Digital Beamforming and Traffic Monitoring Using the new F-SAR System of DLR

S. Baumgartner, M. Gabele, N. Gebert, R. Scheiber, G. Krieger, K.-H. Bethke, A. Moreira
Microwaves and Radar Institute, German Aerospace Center (DLR)
Muenchner Straße 20, 82234 Weßling, GERMANY
Email: stefan.baumgartner@dlr.de

***Abstract*— In November 2006 the first X-band test flight of DLR's new F-SAR system has been performed successfully and in February 2007 the first flight campaign has been conducted for acquiring experimental multi-channel data of controlled ground moving targets. In the paper preliminary results in the field of ground moving target indication and digital beamforming using the experimental data are presented.**

Keywords – Ground moving target indication (GMTI), digital beamforming (DBF), F-SAR

I. Introduction

The Microwaves and Radar Institute of the German Aerospace Center (DLR) has been operating the E-SAR airborne synthetic aperture radar (SAR) sensor successfully for many years [1] [2]. To better accomplish up-to-date and possible future requirements dictated by the remote sensing community and to improve the quality of provided standard products and also to be able to deliver totally new product types, the Institute has started some years ago the development of a multi-functional SAR system, the F-SAR system [3]. With this modern system a multi-spectral and fully polarimetric operation in X-, C-, S-, L- and P- band will be feasible in future. Additionally, fully polarimetric single pass interferometry will be achievable using across- as well as along-track antenna configurations in X-band.

In November 2006, the first X-band test flight of F-SAR has been performed successfully and already a few months later, in February 2007, the first flight campaign has been conducted. Although the primary objective of these campaign was the acquisition of ground moving target signals to validate ground moving target indication (GMTI) and motion parameter estimation algorithms, the acquired data is due to the chosen system setup and along-track antenna configuration also suitable for the application and demonstration of digital beamforming (DBF) on receive techniques.

Preliminary results in both fields (GMTI and DBF) are presented and discussed in the paper.

II. F-SAR X-Band Configuration

Since at the current development stage of F-SAR only two independent down-converter and analog-to-digital converter (ADC) paths are available, a switched aperture technique was deployed to increase the number of channels to four (Fig. 1) and hence enabling the application and investigation of more sophisticated GMTI and DBF techniques. For transmitting (TX) in X-band one slotted waveguide antenna is used and four patch antennas (each 0.2 m long) arranged in along-track direction, are used for receiving (RX).

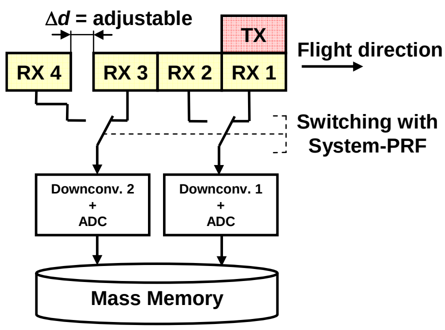


Figure 1. X-band along-track antenna setup.

Additionally, the fourth RX antenna can be shifted about several centimetres Δd in along-track direction to reduce so called blind velocities if the data are supposed to be processed using classical GMTI techniques like for example DPCA [4] and ATI [5] in combination with different baselines. Due to this antenna setup between individual pairs of antennas different effective baselines (i.e. effective phase center separations) are available: 0.1, $0.1+\Delta d/2$, 0.2, $0.2+\Delta d/2$ and $0.3+\Delta d/2$ meters. Instead of operating the system in the just mentioned "aperture-switching" four-channel mode, also an operation in a real two-channel mode with doubled pulse repetition frequency (PRF) is possible.

III. Ground Moving Target Indication

A. GMTI Techniques

Nowadays miscellaneous kinds of single-, two- and multi-channel GMTI techniques are known, but not all of them are verified using real data. An overview of some of these techniques (e.g. ATI, DPCA and STAP) can be found in [6]. In principle each of these techniques can be applied on real multi-channel data acquired with F-SAR and thus, be verified under realistic and complex moving target scenarios. The verification is essential for developing a reliable traffic monitoring system using air- or spacebased radar platforms.

