A Priori Knowledge Based GMTI Algorithm For Traffic Monitoring Applications

Stefan V. Baumgartner, Gerhard Krieger
Microwaves and Radar Institute, German Aerospace Center (DLR)
Münchner Strasse 20, 82234 Wessling, GERMANY, Email: stefan.baumgartner@dlr.de

Abstract

In the paper a ground moving target indication and parameter estimation algorithm applicable on single- as well as on multi-channel airborne synthetic aperture radar data is presented. The algorithm is based on a priori knowledge and operates directly on range-compressed data. Only the intersection points of the moving vehicle signals with the a priori known road axes, which are mapped into the range-compressed data domain, are evaluated. The algorithm needs low computational power and, hence, it is suitable for real-time traffic monitoring applications. The absolute velocities, the headings and the geocoded positions of the detected moving vehicles can be estimated. A verification of the algorithm is done using real dual-channel data acquired with DLR's new airborne system F-SAR.

1 Introduction

Ground moving target indication (GMTI) techniques originated in the military field also can be used for civilian applications like traffic monitoring. 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. Anyway, for performing such an assignment a road database is required. Furthermore, it is not necessary to detect vehicles moving off-road. Thus, the system and GMTI algorithm complexity can be reduced significantly.

The algorithm described in the 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 of the vehicles, occurred due to conventional SAR focusing, for computing the across-track velocities [1]. The required 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).

Our proposed algorithm does not require SAR focusing, it operates on single- or multi-channel range-compressed SAR data. The geocoded position of each detected moving vehicle is directly obtained from the intersection of the road axis, which is mapped into the range-compressed SAR data array, with the moving vehicle signal. Motion parameter computation is done by estimating the Doppler frequency of the signal at the road intersection. Even with a single-channel SAR system for fast moving vehicles the parameters absolute velocity, heading and geocoded position can be estimated with high accuracy.

2 Algorithm

As a first step the a priori known road axis of interest is mapped into the range-compressed SAR data array. The required coordinate transformation, which is the heart of the whole algorithm, is done in such a way, that the geographical coordinates of each road point are transformed to corresponding beam center coordinates in the range/azimuth plane. The beam center position of a detected moving vehicle is then given by the intersection of the vehicle signal with the mapped road point (cf. Fig. 1).

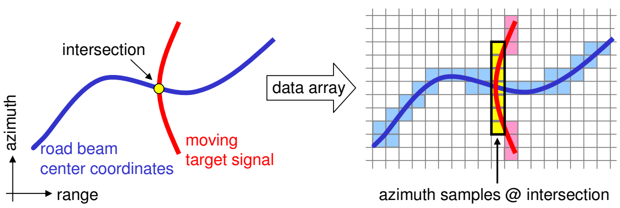

Figure 1: Principle of the proposed algorithm.

Owing to the mapping, the geographical coordinates of the road point and, hence, the geographical coordinates 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. Fig. 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 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. The proposed algorithm is well suited for airborne but not for spaceborne applications, since the detection performance suffers from low SNR.

2.1 Structure of the Algorithm

In Fig. 2 the flow chart of the proposed GMTI algorithm is shown exemplarily for a dual-channel system. RX1 and RX2 are the range-compressed images. Clutter suppression is performed using the displaced phase center antenna (DPCA) technique. The geographical coordinates of the roads of interest are obtained from a road database. Interpolation of these coordinates is necessary to avoid gaps in the range-compressed DPCA data array.

