F-SAR GMTI Processor Concept for Traffic Monitoring Applications

Stefan V. Baumgartner, Gerhard Krieger

Microwaves and Radar Institute, German Aerospace Center (DLR),
Münchner Straße 20, 82234 Weßling, Germany,
E-Mail: Stefan.Baumgartner@dlr.de

Abstract

In the paper a ground moving target indication (GMTI) and parameter estimation algorithm based on a priori knowledge is presented. This algorithm is suitable for real time airborne traffic monitoring applications using single- as well as multi-channel synthetic aperture radar (SAR). It operates directly on range-compressed data. Only the intersection points of the moving vehicle signals with the road axis mapped into the range-compressed data domain are evaluated. Hence, the algorithm needs low computational power. The proposed algorithm enables the estimation of the position and velocity vectors of moving vehicles as well as automatic geocoding. A verification of the algorithm is done using dual-channel SAR data acquired with DLR's new F-SAR system [1].

Introduction

Nowadays, a lot of motorways are equipped with sensors to acquire the actual traffic situation. However, outside of motorways due to a lack of sensor installations the traffic is almost unknown. Traffic monitoring with radar from high altitudes is one way for gathering additional traffic information over this wide unknown areas, independently of day and night and weather conditions. For this task, principally already existing GMTI systems and algorithms can be used. Nevertheless, for traffic monitoring applications each vehicle has to be assigned to a certain road additionally and for performing such an assignment a road database is required. Furthermore, it is not necessary to detect vehicles moving off-road so that the system complexity and also the complexity of GMTI algorithms, as well as the computation time, can be reduced.

The algorithm described in this paper takes into account the road network for vehicle detection and parameter estimation. The idea using a road network is not new, but up to now such a road network mainly was used together with displacement based GMTI algorithms. These algorithms measure the azimuth displacements (which are proportional to the across-track velocities) of the vehicles occurring due to conventional SAR focusing. The processing is time consuming since in general SAR images have to be generated taking into account the full bandwidth given by the pulse repetition frequency (PRF) of the radar. For the proposed algorithm conventional SAR focussing is not necessary. The algorithm operates directly on the range-compressed SAR data. Even with a single-channel SAR system for fast moving vehicles falling outside the clutter band the parameters position, absolute velocity and heading can be estimated with high accuracy.

Principle

As a first step the road axis of interest is mapped into the range-compressed SAR data array. This coordinate transformation, which is the heart of the whole algorithm and which is described in more detail in the next section, is done in such a way, that the geographical coordinates of each road point are transformed to corresponding beam center coordinates. The beam center position of a detected moving vehicle is then directly given by the intersection of the vehicle signal with the mapped road point (cf. Figure 1). Remember that due to the mapping automatically the geographical coordinates of the road point and hence, of the detected vehicle moving on this road point at beam center time t_{bc} are known, so that no further geocoding is required.

For moving vehicle detection and motion parameter estimation only a few azimuth samples around the intersection point are taken (cf. Figure 1 right) and transformed into Doppler domain via FFT. Due to the small number of used azimuth samples, the signal phase is more or less linear over time and so the moving vehicle signal appears as a sharp peak in Doppler domain. For detection the signal amplitude is compared to a certain threshold and for motion parameter estimation the Doppler shift f_{DC} of the signal peak is exploited.

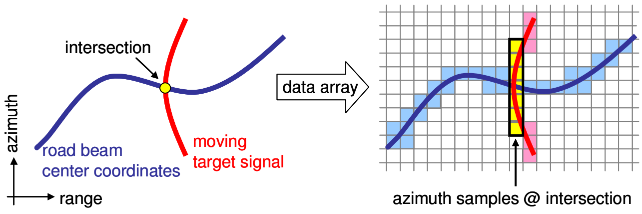

Figure 1 Principle of the proposed algorithm.

