Development of a High Resolution Airborne Millimeter Wave FM-CW SAR

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Abstract— **The combination of compact FM-CW radar technology and high resolution SAR processing techniques should pave the way for the development of a small, lightweight and cost effective imaging radar. In the field of airborne earth observation, SAR is however a novel application for FM-CW radars. At IRCTR a project was started to investigate the practical feasibility of FM-CW SAR. Within the framework of this project a fully operational airborne FM-CW SAR demonstrator system has been developed and tested. An overview of the ground based tests will be given. Moreover, in June 2004, a very successful airborne campaign was carried out at the Strausberg airfield near Berlin. The first, preliminary results from these airborne experiments will be presented.**

I. Introduction

The field of airborne earth observation dedicates special attention to the development and application of low cost imaging radars of high resolution. Such radar systems should be suitable for operation from very small, possibly even unmanned, airborne platforms. These systems should therefore be lightweight and they should consume little power.

Coherent pulse radar systems are usually complex systems, which are neither cost effective nor very compact. Pulse radars are therefore less suitable for operation from very small aircraft or for low cost solutions.

Frequency modulated continuous wave (FM-CW) radar systems are, on the other hand, compact, relatively cheap to purchase and to operate, and they consume little power. Consequently, FM-CW radar technology seems to be of interest to civil earth observation applications, especially in combination with high resolution synthetic aperture radar (SAR) processing techniques. This combination should lead to the development of a small, lightweight and cost effective imaging radar of high resolution.

The concept of FM-CW SAR has already been put forward in literature, [1]-[5]. The area of airborne earth observation is however a very novel application for FM-CW SAR systems, [6]. Therefore, at the IRCTR a project has been started to investigate the viability of FM-CW SAR in this area.

II. Project Outline

The main objective of the project is to show the practicability of FM-CW SAR under operational circumstances. A fully operational airborne FM-CW SAR demonstrator system has therefore been developed. In addition, the demonstrator system should prove that an FM-CW SAR system can indeed be operated in an efficient and cost effective manner from a very small airborne platform.

A detailed system model has been developed in order to estimate and analyze the performance of the demonstrator system. After thorough ground based and airborne experiments, the functioning of the demonstrator system will be evaluated and the findings will be used to improve the system model. This improved system model should allow the development of a future higher performance FM-CW SAR system.

TABLE I
FM-CW SAR demonstrator system specifications.

Carrier Frequency:	35 GHz	Antenna Gain:	24 dB
Frequency Sweep:	500 MHz	Antenna Isolation:	52 dB
PRF:	1000 Hz	Beamwidth Az./El.:	6°/28°
Modulation:	Sawtooth	Platform Velocity:	25 m/s
IF band:	dc to 2.5 MHz	Altitude:	150 m
Transmitted Power:	18 dBm	Max. Range:	730 m

Concurrently, special SAR processing algorithms have been developed. In a later stage of the project, priority will be given to the implementation of real time processing using off-the-shelf parallel computer boards.

III. Demonstrator System Details

The work on the demonstrator system started in 2001. In order to speed up the development and to show that an FM-CW SAR system can be relatively cheap, it was decided to use off-the-shelf components as much as possible.

The demonstrator system operates in stripmap mode. The resolution in range as well as in azimuth direction has primarily been chosen to be 1 m. During the project, the resolution will be gradually enhanced to 30 cm in both range and azimuth direction. Further specifications are listed in table I.

The core of the demonstrator system is a PXI chassis manufactured by National Instruments. The chassis includes a 1.26 GHz Pentium III controller, a 10 MHz, 12-bit A/D board to sample the radar data, a 100 kHz, 16-bit A/D board to sample the motion data, and a 40 MHz, 12-bit D/A board to control the frequency modulation. The radar data are sampled at 5 MHz; resulting in a continuous data rate of approximately 9.5 Mbyte/s. The 35 GHz FM-CW front end is manufactured by Epsilon-Lambda Electronics. In addition, the demonstrator system is supplied with gyroscopes, accelerometers and a GPS receiver to be able to determine the position and the attitude of the system. Finally, a digital camera has been added to supply optical images of the imaged area.

The Stemme S10 glider provides a relatively cheap test platform, see Fig. 1. The Stemme S10 is a twin seat, light surveillance motor glider that can take off unassisted. Two standardized pods can be mounted under the wings. These

Fig. 1. The Stemme motor glider, the pod is attached under the right wing. In the back the wing tips are visible. The tips can be taken off to accommodate transportation of the glider.

