X-Band SAR System for Light-Weight Aircrafts

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Abstract—**In the paper, an X-band airborne SAR system developed and produced at the Institute of Radio Astronomy is described. The system is designed to be operated from light-weight aircrafts. Implemented hardware and real-time software solutions are discussed. Several original approaches to the post-processing of the recorded data are considered. Experimental results are also presented and discussed.**

Index Terms—**airborne radar; radar applications; synthetic aperture radar**

I. Introduction

During the last decade, research and development activities have been carried out at the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine on the development and production of SAR systems for small aircrafts [1]. The usage of small aircrafts as a SAR platform is attractive for many practical applications. In particular, it enables lowering exploitation costs of SAR sensors.

The main problem with SAR systems for small aircrafts is related with trajectory deviations and orientation instabilities of such SAR platforms [2-5]. The formation of SAR images is complicated since motion error compensation procedures are to be applied [3]. The compensation is typically based on measurements of the aircraft trajectory and the orientation with a high accuracy. The problem is that even with expensive navigation systems it is very difficult to achieve high quality of SAR images in the case of significant motion errors.

We have proposed several effective solutions of these problems. First, we have found that the antenna beam orientation angles can be measured by analyzing the Doppler frequency of the backscattered signals [1]. Due to this solution, we have simplified the SAR navigation system considerable by removing the requirement to measure the orientation angles. This solution has been implemented in the SAR system and allows tracking accurately the variations of the antenna beam orientation. Second, we have demonstrated that the aircraft trajectory can be accurately determined in real time from the aircraft velocity measured by a simple GPS receiver. The measured trajectory has a sufficient accuracy to be used for the motion compensation. It allows us to obtain multi-look SAR images in real time. Third, we have developed an effective autofocus technique [6-8] and multi-look processing technique [9-11] for post-processing of recorded raw SAR data. These algorithms allow us to build high-quality SAR images with a large number of looks which reveal features and fine details in ground scenes.

All these solutions have been implemented in a recently developed and produced RIAN-SAR-X system, described in this paper. The system is designed to be operated from light-weight aircraft platforms in side-looking or squinted strip-map modes. It is capable of producing high-quality multi-look SAR images with a 2-m resolution in real time.

II. SAR Hardware Systems

In this section, the SAR hardware systems are described including the transmitter, receiver, antenna, platform, and navigation system. Characteristics of the hardware systems are listed in Table 1.

TABLE I. Characteristics of SAR Hardware Systems

Transmitter	
Transmitter type	Solid-state power amplifier
Operating frequency	10 GHz
Transmitted peak power	120 W
Pulse repetition frequency	3 – 5 kHz
Pulse compression technique	Linear frequency modulation (LFM)
LFM pulse bandwidth	100 MHz
LFM pulse duration	5 – 16 μs
Receiver	
Receiver type	Digital
Receiver bandwidth	100 MHz
Receiver noise figure	2 dB
System losses	2 dB
ADC sampling frequency	200 MHz
ADC capacity	14 bit
Antenna	
Antenna type	Slotted-waveguide horn antenna
Antenna beam width in azimuth / elevation	10° / 40°
Antenna gain	20 dB
Polarization	VV
Side lobe level	< – 20 dB
Operating bandwidth	400 MHz
VSWR	< 1.2
Dimensions	200 × 60 × 57 mm
SAR Platform	
Aircraft flight velocity	30 – 80 m/s
Aircraft flight altitude	1000 – 5000 m

A. Transmitter and Receiver

The radar operates at a frequency of about 10 GHz. The transmitter is based on a modern solid-state power amplifier. The peak transmitted power is 120 W. The radar transmits long pulses with linear frequency modulation (LFM). A direct digital synthesizer provides frequency sweeping. The pulse duration can be chosen from 5 to 16 µs. The transmitted pulse bandwidth is 100 MHz that gives the slant range resolution of 2 m. The pulse repetition frequency is from 3 kHz to 5 kHz that guarantees unambiguous sampling of radar data in the azimuth direction. The digital receiver technique is implemented. The sampling of radar data in the range direction is performed with a 200-MHz ADC with a 14-bit capacity. The noise figure of the receiver is 2 dB.