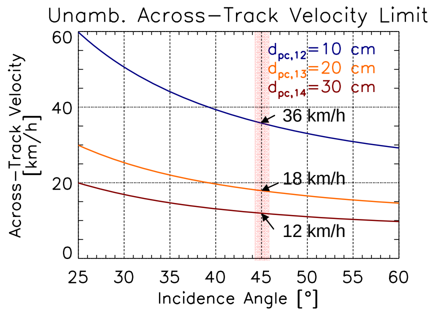


Figure 2. Unambiguously detectable across-track velocities (upper limits) from the ATI phases of different effective baselines d_{pc} at F-SAR.

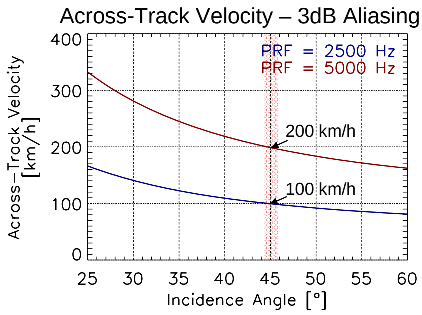


Figure 3. Across-track velocities where 3 dB of the received signal energy is aliased to a neighboring PRF band at F-SAR.

Some known shortcomings of classical ATI and DPCA techniques to overcome using e.g. multi-channel techniques are:

1. *Blind velocities:* The ATI phase drops to zero and the moving targets are no longer visible / detectable in the DPCA image. To reduce this effect, at F-SAR the fourth RX antenna can be shifted by Δd as already mentioned, to get baselines which are not integer multiples of each other (Fig. 1).

2. *ATI phase ambiguities:* If the ATI phase reaches π radians, the information about the driving direction (towards or away from the radar) of the moving target is lost and also the estimated across-track velocity becomes ambiguous (Fig. 2). For estimating the across-track velocity and the azimuth displacement unambiguously, additional information (e.g. information about the range walk) is necessary.

3. *Clutter influence:* ATI performs no clutter suppression and so the across-track velocities are underestimated. To get rid of this problem, at least a three channel system is necessary. ATI can then directly be applied on two clutter suppressed DPCA images [7]. Furthermore, having a four-channel system like F-SAR, more then only one clutter suppressed ATI image and more than one single along-track baseline can be obtained by adequate processing. Also application of STAP techniques becomes possible.

Additional detection bounds for fast moving targets may occur due to aliasing of signal energy. (Fig. 3). However, in [8] it is shown, how the wavenumber domain and the chirp scaling algorithm can be adapted to focus even fast moving and hence Doppler subsampled targets. For traffic monitoring applications it is necessary, that suitable GMTI algorithms, which also can cope with multi-target and real road traffic scenarios, are developed. Hence, the aim of the first F-SAR flight campaign and the performed GMTI experiments was, to acquire even such “realistic” traffic data under a controlled and reproducible environment.

B. *First Flight Campaign*

The first flight campaign was conducted in February 2007 over the Allgäu Airport in Memmingen. During the whole campaign besides the F-SAR also an optical