Fig. 2. The FM-CW SAR demonstrator system installed in the pod. In front of the pod the digital camera, the FM-CW front end and the GPS receiver are clearly visible (from left to right).

pods have a diameter of about 35 cm and they are 80 cm long excluding the aerodynamic fairings. The maximum payload is 50 kg per pod. The complete FM-CW SAR demonstrator system has been fitted in such a pod, see Fig. 2.

During the flights, the demonstrator system can be controlled and monitored from the cockpit with the aid of a pocket PC. To this end, some cables can be pulled from the pod to the cockpit through a tube in the wing. Otherwise, the system is self supporting; it is fed by a battery which is also installed in the under wing pod. The system can run for approximately 2.5 hours on a fully charged battery.

IV. Ground Based Trials

The demonstrator system was put to the test on the ground during the summer of 2003. Throughout the ground based trials, the demonstrator system was placed on top of the building of the Faculty of Electrical Engineering at an altitude of approximately 90 m. A 40 dBm^2 corner reflector was set up on the ground at a slant range of about 370 m. Apart from the angle of incidence, which is much shallower, this geometry is comparable to the airborne scenario.

From these measurements, it could be concluded that the performance of the demonstrator system in terms of resolution and signal-to-noise ratio (SNR) was not as good as anticipated. The response was mainly degraded by the severe frequency sweep nonlinearity.

The sweep nonlinearity was compensated by applying a *linearized* frequency modulation scheme. However, the front end turned out to be extremely sensitive to the D/A board's update rate, resulting in the appearance of a second response if the linearized modulation was applied, [7]-[8]. After increasing the update rate from 2 MHz to 4 MHz, the second response disappeared.

With respect to the airborne measurements, it was expected that the performance would be adequate. It was therefore decided to schedule a first airborne campaign.

A. First Airborne Campaign

The first airborne campaign was carried out at the Strausberg airfield east of Berlin on October 23rd 2003. Unfortunately, the weather was very bad and the actual flight time was therefore limited.

From a technical point of view, the demonstrator system performed satisfactory. The processing of the data was however difficult, mainly due to the very low SNR and the lack of synchronized GPS data; the GPS receiver did not work due to a blown fuse.

The evaluation of the airborne experiments led to several necessary improvements in the demonstrator system as well as in the signal processing software, [8]. The main improvements were: the application of a better linearized frequency modulation to decrease the spread in range direction, the use of a 1 kHz sawtooth modulation (instead of 500 Hz triangular) in order to prevent possible undersampling in azimuth direction, the application of additional amplification to reduce the effect of the A/D board's quantization noise, and finally the installation of better motion sensors to come to a more accurate motion compensation. These improvements were tested in additional ground based experiments carried out throughout the early spring of 2004.

B. Further Ground Based Experiments

In order to verify the signal processing software, an inverse SAR experiment was carried out, [9]. The demonstrator system was again placed on top of the Faculty building, whereas the corner reflector was this time attached to the roof of a car. Several experiments were carried out in which the car was driven through the antenna beam at different velocities ranging from 10 km/hr up to 60 km/hr. During these experiments, the effect of a squint angle was also analyzed.

Fig. 3 shows the result obtained from one of the inverse SAR measurements in the range-Doppler domain. In this case the car was moving at 60 km/hr. The spreading of the response in range direction is due to the frequency sweep nonlinearity; during these measurements the nonlinearity was not compensated. The focusing in azimuth direction is good; the resolution is less than 1 m, proving the processing software to be valid.

So far, the demonstrator system was stationary throughout the ground based experiments. In order to investigate the effect of motion and vibrations, a SAR measurement was performed using a little van. The demonstrator system was put in the van looking sideways. Subsequently, the van was driven over a viaduct along which some corner reflectors were set up.

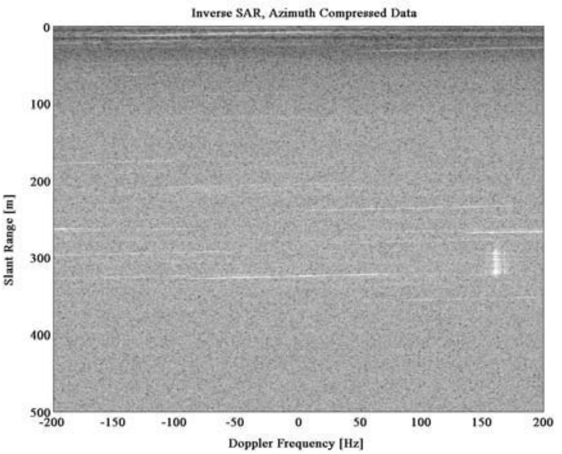

Fig. 3. The response of the corner reflector obtained from the inverse SAR data presented in the range-Doppler domain.

