

# Non-Linear SAR Data Processing By Time-Domain Back-Projection

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## Abstract

Focusing of conventional stripmap SAR data assumes a straight recording track of the sensor platform. Small deviations from that linear trajectory are corrected by motion compensation steps while keeping the assumption of a linear acquisition path. In the following, the processing of SAR data from *non-linear* tracks is discussed as may originate from small aircraft or drones flying at low altitude. They fly not a straight track but one dependent on topography, influences of weather and wind, or dependent on the shape of dedicated areas of interest such as rivers or traffic routes. Experimental data featuring a drop in height, a double bend and a 90-degree curve have been processed using a time-domain back-projection approach. The data was acquired by the German Aerospace Center's E-SAR L-band system.

## 1 Introduction

Processing of raw synthetic aperture radar (SAR) data to focused data products provides the basis to virtually all SAR applications and techniques known today. While being the first and crucial step towards accurate and reliable results of any SAR application, it is also a delicate one with strong dependency on the system hardware, flight geometry, and scene properties. For data collected by airborne sensors the flight path and its incorporation into the processing of the recorded data is crucial. The traditional approach of stripmap SAR is to assume a perfectly straight flight path and to correct for ideally small deviations of the aircraft towards this straight path in a step called motion compensation. However, systems mounted on small aircraft or drones may exhibit *highly non-linear* flight paths, to an extent that a model of a linear sensor trajectory no longer holds. Such a scenario may occur due to various factors such as rugged topography, atmospheric turbulence, but also due to the need for more flexibility in mission design as, for instance, for airborne or drone-based monitoring of curvilinear areas of interest (corridor mapping), such as rivers and nearby potential flooding areas or traffic routes. We pursue a time-domain back-projection (TDBP) approach, which, as we will show with the help of the experimental data, is flexible enough to process such data. This paper consists of a short description of the algorithm used and a description of our experimental set-up. We show and discuss the results obtained for the different flight tracks.

## 2 Non-Linear SAR Data Processing

In [1] an overview of time-domain back-projection processing has been given and, in particular, a fast backpro-

jection technique has been presented, which makes use of an approximation in the form of a factorization of both, the synthetic aperture as well as the size of the reconstruction grid. Thereby the computational complexity can be much reduced, however at the cost of less accurate phase information. It is stated that the back-projection algorithms can in general also be applied to SAR data acquired from non-linear flight tracks. Another source, wherein the subject of time-domain back-projection has been discussed is [2], however only for the case of linear flight tracks with the usual motion errors and the special case of a circular flight track. In [3] the problem of processing SAR data from non-linear flight tracks is treated in more detail and two solutions are proposed. The first solution is processing the data by time-domain back-projection. However, the problem is again described with the help of a two-dimensional formulation of the problem similar to the formulation presented in [2] and there is no remark with respect to how a changing pointing direction of the sensor is handled over azimuth. The second solution, which is proposed, is an  $\omega - k$ -based subaperture processing algorithm which is claimed to give superior results compared to the time-domain back-projection approach. Unfortunately, neither of these publications comes up with results obtained with real SAR data from highly non-linear flight tracks. We want to fill these two gaps by, first, presenting an algorithm, which handles the azimuth-varying pointing direction of the antenna as well as the arbitrary flight path, and, second, by proofing the fitness of our TDBP algorithm using real-world experimental data acquired from highly non-linear flight tracks.

## 3 Algorithm Description

Our TDBP approach has been described in [4, 5]. Here, we mainly focus on the extension that makes the algorithm

suitable to process synthetic aperture radar data acquired from an arbitrary flight track. The key items of the TDBP approach which enable successful processing of such raw data are the following:

1. By processing the data in the time-domain we can exploit the exact three-dimensional configuration (to the extent that the motion of the aircraft is accurately measured) of the acquisition pattern and the surface of the illuminated area. In other words, we can determine the exact reference function for each point of the reconstruction grid based on the 3D coordinates of the target points and the 3D coordinates of the sensor along the synthetic aperture.
2. The Doppler centroid frequency is determined from the sensor's velocity, position and attitude data and is updated for each radar echo.
3. The varying boundaries of the Doppler bandwidth over azimuth are compared to the Doppler frequency under which the individual target points are "seen". The signal contributions to a certain point on the reconstruction grid are weighted according to the Doppler frequency or omitted if the Doppler frequency exceeds the Doppler boundaries.
4. The scene is divided into a user-defined number of patches that can be processed in parallel in order to overcome the high computational burden of the TDBP approach.

