Development of a GMTI Processing System for the Extraction of Traffic Information from TerraSAR-X Data

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Abstract

Synthetic aperture radar (SAR) has a day-and-night and all-weather operating capability, can acquire high-resolution images of large areas within short time frames and can measure the speed of moving objects. That is why its application to ground moving target indication (GMTI) and to traffic monitoring has been intensively investigated in the recent years. The German SAR satellite TerraSAR-X, which is scheduled to be launched later in 2006, will provide various SAR imaging modes with resolutions down to 1m. It will additionally allow for different operating modes for along-track interferometry (ATI) which is sensitive to across-track motions of moving objects. This paper introduces a first approach for the concept of a traffic information extraction processor for TerraSAR-X data.

1 Introduction

Traffic monitoring has become an important issue in today's life. Due to the increasing vehicle density traffic data are required in many applications such as logistics, private travel or transportation research. Although existing monitoring techniques, e.g. induction loops can continuously collect data, their spatial coverage is low. Airborne and spaceborne optical sensors have a larger coverage, but their usability depends on daylight and good weather conditions. As synthetic aperture radar (SAR) works independent of day time and weather and rapidly images large areas, it has a great potential for traffic monitoring. The German SAR satellite TerraSAR-X (TS-X) will be a high-resolution multi-purpose SAR satellite for a variety of commercial as well as scientific applications [1][2]. It will provide various SAR imaging modes with resolutions down to 1m and allow for along-track interferometry. DLR is developing an automatic GMTI processor as an amendment to the TS-X ground segment. Its purpose is to demonstrate the capability to retrieve traffic information with a space borne SAR sensor. As the signatures of moving objects in a radar image usually are degraded with respect to peak energy, shape and position, a complex processing system is required to automatically detect and measure them. In this paper we introduce a first concept for the TS-X GMTI processor. Based on the TS-X sensor modes, there are different data acquisition options for GMTI: Dual-Receive Antenna (DRA), Sub-Aperture Switching and single channel SAR imaging. The first two allow for along-track interferometry and displaced phase centre array (DPCA) techniques, which are sensitive to across-track motions of objects. A detailed analysis of these options is given in [3] and [4]. Exploiting single-channel SAR data enables the detection and indirect measurement of along-track motions (by adapted SAR focussing) and the measurement of across-track motions (by the azimuth displacement method in conjunction with road data) [5].

2 GMTI Processing System

In this section we discuss the functional blocks of the tentative traffic processor structure. It is strongly based on the use of a priori information such as road data. The structure is shown in Figure 1.

SAR Processing and Focussing Parameter Prediction
It is well known that the signatures of moving objects appear misplaced, degraded and blurred in radar images [6][7][8]. The loss of peak energy and its spreading of over several image resolution cells makes detection very hard. The reason for these effects is that with the usual stationary world assumption, moving targets are focussed with a wrong matched filter. If their velocity components were known a priori, the matched filter could be optimally parameterized with respect to the frequency modulation (FM) rate and the Doppler Centroid frequency f_{DC}. Since this is not the case, the SAR data have to be adaptively processed for several assumptions of these components. A possible approach is to focus the complete SAR image for n different FM rates and m different f_{DC} values. In practice m and n are limited due to computational performance reasons. More efficient concepts are discussed in [9] and will be implemented for our system. A modified SAR processor with controlled spatial focussing parameter update will focus only relevant parts of images. Parameters will be updated for each pixel based on a road network and a motion