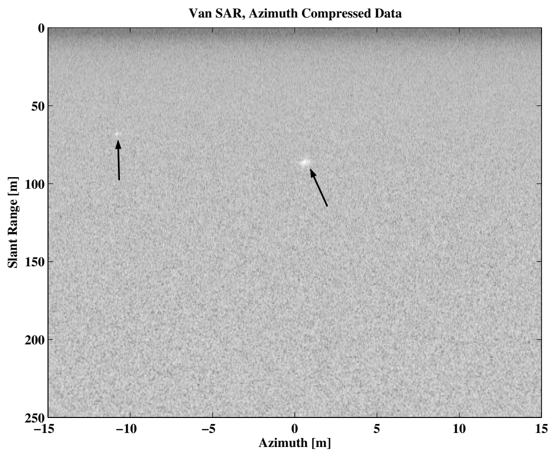

Fig. 4. The final result obtained from the SAR experiments with the little van presented in the range-azimuth domain.

The final result obtained from these SAR experiments is presented in Fig. 4. During this experiment the van was driving at approximately 55 km/hr. Two responses are clearly observable in the image. From the results it was concluded that the frequency sweep linearization was working well; the responses are not spread in range direction. Furthermore, it was concluded that the motion and the vibrations did not affect the demonstrator system.

The elaborate ground based measurements showed that the improvements of the system indeed led to better results. These results gave enough confidence to organize a second airborne campaign.

V. Second Airborne Campaign

The second airborne campaign was performed at the Strausberg airfield on June 22nd and 23rd 2004. Next to the runway, four corner reflectors were placed, see Fig. 5, and the GPS coordinates of their positions were measured. Two small 33 dBm^2 corner reflectors (1 and 2) and two large 40 dBm^2 corner refelctors (3 and 4) were set up. Moreover, a GPS ground station was set up in the middle of the scene.

Several runs were flown along the corner reflectors at 100, 150, and 300 m altitude. Additionally, some flights were made at an altitude of 200 m, during which the engine of the motor glider was switched off. The weather was very turbulent and the wind was directed almost perpendicular to the runway. A squint angle due to the aircraft yaw was therefore present during most measurements.

The data from the second airborne campaign are currently being processed, but some preliminary results will already be shown. The data are from a run flown at 100 m altitude. The slant range to the middle of the scene is around 240 m, see Fig. 6 (the angle of incidence is 65°). In this case, the demonstrator system was operating in low resolution mode. In the low resolution mode the used frequency sweep is only 200 MHz; leading to a theoretical range resolution of 75 cm.

Firstly, the data are converted to the range domain by applying a Fourier transform in range direction. The range domain data are presented in Fig. 7. Around 240 m, the responses of the corner reflectors are slightly visible. Secondly, the data are azimuth compressed by applying a matched filter in azimuth direction. The azimuth compressed data are shown in Fig. 8. The four responses are now clearly visible. Even the difference between the small (numbered 1 and 2) and the large (numbered 3 and 4) corner reflectors can be observed.

The geometry of the responses corresponds very well to the geometry shown in Fig. 5, although the complete image is skewed because of the aircraft yaw. That is why the responses of corner reflectors 1 and 3 are not aligned in range direction.

The practical range resolution is about 2 m, which is almost thrice the theoretical resolution. The spreading is mostly due to the residual frequency sweep nonlinearity. This residual nonlinearity may be further compensated with auxiliary data processing, [9]. The resolution in azimuth direction is around 50 cm, which is already very good. It is however expected that the azimuth resolution can be further enhanced by the application of motion compensation or autofocusing techniques.

The peak level of the response of corner reflector 3 is about 13 dB above the noise level. The peak level is anticipated to increase if the responses are better focused.

The preliminary results from the second airborne campaign are very promising. The application of autofocusing techniques will be the next step to enhance the results.

VI. Conclusion

Airborne SAR is a promising novel application for FM-CW radars. A small, lightweight airborne FM-CW SAR demonstrator system has been developed to show the practicability of FM-CW SAR under operational circumstances.

The main problem encountered throughout the development, was the frequency sweep nonlinearity. Due to the sweep nonlinearity, responses are spread in range direction. The sweep nonlinearity was finally compensated by applying a *linearized* frequency modulation. The results obtained with the linearized modulation are very good, although some residual nonlinearity is still present.

