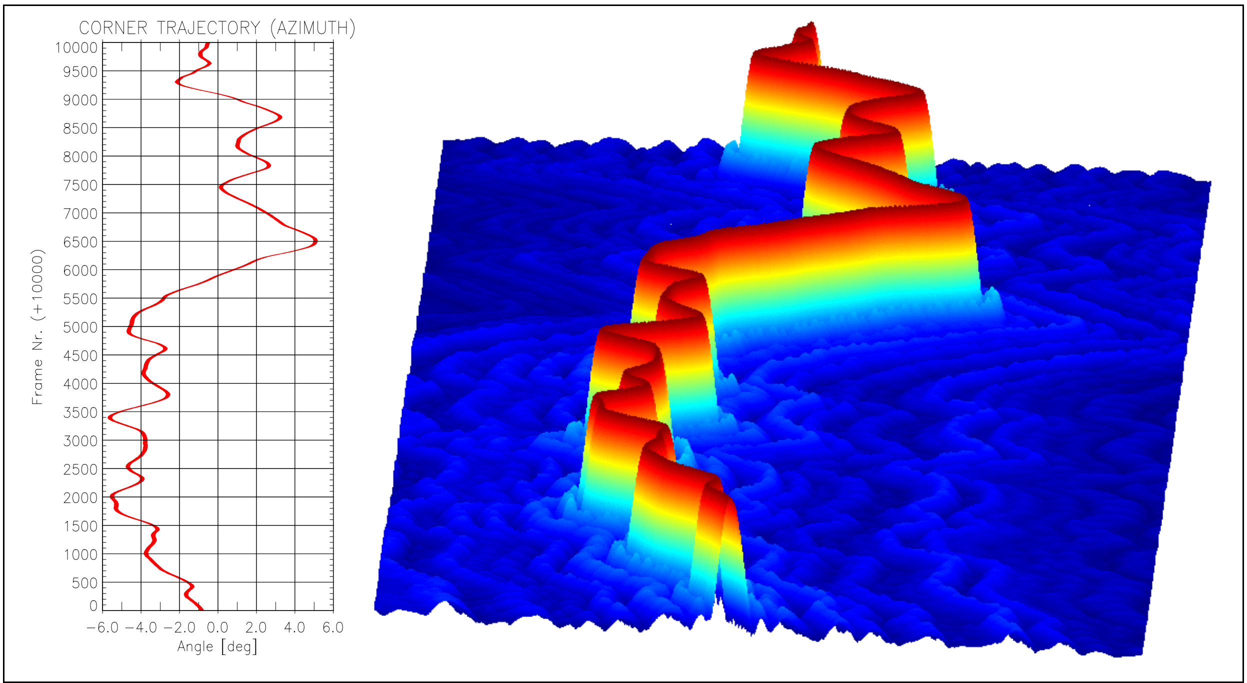


Figure 11: Temporal sequence of corner reflector responses. The azimuth compressed radar data are shown on the right in normalized format as a function of both azimuth angle and frame number. Shown on the left is a 'spatio-temporal trajectory' of the responses with maximum magnitude.

4.2.2 Imaging Results from a Natural Scene

In order to test the functional SIREV model in a realistic application scenario radar raw data were collected during a flight across the river Lech. The data were stored on a hard disk array and processed offline. An example of the processing results obtained from this raw data set is shown in Figure 12. The image on the left shows the focused image obtained from a single raw data frame. It is evident that this image suffers from a contamination with noise. By combining several successive image frames in a coherent averaging process the image quality may be substantially improved (Figure 12, right). Such a phase preserving image enhancement technique requires the computation of an average phase offset which is shown in the middle column of Figure 12. This smoothed interferogram may also be further processed to supply additional information about the topography and obstacles in the field of view. The images shown Figure 12 are represented as function of azimuth and slant range distance. More natural from a pilots point of view is a representation in 'optical coordinates' which may be obtained by an appropriate central perspective projection. The difference between these two display geometries is illustrated by the processed SIREV images in Figure 13 on the left. For comparison, a picture from an optical camera has also been added on the right.