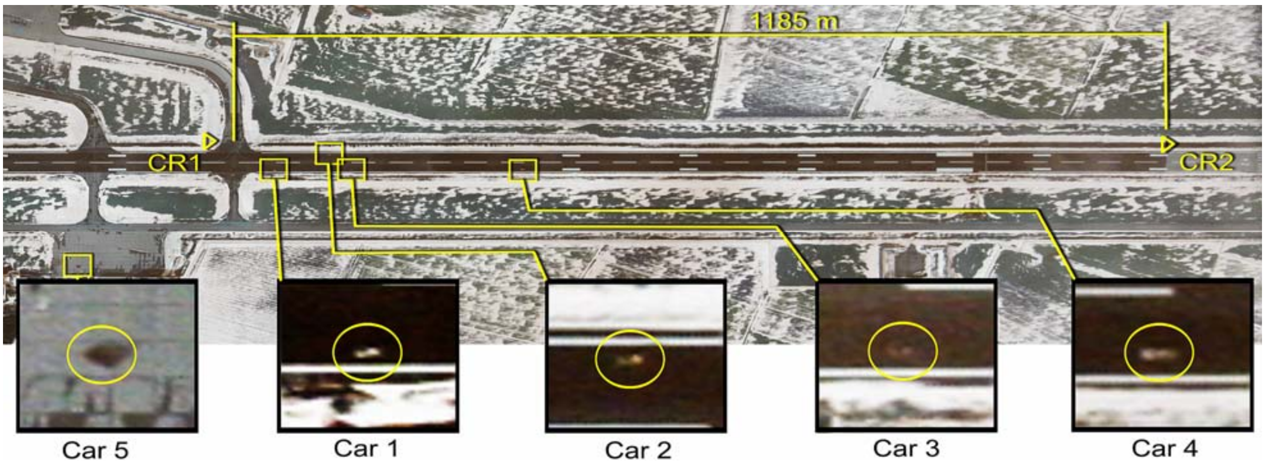


Figure 4. Optical image of the runway, taken at first overflight at the moment where the aircraft with F-SAR was broadside the runway. The positioned corner reflectors are denoted as CR1 and CR2 and the moving vehicles as Car 1 to Car 5.

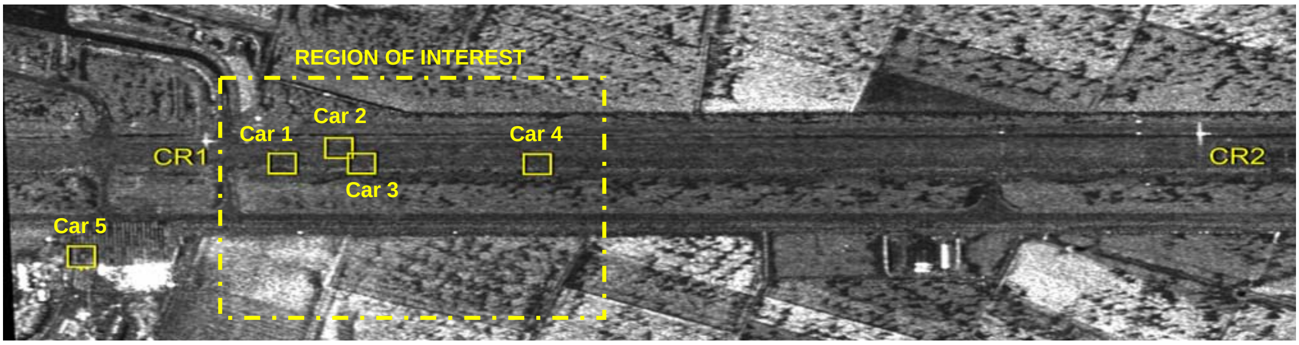


Figure 5. Multilook SAR image of the runway acquired at first overflight by F-SAR.

camera was mounted in the airplane for later ground moving target velocity verification purposes. On the runway (Fig. 4) five controlled ground moving targets (common passenger cars, one of them equipped with a GPS sensor) have moved with certain velocities. Additionally, on three of the cars radar reflectors were mounted to enhance their visibility in the SAR images. During several overflights with different headings different experiments were conducted on ground to obtain a broad spectrum of moving target signals. Also aliased signals from fast moving targets were acquired. A detailed experiment description can be found in [9]. For all conducted experiments a low chirp bandwidth of 100 MHz was chosen to reduce the amount of data (note that F-SAR is not limited to that low chirp bandwidth). The system or transmit pulse repetition frequency (PRF), respectively, was set to 5 kHz, that means due to the aperture switching the effective PRF per RX channel was 2.5 kHz and aliasing of signals from fast moving targets may occur (cf. Fig. 3). The aircraft velocity was about 90 m/s and Δd was adjusted to zero.

C. *Preliminary GMTI Results*

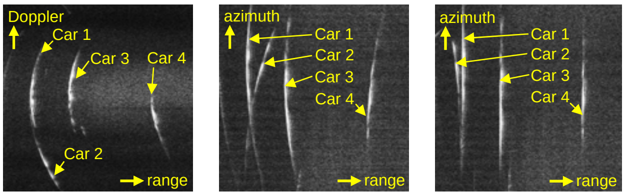
Since the evaluation of the acquired F-SAR data from the first flight campaign and also the optical data is still ongoing, only preliminary results using the data from the first overflight are presented in the paper.

