Novel post-Doppler STAP with a priori knowledge information for traffic monitoring applications

André B. C. da Silva, Stefan V. Baumgartner

Microwaves and Radar Institute, German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Correspondence to: André B. C. da Silva (andre.silva@dlr.de)

Abstract. This paper presents a novel a priori knowledge-based algorithm for traffic monitoring applications. The powerful post-Doppler space-time adaptive processing (PD STAP) is combined with a known road network obtained from the freely available OpenStreetMap (OSM) database. The road information is applied after the PD STAP for recognizing and rejecting the false detections, and moreover, for repositioning the vehicles detected in the vicinity of the roads. The algorithm presents great potential for real-time processing, decreased hardware complexity and low costs compared to state-of-the-art systems. The processor was tested using real data acquired by DLR's airborne system F-SAR. The experimental results are shown and discussed, and the novelties are highlighted (e.g., the benefits of using a priori knowledge information).

1 Introduction

The road traffic has worsened over time in most cities, and the methods employed for monitoring and counting the vehicles on the roads (e.g., cameras, induction loops, even people manually counting) are expensive and limited in spatial coverage. Synthetic aperture radars (SAR) are an effective solution due to the wide-area coverage and the independence from daylight and weather conditions (Moreira, 2013; Tomiyasu, 1978; Curlander and McDonough, 1991). Special attention is given in case of catastrophes, when mobile internet is unavailable and phone communication is impossible, as shown in Fig. 1. In this scenario, the traffic monitoring with real-time information ensures the safety of the road users and can even save lives.

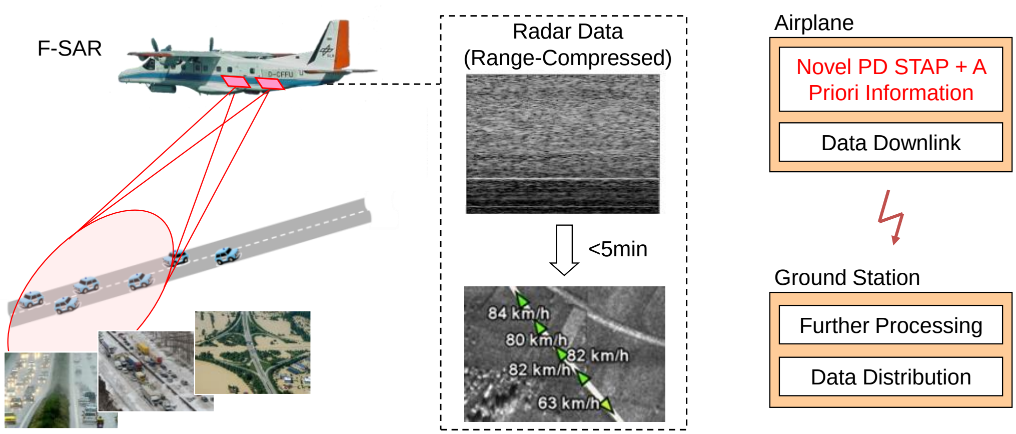

Figure 1: Real-time traffic monitoring in case of catastrophes using SAR and the proposed algorithm.

Numerous ground moving target indication (GMTI) algorithms have been developed for traffic monitoring applications (Cerutti-Maori et al. 2008; Gierull and Sikaneta, 2003). A fast dual-channel processor with a priori knowledge information is presented by Baumgartner and Krieger (2012a), where the position of the vehicle is obtained directly in the intersection between the range-compressed moving target signal and the road axes mapped into the data array. However, false detections are obtained due to signals coming from adjacent roads. In order to recognize and to discard these false detections, the PD STAP is suggested for estimating the direction-of-arrival (DOA) angles of the detections (Baumgartner and Krieger, 2012b). Thus, the algorithm presented in this paper combines the powerful PD STAP with a known road network obtained from the freely available OSM database (OpenStreetMap, 2009). The PD STAP was chosen due to its very good clutter suppression, its sensitivity also to low vehicle velocities, and its accurate target position estimation capabilities (Melvin, 2004; Guerci, 2014; Klemm, 1998). The incorporation of a known road network into the processing chain presents great potential for real-time processing, since only the acquired data related to the roads need to be processed. Thus, decreased processing hardware complexity and low costs compared to the state-of-the-art systems can be achieved. In addition, it is a promising solution for detecting effectively the road vehicles and estimating their positions, velocities and moving directions with high accuracy.