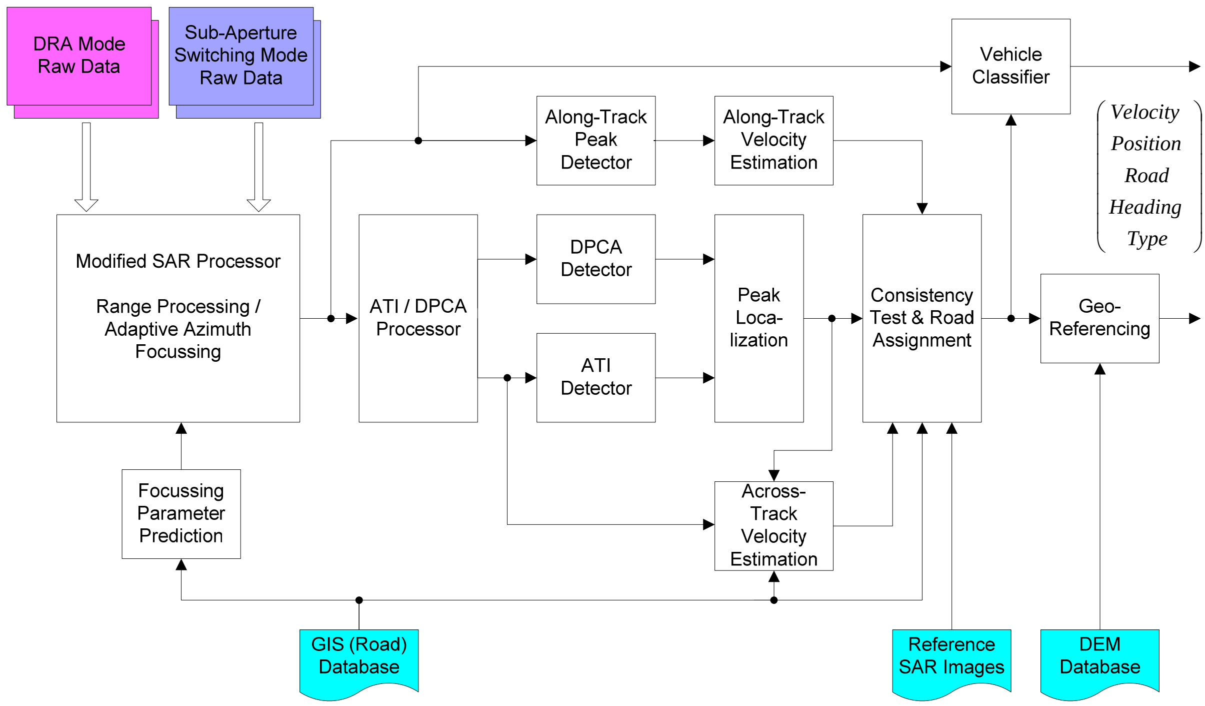

Figure 1: Tentative concept of the TerraSAR-X Traffic Data Extraction Processor

hypothesis so that each moving target will be focussed almost perfectly. The final stages of this processor are sketched in Figure 1 by the functional box "Focussing Parameter Prediction" and by the "Adaptive Azimuth Focussing" part of the modified SAR processor. For the case of roads almost parallel to the flight track a stack of images is focussed with different FM rates. This stack is fed to an along-track peak detector and velocity estimator as described below.

ATI / DPCA Processor

The ATI & DPCA processor performs the channel balancing of the DRA/sub-aperture switching mode data and generates the (multi-looked) interferogram and the DPCA image. Both are used for the detection and measurement of vehicles with across-track velocity components. Channel balancing is required to compensate for slight inequalities in the receiver channel electronics (for DRA) and in the transmit/ receive patterns of the used SAR antenna panels.

Vehicle Detection

Our processing concept is based on a combination of an ATI plus a DPCA detector for across-track and an along-track peak detector for azimuth motions. To design an ATI constant false alarm rate (CFAR) detector, the probability density distributions of vehicles and background in interferometric data need to be known. Using the assumption of jointly Gaussian-distributed data in the two images, the joint probability density function (pdf) $f_c(\eta,\psi)$ of amplitude η and phase ψ of an interferogram have been derived, e.g., in [10]:

$$f_c(\eta,\psi) = \frac{2n^{n+1}\eta^n}{\pi\left(1-|\rho|^2\right)\cdot\Gamma(n)} \cdot K_{n-1}\left(\frac{2n\eta}{1-|\rho|^2}\right) \cdot e^{\frac{2n\eta|\rho|\cos(\psi)}{1-|\rho|^2}} \quad \textbf{(1)}$$