B. Antenna

The radar uses a compact slotted-waveguide horn antenna designed and produced at the Institute of Radio Astronomy. Characteristics of the antenna are listed in Table 1. The antenna pattern is formed by a slotted-waveguide in the azimuth plane and by a horn aperture in the elevation plane. The antenna is firmly mounted on the aircraft in one of two positions: 1) for a side-looking mode and 2) for a 40-degree-squinted mode. The antenna bandwidth is 400 MHz that is sufficient to achieve a slant range resolution up to 0.5 m.

The antenna beam width in azimuth is 10°, which is a rather wide angle for a stripmap mode. It seems that it would be sufficient to use a 2.5° beam in order to achieve the azimuth resolution of 0.5 m. However, the application of such a wide beam has the following advantages. First, it allows avoiding radiometric errors during the formation of SAR images in real time. Second, it enables the formation of high-quality SAR images with a large number of looks at the post-processing stage. Third, but also important, a wide-beam antenna is more compact and light-weight.

C. SAR Platform

The SAR system is designed to be operated from a light-weight aircrafts. During test flights, the SAR system was successfully deployed on an AN-2 aircraft. The aircraft flight altitude could be from 1000 m to 5000 m, and the aircraft flight velocity is expected to be from 30 m/s to 80 m/s. The implemented SAR processing algorithms can also operate beyond of these intervals of the flight parameters with minor adjustments.

D. SAR Navigation System

The hardware part of the SAR navigation system is based on a simple GPS-receiver capable of measuring the aircraft position and velocity vector. The position is measured with the accuracy of an order of several meters and used to link the obtained SAR images to ground maps, and also to get the flight altitude above the ground. The accuracy of the velocity measurements is as high as about 0.05 m/s.

The hardware navigation data is essentially supplemented with additional, absolutely necessary navigation data that is obtained in a software part of the navigation system. First, the accurate aircraft flight trajectory is integrated from the measured aircraft velocity to perform motion error compensation in real time. The achieved accuracy is sufficient to produce full-resolution (up to 2 m) SAR images with up to 15 looks (except some cases of very rough flight conditions). Later, at the data post-processing stage, the aircraft trajectory is further refined by using autofocusing that allows processing the full Doppler bandwidth and forming high-quality SAR images with up to 35 looks at 2-m resolution.

Second, the antenna beam orientation is evaluated from the measured Doppler frequency of the backscattered radar signals in real time. The estimated pitch and yaw antenna orientation angles are used both for motion compensation and for aperture synthesis. Such angle estimation is a kind of clutter-lock processing allowing us to adjusting our SAR data processing algorithms in real time to track the variations of the antenna beam orientation and avoid radiometric errors.

III. Real-Time SAR Data Processing

In this section, the real-time SAR data processing algorithms are described. Characteristics of the SAR data processing system are listed in Table 2.

TABLE II. CHARACTERISTICS OF SAR DATA PROCESSING SYSTEM

Range processing	
Slant range resolution	2 m
Slant range sampling interval	1.5 m
Number of range gates	2048 (processed) / 4096 (raw)
Range swath width	3072 m
Azimuth processing	
SAR processing algorithm	Range-Doppler algorithm
Real-time motion error compensation (trajectory)	Yes, 1st- and 2nd-order MOCO
Clutter-lock*	Frame-by-frame
Pre-filtering	Yes
Azimuth resolution	2.0 m
Number of looks (in real time)	1 – 15
Data recording	
Uncompressed raw data	Yes
Recorded raw data rate	80 MB/s
Pre-filtered data, navigation data, SAR images, etc.	Yes

*Estimation of the antenna beam orientation angles from the backscattered radar data and updating the SAR reference functions.

The real time data processing is realized on a frame-by-frame basis, and each frame counts many intervals of synthesis. A scheme with half-overlapped frames is implemented as illustrated in Fig. 1. In such scheme, each backscattered pulse is put in two frames, and these two frames are processed independently and simultaneously, in parallel, in the hardware. Each frame is processed with its own reference straight flight trajectory, the reference aircraft flight altitude, velocity, and orientation. The SAR images obtained from the sequence of data frames are then stitched together to form a longer strip map SAR image. The SAR image of each frame has invalid zones at its azimuth edges, where the image brightness decays to zero. This is because these areas of the scene are only partly illuminated by the antenna beam during the data frame acquisition time. Neighbor frames have significant overlapped areas. It helps image stitching and guarantees continuous surveillance of the strip without gaps despite of possible motion instabilities.