In Fig. 5 the multilook SAR image corresponding to the optical image of Fig. 4 is shown. The “expected” true positions of the moving targets are marked with small yellow squares.

In the GMTI preprocessing step for each of the four channels adaptive calibration is performed [10],[11]. After the calibration procedure the estimated coherency between each of the channels was better then 0.984, even between the switched and not simultaneously sampled apertures.

During the first overflight the drivers of the cars had the instruction to move with the following velocities: car 1 and 3 with 10 km/h, car 4 with 55 km/h, car 2 with 120 km/h and car 5 along a circle with a radius of 30 m with 30 km/h. Note that the velocities are not yet verified by using the optical reference data. So it is easily possible that the true velocities may differ about several kilometres per hour.

The DPCA range-compressed images of the region of interest (marked in Fig. 5) obtained by subtracting channel RX3 from RX1, are shown in Fig. 6 (car 5 is not considered at our preliminary investigations). The measured SCNR values of the cars are about 20 dB for car 1, 18 dB for car 2, car 3 and car 4 (on car 1 and 2 a radar reflector was installed).



a) Range Doppler DPCA image. b) DPCA image. c) DPCA image after RCMC.

Figure 6. DPCA images of the region of interest.

For motion parameter estimation and focusing of the moving targets for example the adapted chirp scaling algorithm explained in [8] can be used and applied directly on the DPCA image shown in Fig. 6b.

However, for the preliminary results presented in the following, a simpler range Doppler algorithm, adapted only to the Doppler slope of the moving target signal was used. This algorithm was directly applied on the DPCA image shown in Fig. 6c, where as a preprocessing step the RCMC (range cell migration correction) for stationary targets already has been performed. With the estimated Doppler slope of the target of interest the residual range cell migration was corrected. After adapted RCMC the moving target signal energy is more or less distributed along one single azimuth line but slightly displaced in range in presence of across-track velocities.

Preliminary results by using this algorithm are shown in Fig. 7. For estimating the clutter suppressed ATI phases, two DPCA images generated by subtracting RX2 from RX1 and RX3 from RX2 were used. The estimated across-track velocities v_{y0} of the cars 1, 3 and 5 with the values of 7, 11 and 57 km/h are in good agreement with the controlled velocities of the cars and also the estimated along-track displacements Δx and across-track displacements Δy are feasible.

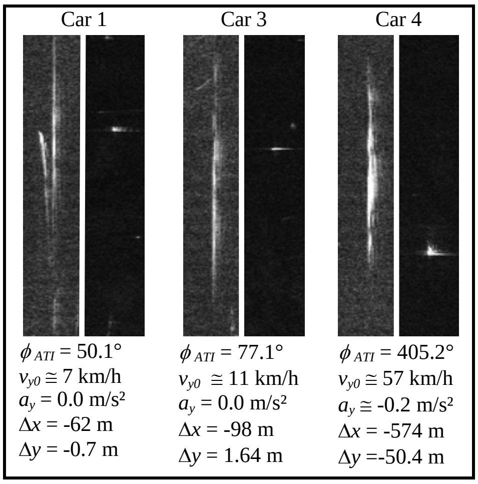


Figure 7. SAR images of moving targets after adapted RCMC (horizontal axis: range; vertical axis: azimuth). First row: range compressed data with adapted RCMC and corresponding focused but displaced moving target image; second row: estimated motion and position parameters.

Although the signal of the fast moving car 2 can easily be recognized in the range-compressed DPCA image (Fig. 6b and 6c), it is not so easy to separate it from the signal of car 1 due to the overlapping range histories and nearly identical slant range distances after stationary or even adapted RCMC. However, for that particular case a separation seems possible by filtering in the range Doppler domain (Fig. 6a).

Nevertheless, a future automatic GMTI processor for traffic monitoring applications, which is currently under development in the Microwaves and Radar Institute, must have also the capability to handle such complex traffic scenarios. The experimental multi-channel data acquired with F-SAR will help to achieve that challenging aim.