with n, the number of looks (effectively the amount of averaging), $\Gamma(\cdot)$, the gamma function and $K_n(\cdot)$, the modified Bessel function of the n^{th} kind. In case of public traffic, where a priori information about position, velocity and movement direction of vehicles is available to a certain extend, the use of this simple CFAR detector is sub-optimal. Since it is also possible to derive expectation values for position, interferometric phase and aspect-dependent radar cross section of vehicles using ancillary data, a pdf $f_{cm}(\eta,\psi)$ incorporating this kind of a priori knowledge improves the underlying model. An analytic pdf has not been found yet, but an approximation valid for $n >> 1$ is given in [5]. Using this approximation as an alternative hypothesis, $f_{cm}(\eta,\psi)$ allows us to define a likelihood ratio to which a threshold can be applied. In a very similar way one may proceed for deriving a CFAR detector based on the DPCA technique, which is essentially the difference of the two complex images. In this case, the classification relies purely on the interferometric phase value since the amplitude cancels out. For more details we refer, e.g. to [11]. The approach outlined so far can only be applied if displacement or interferometric phase occurs at all.
This does not happen for objects moving purely in along-track direction. Our strategy to estimate a vehicle's velocity in along-track direction relies on hypothesizing a series of FM rates and analyzing each pixel's "sharpness function" over these FM rates, eventually yielding the correct estimate of the along-track velocity. Since blurring due to along-track movement occurs only in azimuth direction, searching the correct FM rate for a given pixel reduces to a 2D-problem. The known locations of roads as well as the expected range of vehicle velocities allow to further

restrict the search space to a limited number of FM rates. To extract the energy peak, we implemented a simple but effective blob detection scheme that analyzes the local curvatures in azimuth- and FM-direction, thereby incorporating a certain amount of smoothing depending on the expected noise level of the images. Combining local curvature maxima and energy amplitude by the geometric mean yields the final decision function, from which the maximum is selected. Details of this algorithm can be found in [12].

Peak Localization

The ATI and the DPCA detector create binary detection masks. A mask value of $M_{ij} \neq 0$ indicates the presence of a moving object. As the signature of a target will usually be spread over several pixels due to range/azimuth side lobes of the main peak, residual defocusing or simply due to the vehicle dimensions when compared to the image resolution cell size, it will be represented by several mask pixels. To avoid multiple detections of the same vehicle a transformation from a pixel to an object based processing is required at this stage. Most targets appear as pixel clusters in the detection mask. The peak localization extracts the separate pixel clusters and analyzes the radar data inside of each in order to get the target peak position with sub-pixel accuracy.

Across-Track Velocity Estimation

The across-track velocity v_y of the moving targets is estimated from the ATI phase ψ_{ATI} at the detected peak positions according to:

$$\psi_{ATI} = \frac{2\pi \cdot d \cdot v_y \cdot \sin(\theta)}{\lambda \cdot v_s} \quad \text{[rad]} \qquad \textbf{(2).}$$

Here, d is the phase centre separation of the antenna sub-apertures, θ the incidence angle, λ the wavelength and v_s the satellite velocity. The unambiguous velocity range retrievable from ψ_{ATI} is about ±240 km/h in ground range (θ=40deg). The accuracy of the estimation depends on the SCR and the phase noise. A second estimate is obtained via the azimuth displacement Δaz of the target peak from the true position (by using the a priori information of roads). It is linked to Δaz according to:

$$\Delta az = -R \frac{v_y \cdot \sin(\theta)}{v_s} \quad \text{[m]} \qquad \textbf{(3)}$$

with the sensor-to-target distance R at the time of imaging. For most motorways and less dense road networks the velocity can easily be determined from Δaz. A more complicated case occurs if roads lie so close that their displacement intervals overlap. A target peak detected in such an area has several possible Δaz based across-track velocity estimates. These ambiguities can only be solved in conjunction with one of the other velocity estimation methods (ATI phase, azimuth sharpening). Figure 2 shows a displacement simulation for a road network north of Munich for θ=23deg and typical truck velocities. The number of overlaps is given in grey values.

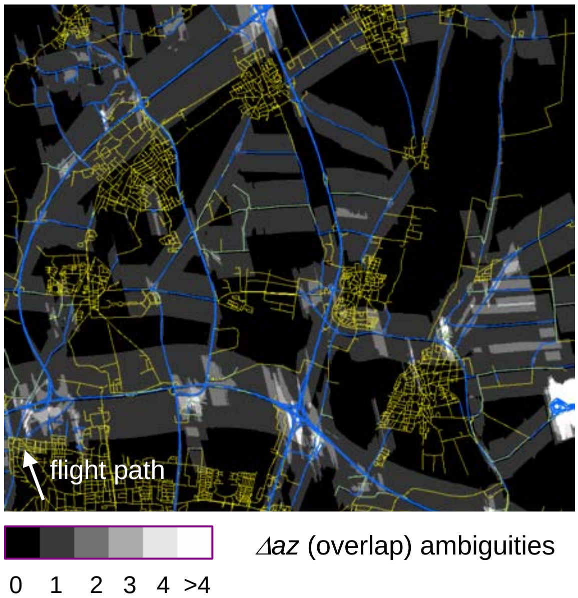

Figure 2: Simulation of Δaz overlap in a road network north of Munich (v_{road}=*60 km/h* assumed)