The Doppler centroid frequency  $f_{dc_j}$  is calculated from the navigational data for each radar echo:

$$f_{dc_j} = \frac{2}{\lambda_c} \cdot \vec{v}_{S_j} \cdot \vec{u}_{P_j}, \quad (1)$$

where  $\lambda_c$  is the wave length of the carrier signal,  $\vec{v}_{S_j}$  is the velocity vector of the sensor corresponding to the  $j$ -th radar echo and  $\vec{u}_{P_j}$  is the unit vector in direction where the antenna is pointing to.  $\vec{u}_{P_j}$  is calculated from the sensors positioning and attitude data (roll, pitch and heading) and is updated for each radar echo. Using  $f_{dc_j}$  the azimuth-varying upper and lower limit of the Doppler bandwidth to process yield  $f_{d_{max_j}} = f_{dc_j} + f_B/2$  and  $f_{d_{min_j}} = f_{dc_j} - f_B/2$ , where  $f_B$  is the constant absolute Doppler bandwidth.

For each pixel on the reconstruction grid the Doppler frequency  $f_{d_{ij}}$  is calculated based on the varying geometric constellation given by the position vector on the ground  $\vec{r}_i$ , the position vector  $\vec{r}_{S_j}$  and velocity vector  $\vec{v}_{S_j}$  of the sensor:

$$f_{d_{ij}} = \frac{2}{\lambda_c} \cdot \frac{\vec{v}_{S_j}(\vec{r}_i - \vec{r}_{S_j})}{|\vec{r}_i - \vec{r}_{S_j}|} \quad (2)$$

During the coherent summation in the time domain a weighting function  $w(df_{d_{ij}})$  is applied, where  $df_{d_{ij}} = f_{d_{ij}} - f_{dc_j}$ . The weighting term  $w$  ensures that only signal contributions according to the actual orientation of the sensor at each azimuth time step are coherently added:

$$w(df_{d_{ij}}) = \begin{cases} \cos\left(\frac{\pi}{2} \cdot \frac{df_{d_{ij}}}{B/2}\right) & , |df_{d_{ij}}| \leq B/2 \\ 0 & , |df_{d_{ij}}| > B/2 \end{cases} \quad (3)$$

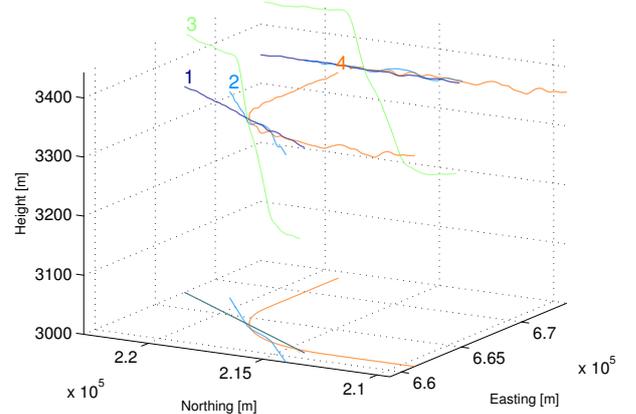
Eventually, the weighting function in eq. (3) is incorporated in the TDBP focusing algorithm and we obtain the focused signal  $s(\vec{r}_i)$ :

$$s(\vec{r}_i) = \sum_{j=a(\vec{r}_i)}^{b(\vec{r}_i)} w(df_{d_{ij}}) \cdot g(|\vec{r}_i - \vec{r}_{S_j}|, \vec{r}_{S_j}) \cdot |\vec{r}_i - \vec{r}_{S_j}| \cdot \exp(j2k_c|\vec{r}_i - \vec{r}_{S_j}|). \quad (4)$$

$a$  and  $b$  are the indices of the first and last sensor position, respectively, the echo of which still contributes to the grid position  $\vec{r}_i$ .  $g(\cdot)$  is the range-compressed, demodulated two-way response and  $k_c$  is the central wavenumber.

## 4 Description of the Experiment

Four tracks have been flown: a quasi-linear reference track, a drop in height of 300 m (*dive*), a double bend and a 90-degree curve flight as depicted in Fig. 1.



**Figure 1:** Flight tracks flown during the experiment as obtained from the DGPS/INS unit of the E-SAR system: 1. Quasi-linear reference track, 2. double bend, 3. dive, 4. 90-degree curve.