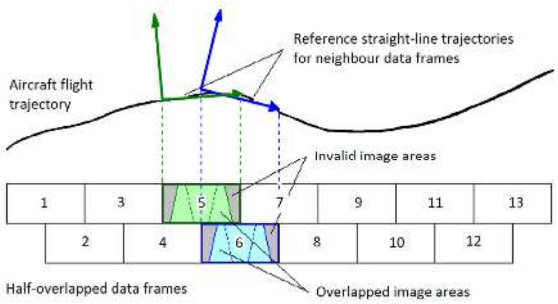


Figure 1. SAR processing with half-overlapped data frames.

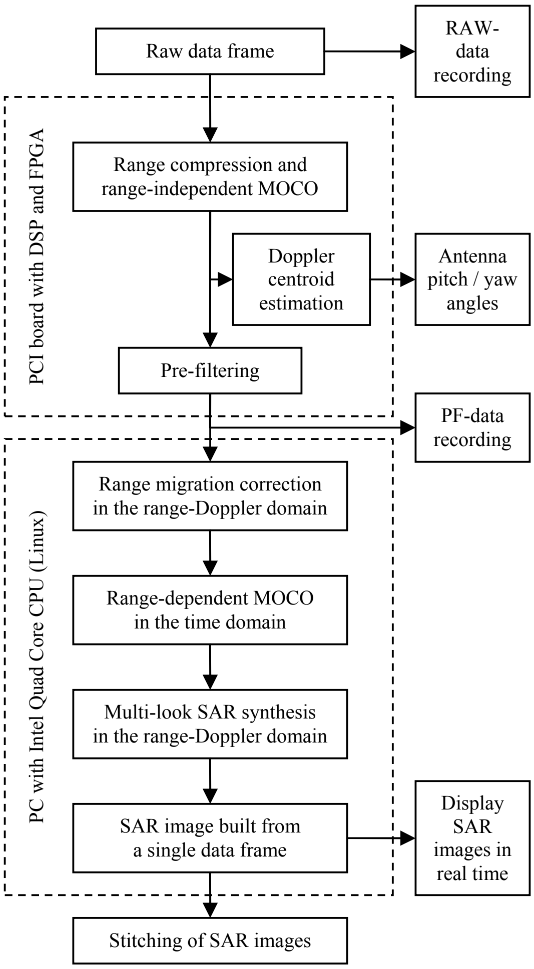


Figure 2. Block-scheme of the real-time SAR data processing algorithms.

The real-time data processing is performed by using the range-Doppler algorithm [5] with the 1^{st}- and 2^{nd}-order motion compensation [2]. The block-scheme of the algorithm is shown in Fig. 2. The SAR data processing system consists of two parts. The first part of the system performs: 1) range compression of LFM pulses combined with the 1st-order (range-independent) motion compensation, 2) calculation of Doppler centroid values for each range gate (by FFT in azimuth) and estimation of the antenna orientation angles, and 3) pre-filtering of the range-compressed data. This processing is performed in a special PCI-board equipped with a DSP and an FPGA.

The second part of the data processing system forms multi-look SAR images by using a range-Doppler algorithm with the 2nd-order (range-dependent) motion compensation. This processing is performed on a PC with an Intel Quad Core CPU (the above-mentioned PCI board is installed in this PC).

The SAR system is capable of recording the original uncompressed radar data on solid-state drives organized in a RAID-0 array at the full pulse repetition rate up to 5 kHz. These data are stored together with the navigation data (original GPS measurements, integrated trajectories, estimated orientation angles, motion compensation curves, etc.), as well as the pre-filtered range-compressed data and the SAR images formed in real time. Stitching of the obtained SAR images into a continuous strip map can be performed, while viewing the data in real time or offline.