IV. Digital Beamforming

In the following section, the capability to perform digital beamforming with the multi-channel system of F-SAR is demonstrated. Therefore, two simultaneously acquired X-band channels are combined coherently by using the multi-aperture reconstruction algorithm investigated in [12].

In order to generate two aliased channels in azimuth dimension, the F-SAR data is lowpass filtered to limit the Doppler frequency to [-312.5 Hz, 312.5 Hz]. Then each of the channels is sub-sampled with a PRF of 312.5 Hz, what corresponds to half of the Nyquist frequency. These two channels are then processed by the aforementioned digital beamforming algorithm. Note, that in combination with the platform velocity of 90 m/s, this yields a distance of ~0.29 m between two subsequent samples of the same channel. As the effective phase centers are separated by 0.2 m, this results in a clearly non-uniform spatial sampling in azimuth. To evaluate the performance of the beamforming algorithm, a SAR image with a processed Doppler bandwidth of 350 Hz around a Doppler centroid of 100 Hz is generated from the single channel and from the two combined channels. The results are compared to a single channel that is sampled according to Nyquist with 625 Hz, what corresponds to the effective PRF of the two combined channels.

The resulting SAR images are given in Fig 8. They show a small scene around a corner reflector (i.e. CR2) at the end of the runway. As expected, the sub-sampled channel contains strong azimuth ambiguities (cf. Fig. 8 left), while the coherent combination of both sub-sampled channels yields a clearly improved SAR image, as shown in Fig. 8, middle. Numerically, the azimuth ambiguities are reduced from -9.5 dB and -9.4 dB in case of the single channel to nearly -19.5 dB and -18-.7 dB, respectively, when applying the multi-aperture reconstruction. Further, the geometric resolution in azimuth is improved from 0.37 m to 0.32 m what corresponds exactly to the resolution of the reference scenario, shown in Fig. 8 on the left.

It should be noted that calibration and balancing of the two channels is currently in progress, but has not yet been effectuated for the present images. For well balanced channels, a further improvement of the image quality is expected, especially regarding the level of residual ambiguities.

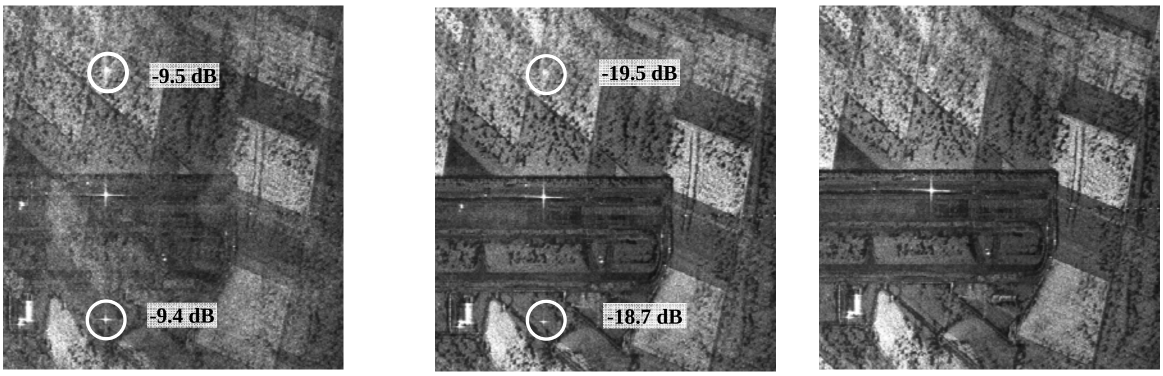


Figure 8. SAR images for a single, sub-sampled channel (left), the combination of two sub-sampled channels by digital beamforming (middle) and a nyquist-sampled single channel as a reference (right).

V. CONCLUSIONS

The preliminary results in the field of GMTI and DBF indicate that the new F-SAR system will be suitable for current and possible future applications in both fields. Although in the paper GMTI and DBF were treated as two different and from each other independent techniques, a lot of new applications will arise by combining both techniques. An example is the combination of azimuth ambiguity suppression with GMTI. This will allow for a reduced PRF as required for wide swath traffic monitoring.

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