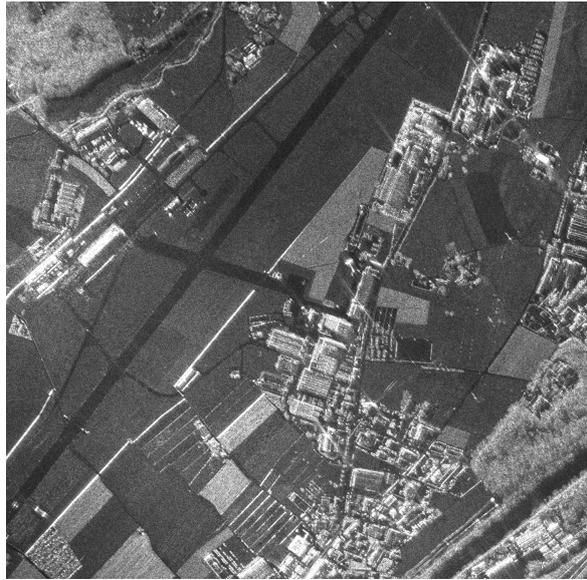
Besides the focusing quality, the geometric fidelity of the final image is an important point for the user. In order to be able to assess the preservation of dedicated features in the focused image an airfield has been chosen as our test site. On the airfield a lot of linear elements like a runway or fences and large buildings are present.

## 5 Results

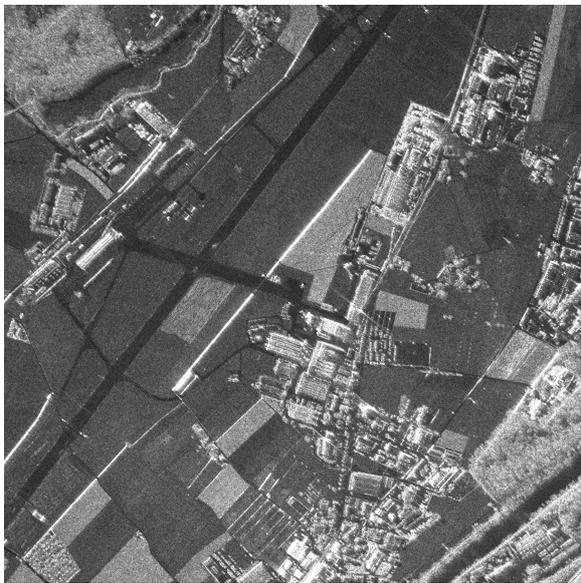
All four data sets have directly been focused onto a reconstruction grid based on a digital elevation model in map geometry. In Fig. 2 a common area that was illuminated during all four data takes is depicted. A high focusing quality within the whole area is achieved and all linear features, as for instance the runway, are well-preserved in all cases regardless of the geometry of the flight path.