Coordinate Transformation

The relation of the global Cartesian UTM coordinate system $\{x_{UTM}, y_{UTM}, z_{UTM}\}$ and the local Cartesian coordinate system $\{x, y, z\}$ relevant for GMTI processing is sketched in Figure 2. The x-axis is defined by the platform velocity vector $\vec{v}_p(t)$. Since it can not be ensured that the squint angle and, hence, the Doppler centroid of the clutter in general is negligibly small, a squinted geometry has to be considered. In Figure 3 it is shown how the received non-squinted and squinted data of one and the same stationary road point are stored in the range-compressed SAR data array. With T_{SA} the illumination time is meant, x_{r0} is the azimuth position of the road point at minimum range r_0, x_0 is the azimuth offset due to the squint angle and r_{10} is the beam center range in the squinted case. The azimuth position x_{r0} can be computed by decomposing the range vector $\vec{r}(t)$ into a component $\vec{x}_{r0}$ parallel or anti-parallel to flight direction, respectively, and a component r_0 perpendicular to flight direction:

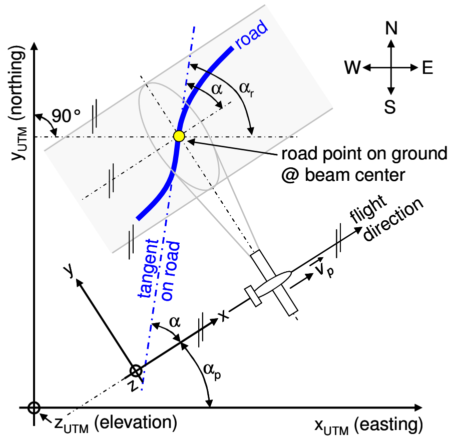

Figure 2 Relation between global geographical UTM and local Cartesian coordinate system.

$$\vec{x}_{r0}(t=t_s) = \left\langle \vec{v}_p(t=t_s), \vec{r}(t=t_s) \right\rangle \frac{\vec{v}_p(t=t_s)}{\left\| \vec{v}_p(t=t_s) \right\|^2}, \quad (1)$$

where t_s is the absolute start time of data acquisition (i.e. the start time of the first range line stored in the SAR data array), $\langle . \rangle$ denotes the inner product and $\|.\|$ is the L_2 norm. The vectors $\vec{v}_p(t=t_s)$ and $\vec{r}(t=t_s)$ can be computed by using the known UTM coordinates of the road point and the radar platform at any time instant. The minimum range r_0 is then given as

$$r_0 = \left\| \vec{r}(t=t_s) - \vec{x}_{r0}(t=t_s) \right\|. \quad (2)$$

For computing the azimuth position x_{pt} of the road point within the data array the following equation can be used:

$$x_{pt} = \left\langle \frac{\vec{v}_p(t=t_s)}{\left\| \vec{v}_p(t=t_s) \right\|}, \frac{\vec{x}_{r0}(t=t_s)}{\left\| \vec{x}_{r0}(t=t_s) \right\|} \right\rangle \left\| \vec{x}_{r0}(t=t_s) \right\| - x_0. \quad (3)$$

The azimuth offset x_0 can be computed as

$$x_0 = r_0 \tan \psi, \quad (4)$$

where ψ is the squint angle given by

$$\psi = \arcsin\left(\frac{\lambda f_{DC,st}}{2 v_p} \right). \quad (5)$$

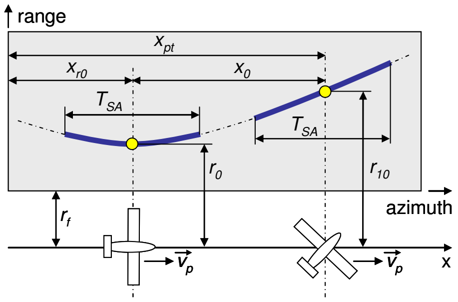

Figure 3 SAR data array containing range-compressed data of a single road point in the non-squinted (left) and squinted (right) case. The beam center positions of the road point are marked with a circle.

In the previous equation λ is the radar wavelength, v_p the average platform velocity and $f_{DC,st}$ the Doppler centroid of the clutter which can be estimated from the range-compressed data of one single channel. In general the Doppler centroid $f_{DC,st}$ itself is range dependent, but for the proposed algorithm also the average value can be used by introducing only a small error (i.e. the road point of interest is not mapped exactly at the beam center position). Knowing the squint angle also the beam center range r_{10} can be computed:

$$r_{10} = \frac{r_0}{\cos\psi} . \tag{6}$$

Additionally, the beam center time of the road point can be calculated as

$$t_{bc} = t_s + \frac{x_{pt}}{v_p} . \tag{7}$$

Motion Parameter Estimation

The motion equations of a moving vehicle under the assumption that it moves with constant acceleration at constant altitude can be written as:

$$x(t) = x_0 + v_{x0}(t - t_{bc}) + \frac{1}{2}a_x(t - t_{bc})^2 , \qquad y(t) = y_0 + v_{y0}(t - t_{bc}) + \frac{1}{2}a_y(t - t_{bc})^2 , \tag{8}$$

where a_x and a_y are the constant acceleration components in along- and across-track direction, respectively, and v_{x0} and v_{y0} are the velocity components at beam center time t_{bc}. The across-track position y_0 of the target at beam center time can be expressed as

$$y_0 = \sqrt{r_0^2 - \Delta h^2} , \tag{9}$$

where Δh is the altitude difference between the moving vehicle and the radar platform. The distance from the transmit antenna to the moving vehicle is then given as

$$r(t) = \sqrt{\left[x(t) - v_p(t - t_{bc})\right]^2 + y^2(t) + \Delta h^2} . \tag{10}$$

After performing a second order Taylor expansion around t_{bc} and some mathematics the range history can be approximated as [2]

$$r(t) \cong r_{10} - \frac{\lambda}{2} f_{DC}(t - t_{bc}) - \frac{\lambda}{4} k_a (t - t_{bc})^2 , \tag{11}$$

where f_{DC} is the total Doppler shift of the received moving vehicle signal and k_a the Doppler slope. It can be shown, that the absolute beam center velocity of the moving target can then be computed as

$$v_0 = |v_{abs}| = \left| \frac{\lambda r_{10}(f_{DC,st} - f_{DC})}{2(x_0 \cos\alpha + y_0 \sin\alpha)} \right| , \tag{12}$$

where α is the road angle with respect to the x-axis or flight direction, respectively. The heading of the moving vehicle, with respect to the x-axis, is then given by

$$\alpha_v = \begin{cases} \alpha & \text{if } \operatorname{sgn}(v_{abs}) = +1 \\ \alpha - 180° & \text{if } \operatorname{sgn}(v_{abs}) = -1 \end{cases} , \tag{13}$$

where sgn(.) is the signum function.

Practical Implementation for the F-SAR Dual-Channel Mode

Figure 4 shows the flow chart of the proposed algorithm for the F-SAR system operated in dual-channel mode, where for clutter suppression the displaced phase center antenna (DPCA) technique is used. RX1 and RX2 are the range-compressed data arrays acquired with the two receiving channels separated by an along-track baseline. The geographical coordinates of the roads are obtained from the free available OpenStreetMap road database

[4]. The elevations corresponding to the road points are obtained from the SRTM digital elevation model [5]. Before mapping the roads into the range/azimuth plane interpolation is required. Within the "Clustering" block several pixel based detections of one and the same vehicle are merged to one physical vehicle. Afterwards all detections are brought to a certain output format by the "Formatting" stage. These data can then be transmitted from the radar platform to a ground station where it will be distributed to e.g. a traffic monitoring and traffic management system. Please note that the proposed GMTI algorithm is not limited to the dual-channel case. It can also be applied on single-channel data as well as on multi-channel data.