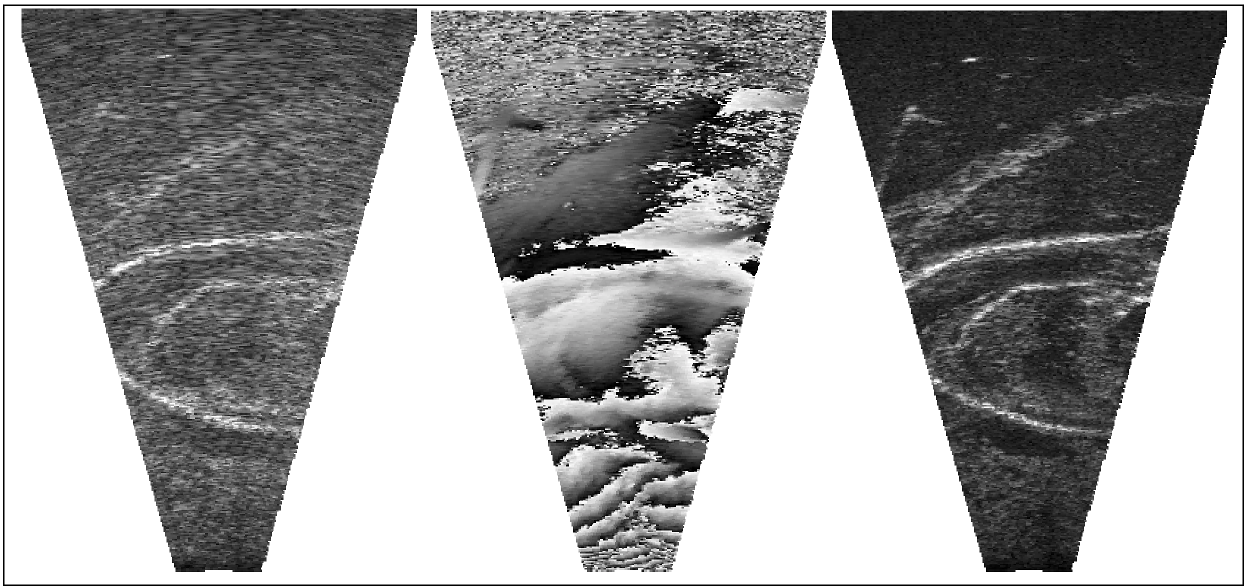
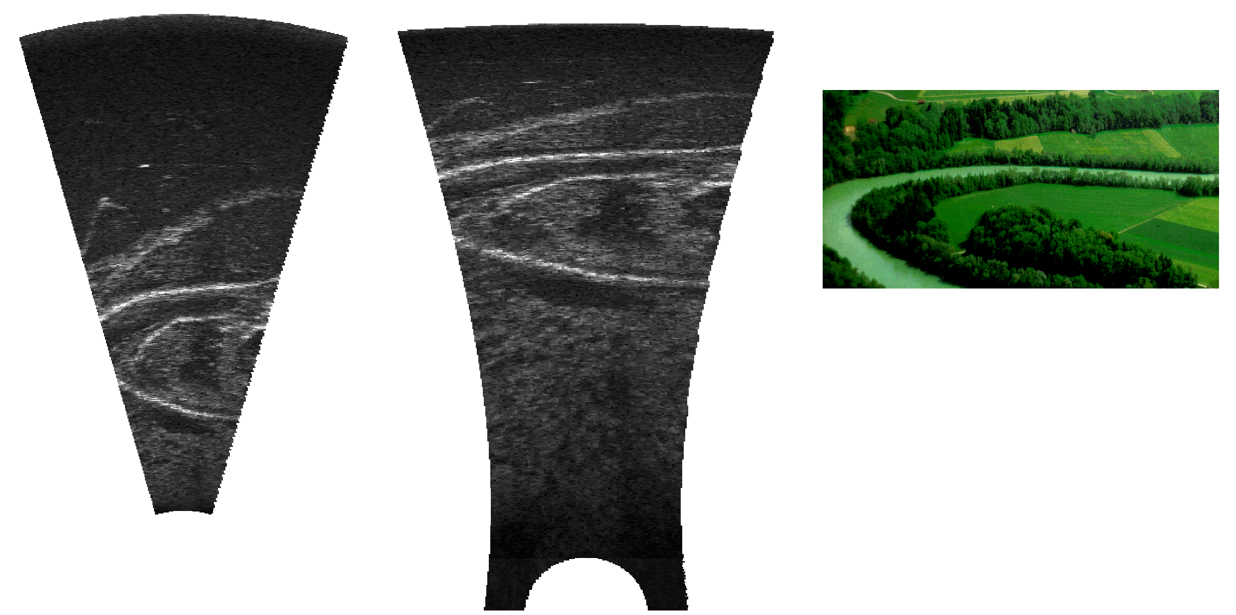


Figure 12: Results of image processing: single image (left), average phase offset (middle), and coherent average of 50 frames (right).



(a) (b) (c)

Figure 13: Comparison of different display geometries: (a) Slant range geometry. (b) Pilot's view. (c) Optical image. Note that the optical image on the right was recorded from a slightly different height and viewing position during a separate flight.

5 Conclusions

The main objective of the SIREV project was to show the correctness and the applicability of the SIREV principle. This objective is fulfilled by the development and test of a functional hardware model and by the successful processing of the SIREV raw data, acquired by the hardware model. The hardware consists of the SIREV antenna with one transmit and 56 receive antennas and the radar instrument. For the data processing a raw data simulator, the processor and post-processing procedures have been developed.

The antenna development by IHE is based on a new technology and was a very challenging part of the SIREV project. The performance of the antenna is good for the prototype model. However, improvements in the antenna performance are still possible, i.e. the ripple in the main beam have to be reduced and the receive pattern as well as the signal delays in the different receive paths should be further equalized.

The radar instrument from Aerosensing was modified in order to be compatible with the SIREV antenna. The data recording and the transcription of the data was developed for the SIREV data format. Test flight campaigns have been carried out and the overall system was working very well. The first real SIREV raw data have been acquired during these test flights.

The simulator implemented at DLR provides the raw data to design the processing algorithms. The Extended Chirp Scaling for SIREV has been developed, analytically modeled, implemented and tested with the simulated raw data. Additionally, motion compensation can be introduced into the processing chain. The motion errors have been modeled and the expected motion errors have been estimated. Finally, the data acquired during the SIREV hardware model test flights have been successfully processed and the achieved image quality is very good for this first hardware realization.

A post processing has been introduced for further image quality enhancement. Several methods for noise reduction have been developed by DLR and the transformation from the slant range / azimuth geometry into a pilots view representation has been performed. The final result of the processing and post processing was a short movie, composed of several successive SIREV images, which demonstrates the capabilities of the SIREV prototype system also in the dynamic case with a constant forward velocity. An excerpt of the movie is accessible on Internet at http://www.dlr.de/hr/sirev/home.html .

The validity of the SIREV principle has been demonstrated. Further work includes the improvement of the imaging quality and research into new SIREV imaging modes, for example interferometry for terrain height determination. The imaging quality can significantly be improved by a second generation SIREV antenna with improved pattern and equalized receive path properties. Another improvement can be achieved with a higher carrier frequency, i.e. Ka-band as shown by the simulations within this report. The SIREV approach developed in the frame of this project is a very good basis for the development of operational radar systems looking to the forward direction.