2 Signal Processing Algorithm

The simplified flowchart of the proposed GMTI algorithm is shown in Fig. 2. The processor operates directly on range-compressed data. After data calibration, the training data are selected in order to estimate the clutter covariance matrix, used by the PD STAP for clutter suppression. The PD STAP is well-known (Cerutti-Maori et al. 2010; Ender, 1999) and is used for estimating the range velocity and the position of the target. The detections are transformed into the Universal Transverse Mercator (UTM) coordinate system, used by the post-detection module. The OSM database provides the angle and the position of each road point. The roads of interest are selected for each coherent processing interval (CPI) and an interpolation is carried out to fill possible gaps between the road points. The road angle is used to compute the velocity of the target on the road, according to: $v_t = v_{gr}/\sin(\alpha)$, $\alpha = \alpha_r - \alpha_p$, where v_{gr} is the ground range velocity of the target (estimated by the PD

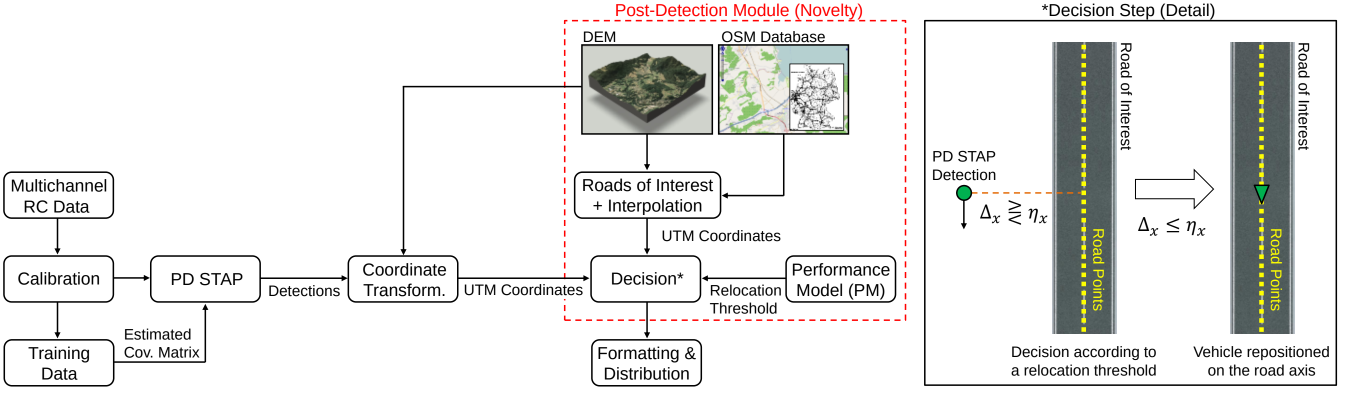

Figure 2: Simplified flowchart of the proposed GMTI algorithm (left) and detail of the decision step (right).

STAP), α_r and α_p are the road angle and the platform heading angle with respect to the UTM easting axis, respectively.

In the decision step (cf. Fig. 2 right), the distance Δ_x between the estimated position of the target and its closest road point is measured and compared to a relocation threshold η_x in order to decide whether the target corresponds to a true road vehicle or to a false detection. If the first condition is fulfilled, the target is repositioned to the closest road point; otherwise it is discarded. The relocation threshold is computed adaptively for each detection by using an appropriate performance model (cf. Section 3). Finally, the data are formatted and distributed, e.g., to the traffic management center.

Other two promising solutions are currently under investigation for combining the PD STAP with a road network:

1. Use the algorithm from Baumgartner and Krieger (2012a) and estimate the DOA of the detections using the PD STAP;
2. Extend the algorithm from Baumgartner and Krieger (2012a) using more than one aspect angle for mapping the road into the range compressed data array.

The first solution has the advantage that real-time processing is feasible without the need for high computational power. However, since only one aspect angle is considered the probability of detection may suffer. The second solution might be the best compromise between the probability of detection and the computational time.