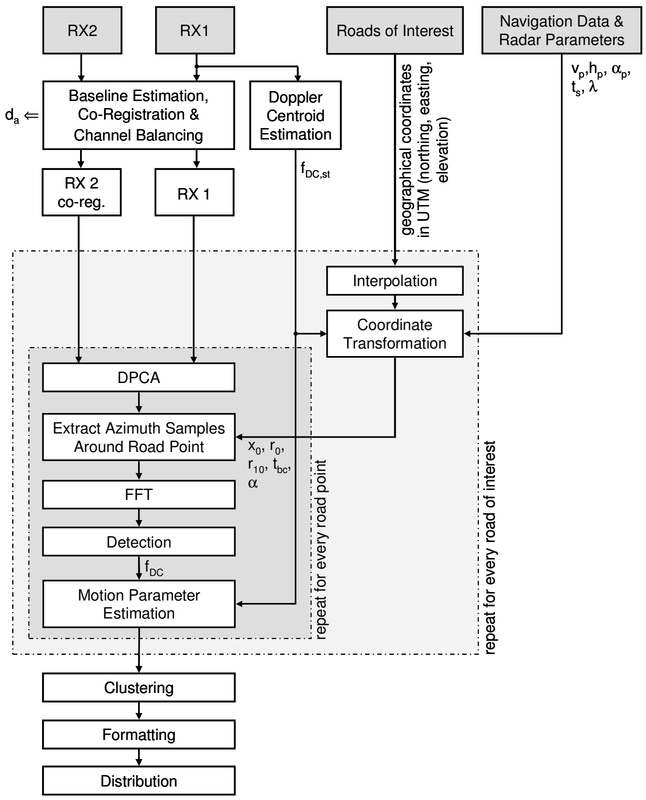

Figure 4 Simplified flow chart of the proposed GMTI algorithm for a dual-channel SAR system.

Experimental Data

In 2007 several GMTI experiments have been performed using DLR's new multi-channel and multi-frequency F-SAR system [1]. As test sites the former military airfield in Memmingen and a region around the Chiemsee, both located in Germany, have been used. F-SAR has been operated in X-band with a range bandwidth of 100 MHz in a dual-channel as well as in a switched four-channel mode with effective PRFs of 5 and 2.5 kHz [3]. Some of the controlled ground moving targets were equipped with GPS to gain geographical reference positions and velocities for the GMTI algorithm verification. Additionally, simultaneously with the radar also optical images from the same scene were taken to gain also knowledge about other road vehicles.

In Figure 5 the obtained dual-channel GMTI results from a data take acquired over the Memmingen airfield are shown. During that data take all controlled vehicles have moved in across-track direction. The estimated velocities of the vehicles are: 8.6, 84.2, 14.2 and 42.7 km/h. Compared to the optical reference data the velocity estimation errors are: -1.5, 3.5, -1.8 and -1.3 km/h. The corresponding position errors are: 17.9, 9.9, 17.3 and 16.5 m. The runway in Memmingen is about 30 m broad and as road axis for the coordinate transform the middle of the runway was chosen, but during the experiment the vehicles have moved on the edge. This fact explains a position estimation error in the order of 15 m. Furthermore, the accuracy of the optical reference data itself is also limited to about ±3.5 km/h velocity accuracy and to ±5 to ±15 m absolute position accuracy. Under this aspect, the obtained accuracy of the GMTI processor is quite good.

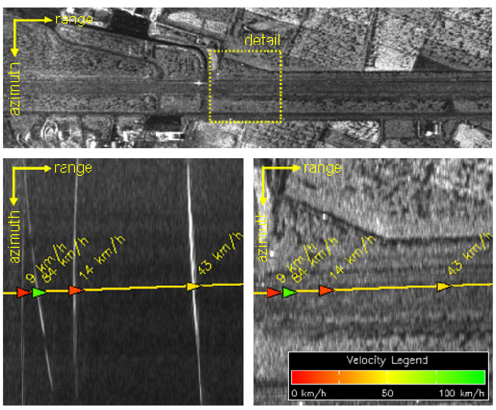

Figure 5 SAR image (data take rc07trmrad0101x1) of Memmingen airfield (top), range-compressed DPCA image of the "detail" with overlaid runway axis and detected vehicles as triangles (bottom left) and corresponding SAR image (bottom right).

For smaller road angles α the performance of the algorithm decreases. In Figure 6 the GMTI results for the runway lying in an angle of $\alpha = 45°$ to the flight path are shown. The Doppler centroid was with 491 Hz (4.8° squint angle) quite large. Compared to the optical reference the largest velocity error is 9.3 km/h and the largest position error 26.4 m. However, we

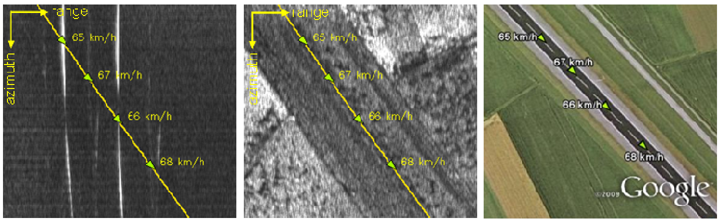

Figure 6 DPCA image of data take rc07trmrad0103x1 (left), corresponding SAR image (middle) and Google Earth image with overlaid moving vehicle symbols (right).

think that an error below 10 km/h is still good for many traffic monitoring applications.