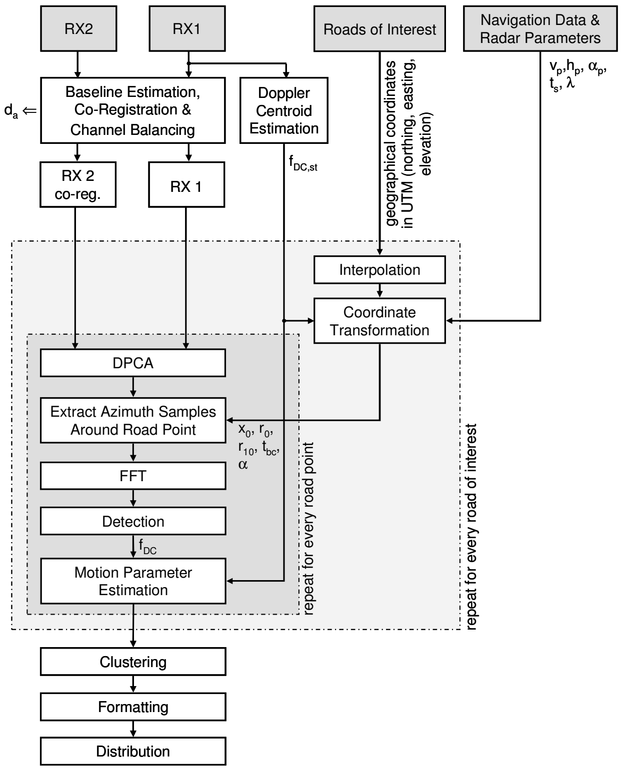

Figure 2: Simplified flow chart of the proposed GMTI algorithm for a dual-channel system.

Around each road point in the DPCA data array some azimuth samples are extracted and transformed into Doppler domain using the FFT. Each detected signal peak in Doppler domain corresponds to one potential moving vehicle. The parameter estimation procedure is explained in section 2.3. Before formatting and distributing the data e.g. to a traffic management institution, a clustering operation is performed, where multiple detections of one and the same vehicle are merged to only one physical vehicle. The whole algorithm sketched in Fig. 2 also can be used for single-channel systems by just omitting the stages "Baseline Estimation, ..." and "DPCA". With single-channel systems only fast moving vehicles are detectable, but for these fast vehicles all relevant motion and position parameters can be estimated. Furthermore, the algorithm also works with multiple channels and more sophisticated techniques like space-time adaptive processing (STAP) [2]. Multiple channels allow also for accurate direction-of-arrival estimation, so that false and ambiguous detections caused by strong stationary targets or by vehicles moving on adjacent roads, respectively, can be reduced.

2.2 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 Fig. 3. The x-axis is defined by the platform velocity vector $\vec{v}_p$, which is assumed to be constant.

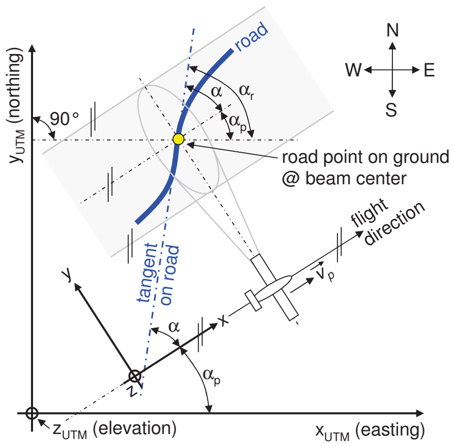

Figure 3: Relation between the global geographical UTM and the local Cartesian coordinate system.

A squinted geometry has to be considered, since in general it can not be ensured that the squint angle and, hence, the Doppler centroid of the clutter is negligibly small. In Fig. 4 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.

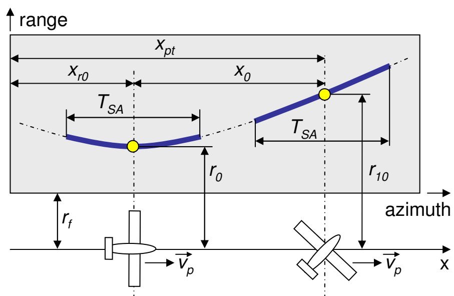

Figure 4: Range-compressed SAR data array containing a single road point in the non-squinted (left) and squinted (right) case. The beam center positions of the road point are marked with a yellow circle.

In Fig. 4 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. By decomposing the range vector $\vec{r}$ into a component parallel and into a component perpendicular to flight direction, the vectors $\vec{x}_{r0}$ and $\vec{r}_0$ are obtained

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

where t_s is the absolute start time of data acquisition, $\langle . \rangle$ is the inner product and $\|.\|$ is the L_2 norm. The vectors $\vec{v}_p$ and $\vec{r}$ can be computed using the known UTM coordinates of the stationary road point and the radar platform at any time instant. The minimum range r_0 is than given as

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

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

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

The azimuth offset x_0 can be computed as

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

where the squint angle ψ is given by

$$\psi = \arcsin\left(\frac{\lambda f_{DC,st}}{2 v_p}\right) = \arccos\left(\frac{r_0}{r_{10}}\right). \quad (5)$$