3 Performance Model

The PD STAP performance model uses the framework introduced in Ender et al. (2008) and the system parameters given in Baumgartner and Krieger (2012b). However, the signal-to-clutter plus noise ratio (SCNR) and the range velocity of each PD STAP detection is used as input parameters, so that an adaptive relocation threshold is computed. For instance, Fig. 3 shows the expected azimuth relocation error for one particular detection with a signal-to-noise ratio (SNR) of 25dB, where the maximum relocation error at the broadside direction is around 15 m (cf. Fig. 3 right). It has to be pointed out that this is an optimal case, since additional errors may arise (e.g., due to the pointing direction and the road axis uncertainty – in the order of 5-10 m for the OSM). These additional errors will be considered in the next version of the proposed algorithm.

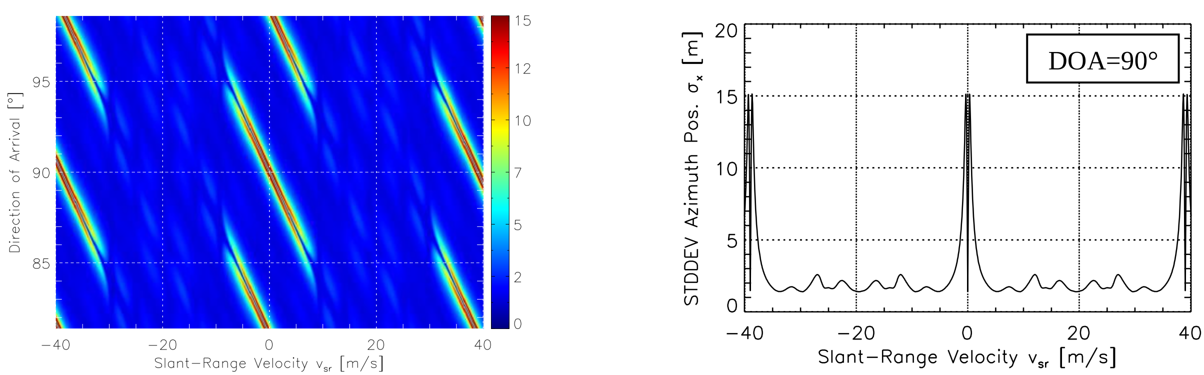

Figure 3: Standard deviation of the azimuth relocation error for one particular detection at the PD STAP output. Wide range of DOA angles (left); and a cut along the broadside direction (i.e., DOA=90°) (right).

4 Experimental Data

The proposed algorithm was tested using real 4-channel aperture switching data acquired by DLR's airborne system F-SAR. The flight campaign was conducted in February 2007 over the Allgäu airport in Memmingen, where five controlled cars were considered (Baumgartner et al., 2007). The velocities of the vehicles and the radar parameters are given in Baumgartner and Krieger (2012a). The data were processed using CPIs of 1024x128 range-Doppler samples, and the beamformers were applied using DOA angle steps of 0.1° within an interval determined by the azimuth antenna beam width.

The experimental results are shown in Fig. 4. The optical reference data (acquired simultaneously with the radar data) are shown at the top left, where the cars 1-4 move on the edges of the runway and Car 5 moves "off-road" in circle. The radar detections are shown at the bottom as a Google Earth overlay, and the center of the runway (yellow line) was considered as the road axis. The detections are shown before (circles) and after (triangles) using the road information, where the colors are related to the velocities of the cars. Moreover, the triangles point to the moving direction and the white lines connect the PD STAP detections to their closest road points (on the road axis). It has to be pointed out that, since the center of the runway is used as the road axis and the cars move on the edges, an offset of around 15 m is introduced (in real road data scenarios, the width of the conventional road lanes is in the order of 2.5 m and thus the offset to the road axis is much smaller). The detections of Car 4 are shown in detail at the top right. At the time instant 13:33:37.11 UTC the estimated velocity of Car 4 is 44.62 km/h, which agrees with the differential GPS reference data (Baumgartner and Krieger, 2012a); and its estimated position accuracy is better than 5 m, taking into account the road axis offset. To sum up, the PD STAP detected each car several times due to the small CPIs used. Car 5 was rejected after applying the road information because it moves "off-road".