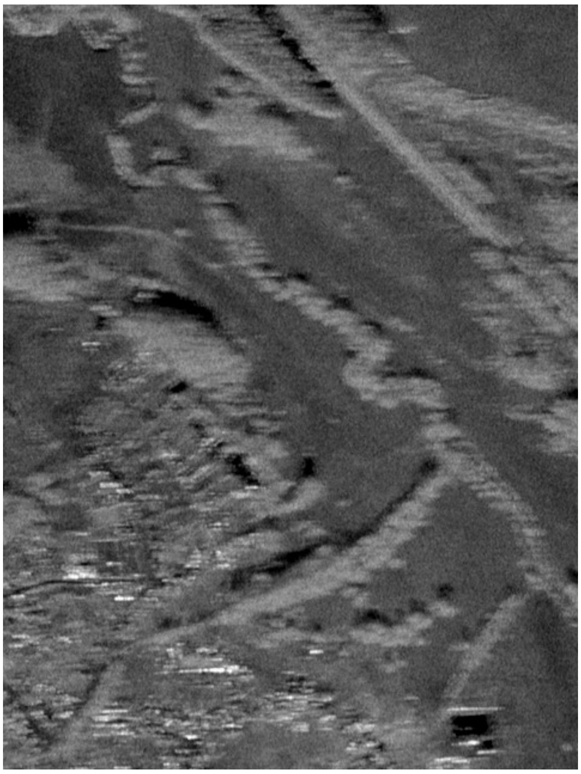
IV. Post-Processing of Recorded Data

Recorded SAR data are used further at the post-processing stage to obtain SAR images of a better quality. The post-processing includes: 1) autofocusing using an original local-quadratic map-drift autofocus (LQMDA), 2) multi-look processing with many looks used to suppress speckle noise and compensate for radiometric errors, 3) the most accurate motion error compensation via the data processing in the time domain.

A. Local-Quadratic Map-Drift Autofocus

Recently A novel method for the estimation of residual trajectory deviations from SAR data has developed. The method is called the local-quadratic map-drift autofocus (LQMDA) [6-8]. The idea of the method is to estimate the local quadratic phase errors on small time intervals. These estimates are used to evaluate the cross-track components of the aircraft acceleration. Then, the residual uncompensated trajectory deviations are obtained by double integration. It should be emphasized that the method can handle time-varying and range-dependent phase errors.

The LQMDA has been successfully applied with the described X-band airborne SAR system. A 25-look SAR image with a 2-meter resolution built without autofocusing is shown in Fig 3a. One can see that the image is significantly defocused. The well-focused SAR image built with the proposed LQMDA algorithm is shown in Fig. 3b. The image shows significant improvement. One can now recognize lots of fine details, sharp edges and readable radio-shadows. The provided example demonstrates the high efficiency of the LQMDA method.



(a)

(b)

Figure 3. Autofocusing using LQMDA. A fragment of a 25-look, 2-m resolution SAR image: (a) before autofocusing, (b) after autofocusing.

B. Multi-Look Processing with Large Number of Looks

Multi-look processing is a common technique used to reduce speckle noise in SAR images. In most SAR systems, only a relatively small number of SAR looks (up to about 10) are formed aiming the suppression of speckle noise. With the described LQMDA method, we are able to produce a larger number of SAR looks of the same scene using a wide-beam antenna. The formation of many looks is advantageous not only for the suppression of speckle noise and improving the radiometric resolution, but also for revealing many fine details in SAR images, especially on artificial targets that typically demonstrate strong angular dependences and scintillations of the radar cross-section.

(a)

(b)

Figure 4. Speckle noise suppresion and revealing fine details of a scene via multi-look processing: (a) 1-look SAR image, (b) 65-look SAR image.

Moreover, we have proposed an original radiometric correction approach which is based on multi-look SAR processing with an extended number of looks [9-11]. The idea of the approach is to build so many looks that they fill a wide interval of the azimuth directions covering the real antenna beam and its expected orientation instabilities. In this case, we always can find the brightest, undistorted value of each pixel of the scene among all SAR looks and use it as a reference for the radiometric correction.

An example of multi-look processing with 2-m resolution and 65 looks is shown in Fig. 4. Comparing the single-look image in Fig. 4a to the multi-look image in Fig. 4b, one can observe essential improvements in fine details and radiometric resolution.

V. Conclusion

The X-band SAR system developed at the Institute of Radio Astronomy are demonstrated to be capable of effective operation from small aircrafts. The presented results indicate that many essential problems of SAR systems for such platforms have been solved. In particular, the problem of the antenna beam orientation instabilities has been handled, on the one hand, by estimation of the current orientation from the Doppler frequencies of the radar echoes, and, on the other hand, by the radiometric correction via multi-look processing with extended number of looks. In addition, the unknown trajectory deviations have been precisely estimated by using the developed local-quadratic mad-drift autofocus method. All these techniques applied together enable a reliable operation of the SAR system from the light-weight aircraft platform. It should be noted that these solutions are useful for SAR systems deployed on other platforms as well.

Acknowledgment

The authors would like to thank all their colleagues at the Department of Microwave Electronics of the Institute of Radio Astronomy for their effort in the development of SAR systems.

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