The demonstrator system has been put to test extensively during the summer of 2003, followed by a first airborne campaign in October 2003. The processing of the airborne data was however complicated by the low SNR and the lack of GPS data. The evaluation of the airborne campaign led therefore to some mandatory improvements of the demonstrator system.

These improvements were comprehensively tested during further ground based measurements. Subsequently, a second

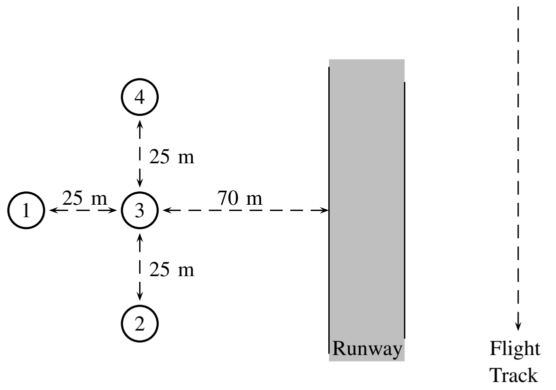

Fig. 5. Top view of the geometry of the corner reflectors (numbered 1 to 4). The GPS ground station was set up next to the corner reflector at position 3.

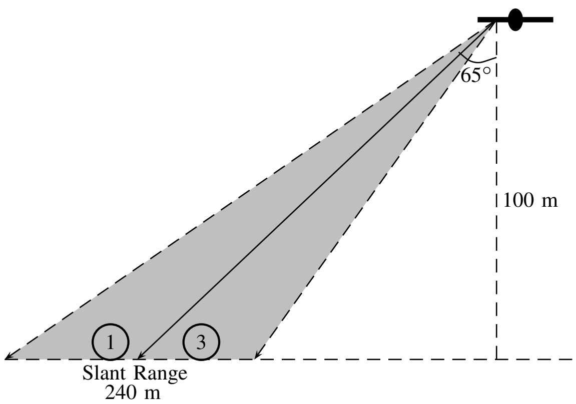

Fig. 6. Front view of the SAR geometry if the altitude is 100 m. The positions of the corner reflectors (numbered 1 and 3) are also indicated.

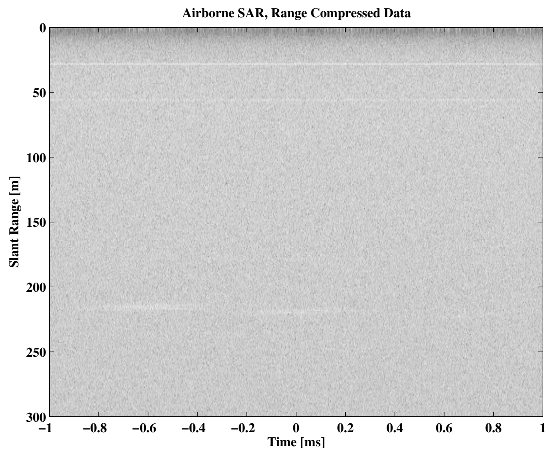

Fig. 7. The range domain data obtained from the airborne experiments.

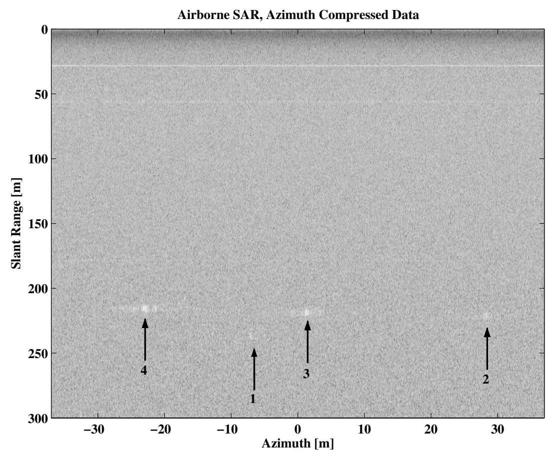

Fig. 8. The azimuth compressed data obtained from the airborne measurements.

airborne campaign was organized in June 2004. This second campaign was very successful. The preliminary results from a measurement run made at 100 m altitude during which the demonstrator system was operating in low resolution mode, are very good. By taking into account that the image is skewed because of the aircraft yaw, the geometry of the responses matches the geometry of the corner reflectors.

The range resolution is almost three times the theoretical value. The range spread is mainly caused by the residual frequency sweep nonlinearity. The azimuth resolution is already very good: 50 cm. The next step will be the application of motion compensation and autofocusing techniques.

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