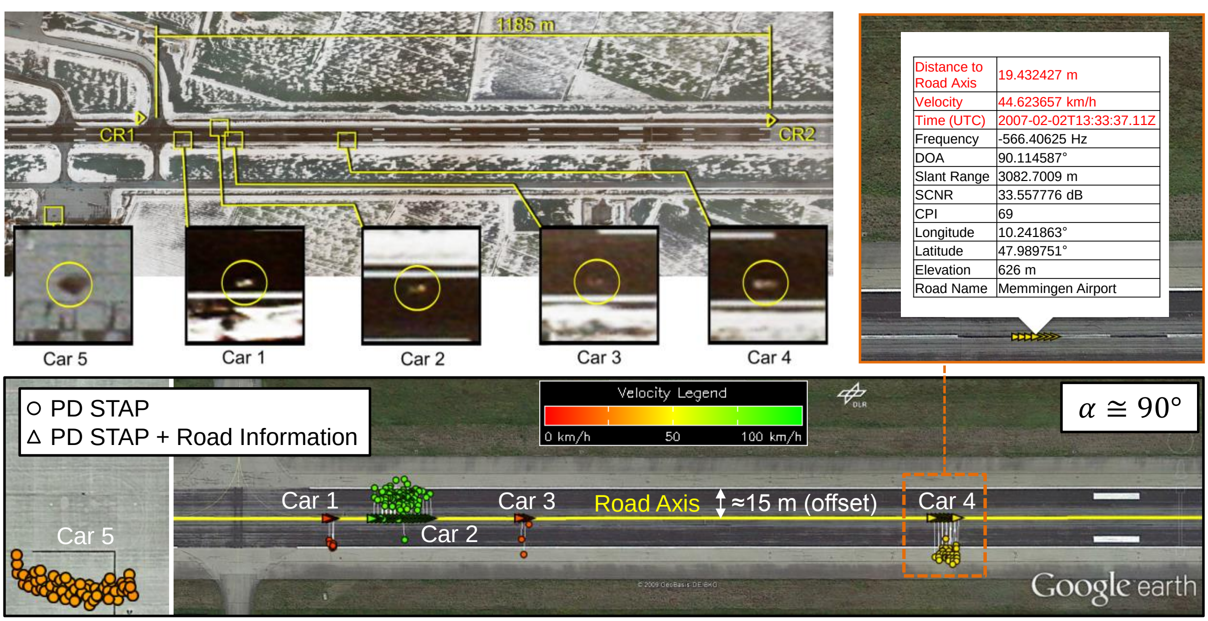

Figure 4: Flight campaign over the Allgäu airport in Memmingen. Optical reference data (top left); Google Earth images overlaid with radar detections before (circle) and after (triangle) using a priori knowledge information (bottom); detail of Car 4 showing the estimated parameters at the time instant 13:33:37.11 UTC (top right). The considered road axis is highlighted in yellow color.

Fig. 5 shows the velocity distribution of the detections shown in Fig. 4 (bottom) before using the road information (left) and afterwards (right), for $\eta_x = 20$ m. This comparison can only be done because the cars moved nearly in across-track direction (i.e., $\alpha \cong 90°$), and thus the estimated range velocities v_{gr} were nearly equal to the velocities on the road v_t. As a matter of fact, since most of the false detections were discarded (i.e., detections that lied farther than 20 m from the runway), the result is a clear histogram where the cars 1-4 can be easily identified (with a SCNR in the range of 20-35dB) (cf. Fig. 5 right).

The proposed algorithm was also tested using a data take containing real autobahn traffic scenario. The flight campaign was conducted in October 2013 over the Ammersee region. Fig. 6 shows the experimental result, where several road vehicles are detected on the highway and on residential roads. The considered roads from the OSM database are shown in white color.

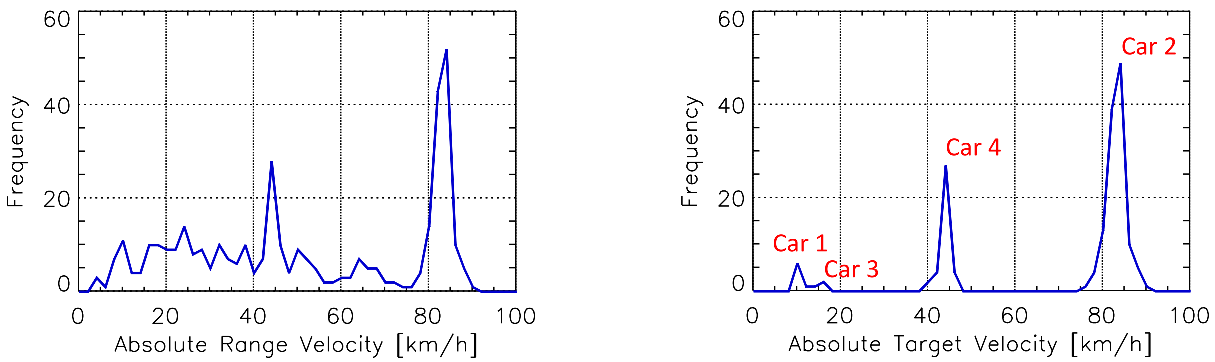

Figure 5: Velocity distribution of the detections from Fig. 4 (bottom). Absolute ground range velocity estimated by PD STAP (left); and absolute velocity on the road after using the road information (right).