In previous equation λ is the radar wavelength and $f_{DC,st}$ is the Doppler centroid of the clutter, which can be estimated from the data of a single channel. Knowing the squint angle the beam center range can be computed

$$r_{10} = \frac{r_0}{\cos \psi}. \quad (6)$$

The beam center time of the road point is given as

$$t_{bc} = t_s + \frac{x_{pt}}{v_p}. \quad (7)$$

2.3 Motion Parameter Estimation

The motion equations of a vehicle moving at constant altitude h_v can be written as

$$x_v = x_{pt} + v_0(t - t_{bc}) \cos \alpha + \frac{1}{2} a (t - t_{bc})^2 \cos \alpha, \quad (8)$$

$$y_v = y_0 + v_0(t - t_{bc}) \sin \alpha + \frac{1}{2} a (t - t_{bc})^2 \sin \alpha, \quad (9)$$

where v_0 is the absolute velocity at beam center time t_{bc}, a is the constant acceleration and α is the road angle with respect to the x-axis (cf. Fig. 3). The across-track position of the target at $t = t_{bc}$ is denoted as y_0 and given as

$$y_0 = \sqrt{r_0^2 - \Delta h^2}, \quad (10)$$

where $\Delta h = h_v - h_p$ is the altitude difference between the moving vehicle and the radar platform. The distance from the transmit antenna to the target is then

$$r(t) = \sqrt{[x_v - x_{pt} + x_0 - v_p(t - t_{bc})]^2 + y_v^2 + \Delta h^2}. \quad (11)$$

After performing a second order Taylor expansion and some substitutions the range can be approximated as [3]

$$r(t) \cong r_{10} - \frac{\lambda}{2} f_{DC} (t - t_{bc}) - \frac{\lambda}{4} k_a (t - t_{bc})^2, \quad (12)$$

where f_{DC} is the total Doppler shift of the received signal due to squint and target motion and k_a is the Doppler slope. The Doppler shift f_{DC} can be estimated after transforming the azimuth samples around the road intersection point (cf. Fig. 1 right) into Doppler domain. The absolute beam center vehicle velocity can then be computed as

$$v_0 = \left| \frac{\lambda r_{10} (f_{DC,st} - f_{DC})}{2(x_0 \cos \alpha + y_0 \sin \alpha)} \right| = |v_{abs}|. \quad (13)$$

The heading of the vehicle is given by

$$\alpha_v = \begin{cases} \alpha & \text{if } \operatorname{sgn}(v_{abs}) = +1 \\ \alpha - 180° & \text{if } \operatorname{sgn}(v_{abs}) = -1 \end{cases}, \quad (14)$$

where $\operatorname{sgn}(.)$ is the signum function.

3 Experimental Data

In 2007 several GMTI experiments have been performed using DLR's new F-SAR system [4]. 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 in a dual-channel mode. Some of the controlled vehicles were equipped with GPS to gain geographical reference positions and velocities for the GMTI algorithm verification. Simultaneously with the radar optical images from the same scene were taken to gain also knowledge about other road vehicles.

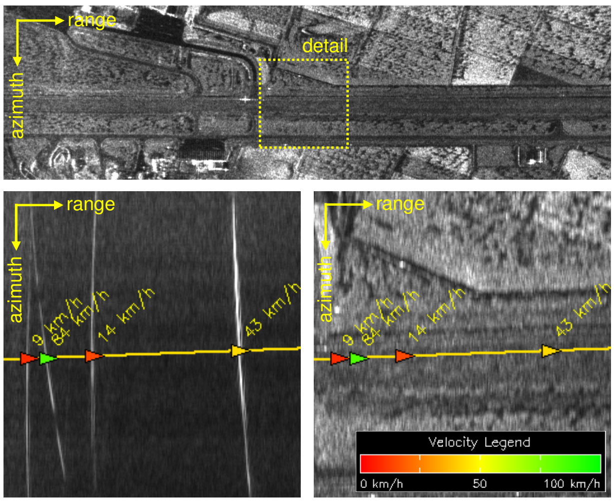

Figure 5: SAR image (data take rc07trmrad0101x1) of Memmingen airfield (top), range-compressed DPCA image of the "detail" with overlaid runway axis and detected moving vehicles as triangles (bottom left) and corresponding SAR image (bottom right).