Consistency Test and Road Assignment

After detection and peak localization a consistency test of the results is required for several reasons. Firstly, the vehicle detectors have a certain false alarm rate, i.e. a number of stationary targets will be among the detection results. Secondly, some of the velocity estimates may be ambiguous or inaccurate. Thirdly, the detected targets are still displaced from their true positions. The consistency test cross-checks the different velocity estimates of a target and tests certain conditions that must be fulfilled for a correctly detected/measured moving vehicle. Possible ambiguities of the azimuth displacement and of the ATI phase are taken into account. One necessary condition for a correctly detected/measured target is that the velocity estimates from at least two different methods are very close. The incorporation of multi-temporal SAR reference images of the same site can help to exclude stationary targets. The realization of this option is currently under investigation.

Vehicle Classification

Passenger cars and trucks usually drive with significantly different average speeds on motorways. To derive traffic parameters such as travel time or velocity profiles with sufficient accuracy, a coarse classification of detected vehicles into the two categories is required. This is currently investigated.

Geo-Referencing

In the Geo-Referencing step, the estimated true vehicle positions are converted from the radar to the WGS84 geometry. This way the extracted data can be used to estimate traffic parameters.

3 Experimental Results

Besides a thorough theoretical GMTI analysis for TS-X, the system development is based on the evaluation of airborne SAR data. An experimental GMTI processing system for data of DLR's E-SAR sensor has been developed. Except for the adaptive focussing, the vehicle classifier and the use of reference SAR images, it comprises prototypes of the functionalities discussed in section 2. Figure 3 shows a first result obtained with this processor. The motorway A96 near Germering had been imaged on May 12, 2005. The situation was a congestion in the direction to Munich (from left to right) and nearly no traffic in the opposite direction. The red squares mark the automatically detected moving target peaks. The triangles are the detected cars after velocity estimation, peak localization and consistency test at their estimated true positions. Their colours correspond to the estimated velocities. They were verified using car tracks extracted from optical reference images simultaneously acquired with the E-SAR data. The velocity range and mean obtained from the camera data for the test area is 2-41 km/h and 21 km/h respectively. From the targets detected in the E-SAR data, a velocity range and mean of 11-35 km/h and 21 km/h were obtained.

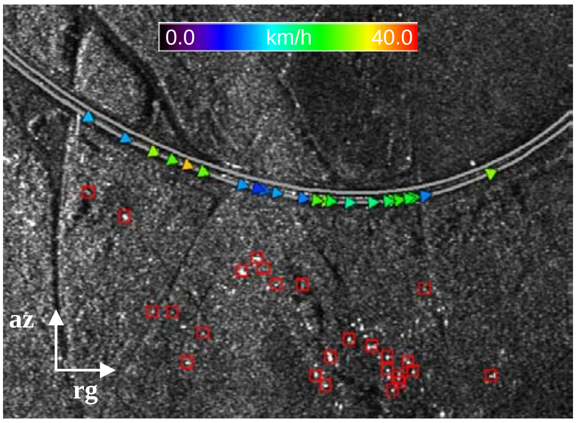

Figure 3: Vehicles automatically detected in E-SAR data by using an experimental GMTI processor

4 Conclusions

The extraction of traffic information from TS-X data requires a complex processing system. The possibility to automatically detect and measure moving objects has been shown for airborne SAR data. The TS-X traffic monitoring project aims at demonstrating the usability of a spaceborne SAR sensor to retrieve traffic data. However, besides the vehicle detection itself, aspects such as processing time are also relevant in promoting this new SAR application. For monitoring or even controlling traffic flows in an area, traffic information must normally be available within minutes. Hence, the TS-X traffic processor needs an efficient software implementation. The SAR focussing has been identified as the computationally most demanding part so far. A significant reduction of the computation time is possible through our concept of processing only GMTI relevant image parts as predicted from a priori knowledge. With a parallelized software architecture we expect processing times that allow for practical applications of the extracted traffic data.

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