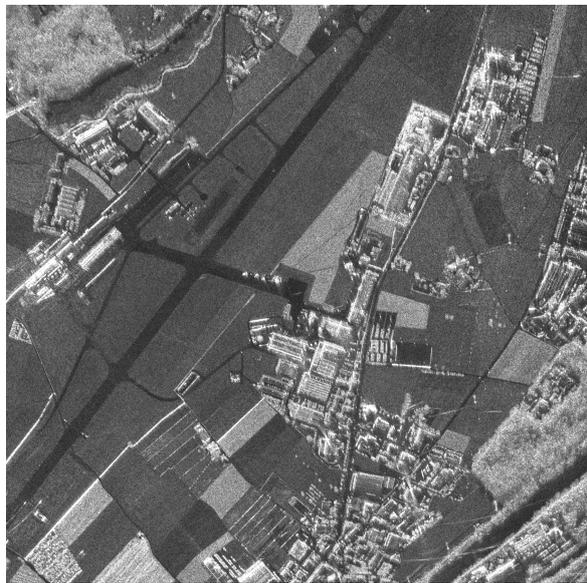
(a) Quasi-linear reference track



(b) Double bend



(c) Dive



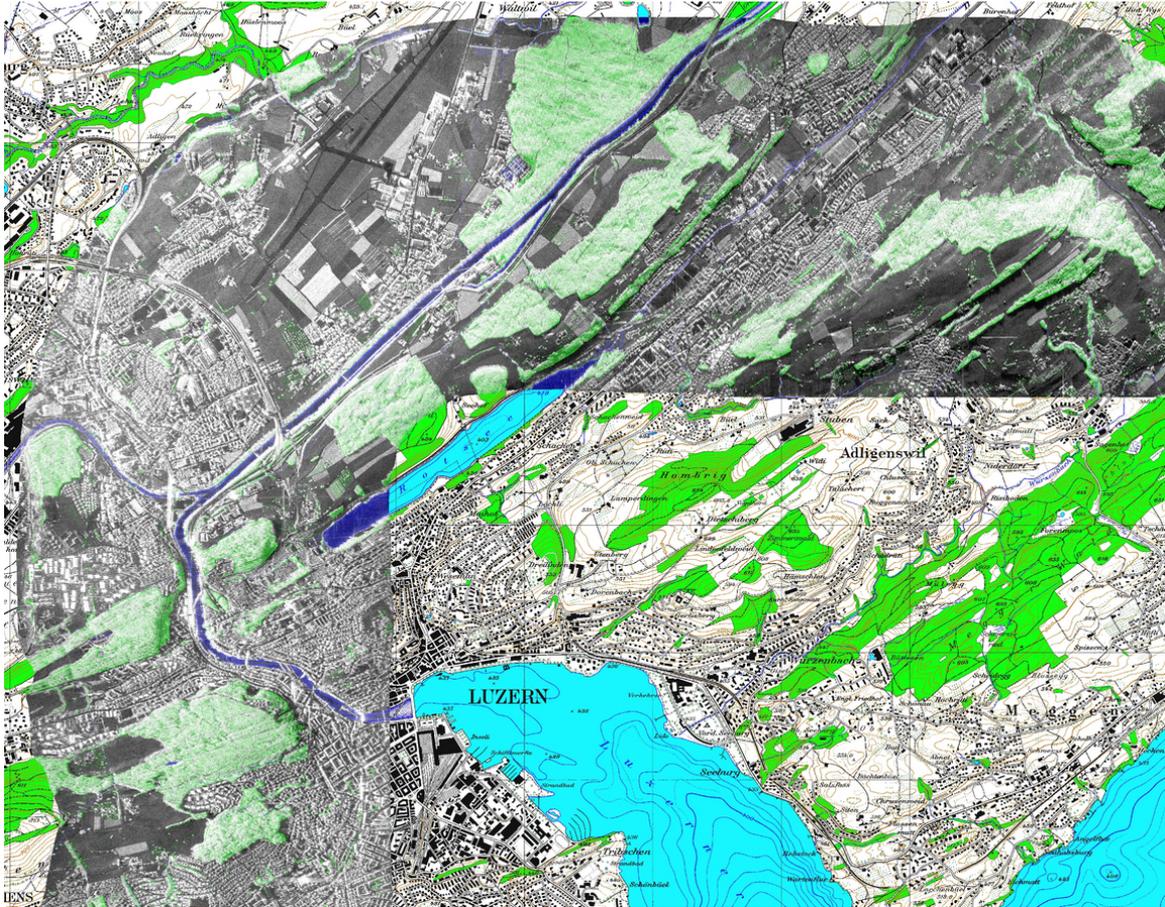
(d) 90-degree curve

**Figure 2:** Detail of a common area in all four experimental data sets: (a) quasi-linear reference track, (b) double bend, (c) dive, and (d) 90-degree curve. The data sets were focused on a DEM-based reconstruction grid in map geometry by time-domain back-projection processing.

This is the result of keeping track of the three-dimensional geometry during the focusing step. Further, the weighting function ensures that the varying looking direction of the antenna is accounted for thereby eliminating ghost targets. The small variations in the four images are due to different look directions. The most noticeable difference is obviously given for the 90-degree curvilinear track where

strong back-scattering of targets perpendicular to the flight track is practically eliminated by the change in the direction of illumination.

In order to illustrate the flexibility of our processing approach the whole data strip for the curvilinear acquisition mode is depicted in Fig. 3. Again, the image is given in map coordinates (easting/northing).



**Figure 3:** E-SAR L-band HH SAR image in map geometry acquired from a 90-degree curve track (see: track No. 4 in Fig. 1). Processing: Time-domain back-projection. Map reproduced by permission of swisstopo (BA081196).

## 6 Summary

We have presented a time-domain back-projection based algorithm that is able to produce high-quality images for airborne SAR data from highly non-linear flight tracks. The processing quality as well as the geometric fidelity is demonstrated by a comparison of an overlapping region occurring in all four data sets. The focusing quality is excellent regardless of the acquisition geometry. And as a natural side-effect of the back-projection algorithm we obtain geo-referenced complex-valued SAR images. Please note, that there is a companion paper by Magnard et al. on this subject where a different processing approach in the form of a patch-wise processing and mosaicking of small parts of the scene was pursued.

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## References

- [1] L. M. H. Ulander, H. Hellsten, and G. Stenström, "Synthetic-Aperture Radar Processing Using Fast Factorized Back-Projection," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 39, no. 3, pp. 760–776, July 2003.
- [2] M. Soumekh, *Synthetic Aperture Radar Signal Processing: with MATLAB Algorithms*. John Wiley & Sons, 1999.
- [3] —, "Time Domain Non-Linear SAR Processing," Department of Electrical Engineering, State University of New York, Tech. Rep., 2006.
- [4] O. Frey, E. Meier, and D. Nüesch, "An Integrated Focusing and Calibration Procedure for Airborne SAR Data," in *Proc. EUSAR*, Dresden, Germany, May 2006, pp. 1–4.
- [5] —, "Processing SAR Data of Rugged Terrain by Time-Domain Back-Projection," in *Proc. SPIE*, vol. 5980, Bruges, Belgium, Sept. 2005, pp. 1–9.