In Fig. 5 the obtained GMTI results from a data take acquired over the Memmingen airfield are shown. All controlled vehicles have moved on the runway in across-track direction. The estimated velocities are 8.6, 84.2, 14.2 and 42.7 km/h (128 azimuth samples were used for parameter estimation). Compared to the optical reference data the velocity estimation errors are -1.5, 3.5, -1.8 and -1.3 km/h. The 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 transformation the middle of the runway was chosen, but during the experiment the vehicles have moved on the edge. Under this aspect, the estimation accuracy of the GMTI processor is quite good.
In the "Formatting" stage also KML files are produced, which easily can be visualized using Google Earth as shown in Fig. 6. 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.

4 Conclusions

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

References

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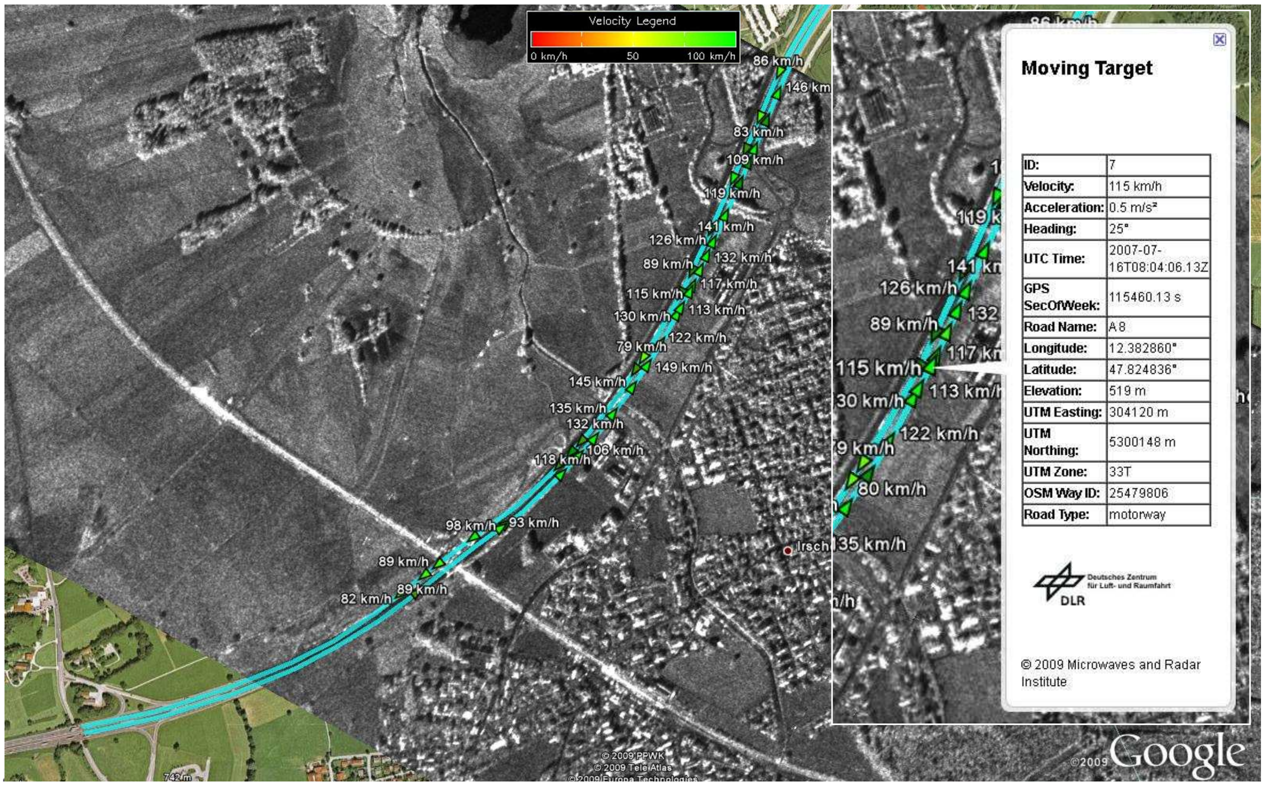

Figure 6: Google Earth image overlaid with a single-channel F-SAR image (image size approximately 2.0 x 2.8 km, data take rc07trmrad0302x1). The shown vehicles (colour coded triangles) on the autobahn A8 near Chiemsee were automatically detected and their parameters were automatically estimated using the proposed GMTI algorithm (preliminary result).