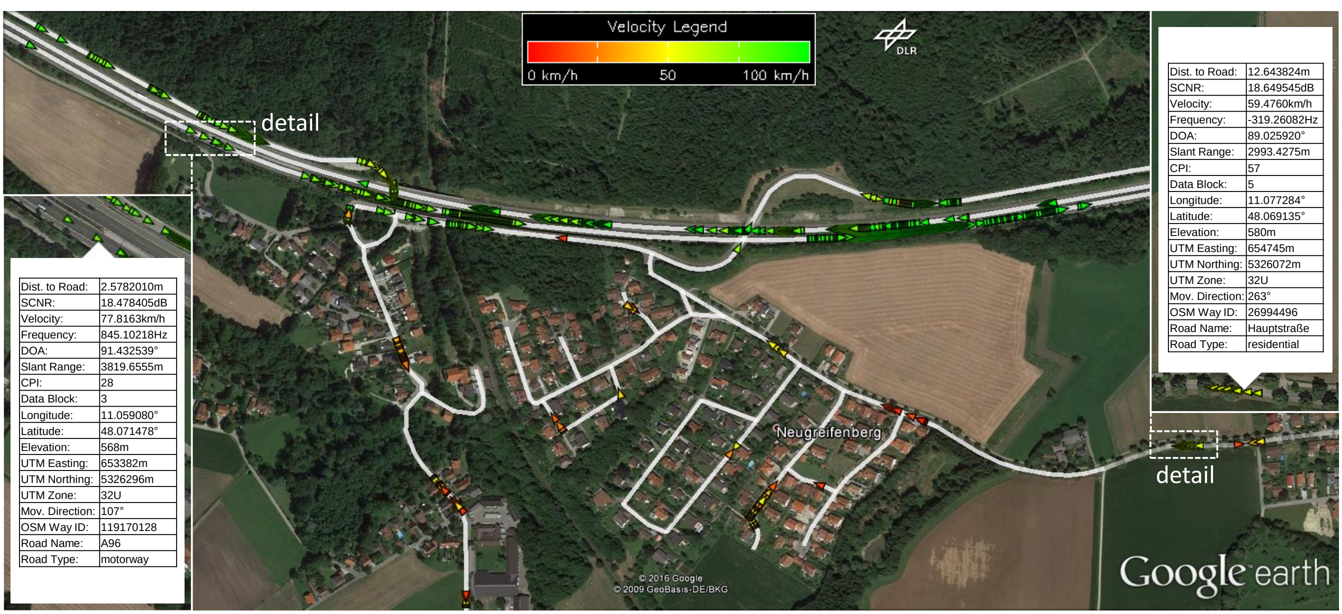

Figure 6: Flight campaign over the Ammersee region. Google Earth image overlaid with radar detections and their corresponding velocity estimations after using the road information. The cars (triangles) were automatically detected and their parameters were estimated using the proposed algorithm. The considered roads from the OSM database are highlighted in white color.

5 Conclusion

The experimental results revealed a powerful GMTI algorithm that detects even slow vehicles and discards most of the false detections, being suitable for many traffic monitoring applications. In the radar data takes examined so far, the PD STAP detected vehicles as slow as 7 km/h, with an overall position estimation accuracy better than 10 m. Besides, the estimated velocities of the vehicles were in very good agreement with the differential GPS reference data. For the a priori information module, a road point interpolation of 2 m was considered. Since several detections are obtained for each vehicle, a clustering and a tracking algorithms are currently under investigation to be incorporated in the next version of the proposed algorithm. We will not limit our further investigations to the data takes whose results are shown in this paper. We have a large pool of multi-channel F-SAR data takes containing real highway traffic scenarios with dozens or even hundreds of vehicles.

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