In the automatic GMTI processing chain in the “Formatting” stage also KML files are produced, which easily can be visualized using Google Earth as shown in Figure 7. Here a preliminary GMTI result of a Chiemsee data take, where a lot of customary road vehicles have been detected on the autobahn A8, is visualized.

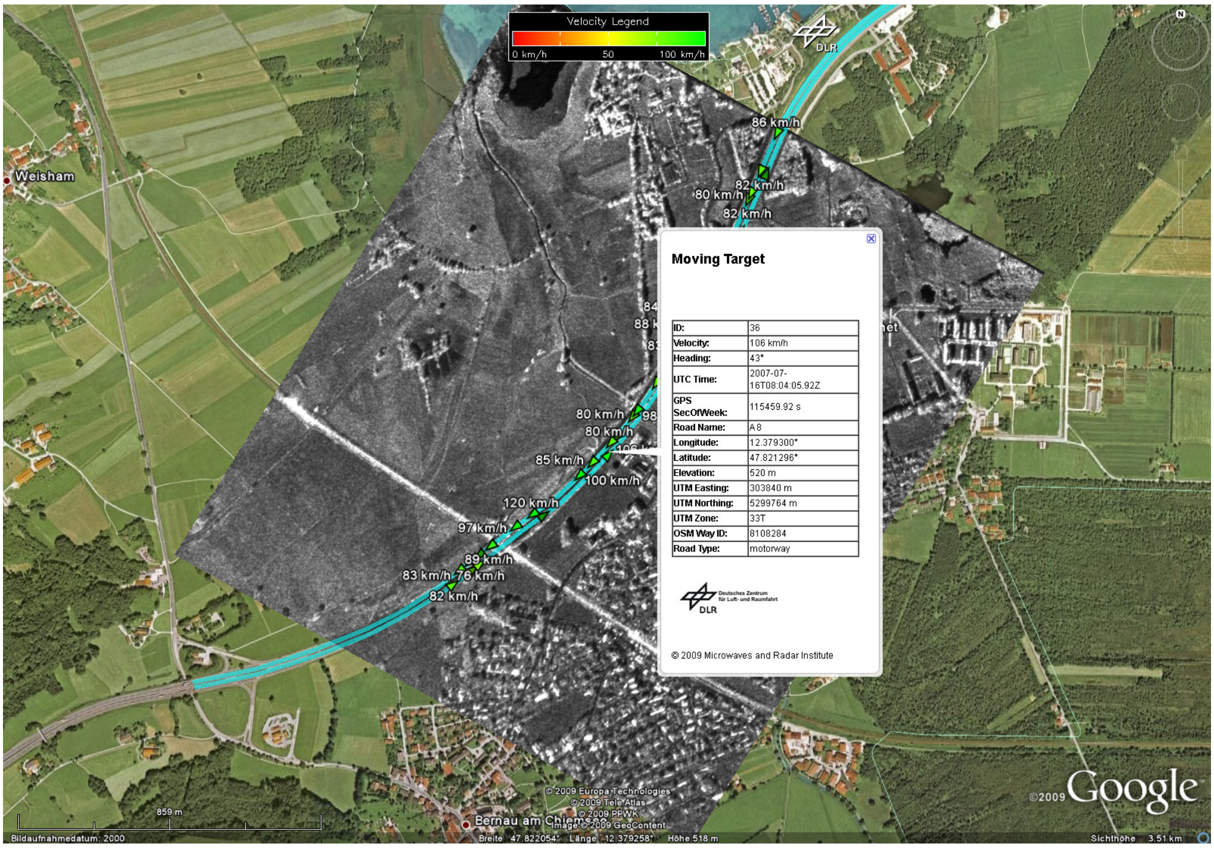

Figure 7 Google Earth image overlaid with a single-channel SAR image acquired with F-SAR (image not processed with full quality, image size 1.7 x 1.9 km, data take rc07trmrad0302x1). The shown vehicles (colour coded triangles) on the autobahn A8 near Chiemsee were automatically detected and their parameters were automatically estimated using the proposed GMTI algorithm (preliminary result).

Conclusion

A GMTI algorithm suitable for single- and multi-channel SAR data based on a priori knowledge was presented. The algorithm was verified using real dual-channel SAR data acquired with DLR’s F-SAR system. The obtained performance implies that the algorithm is applicable for real time traffic monitoring applications.

References

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