Traffic Monitoring with SAR: Implications of Target Acceleration

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Abstract

In this paper the problem of reliable along-track velocity estimation is addressed. It is known that the neglection of across-track accelerations can bias the estimates of along-track velocities, but up to now it is unknown which vehicle accelerations appear in real traffic scenarios. On this account an experiment to measure accelerations was conducted. The measurement results, which are presented and discussed in this paper, imply that accelerations must not be neglected in the along-track velocity estimation step if accurate estimates are required. Finally, some basic ideas are given which enable a reliable separation of along-track velocity and across-track acceleration and so improve the estimation accuracy.

1 Introduction

In recent years many powerful techniques and algorithms have been developed to detect moving targets and to estimate their motion parameters from single- or two-channel SAR data. Most of these algorithms rely more or less on the analysis of the Doppler history of the moving target signal. It is known that the Doppler shift relates mainly to moving target's across-track velocity and the Doppler slope to the along-track velocity as well as to the across-track acceleration. However, in most of the existing algorithms the along-track velocity is calculated by using the estimated Doppler slope under the implicit assumption that the across-track acceleration is very small and therefore negligible.

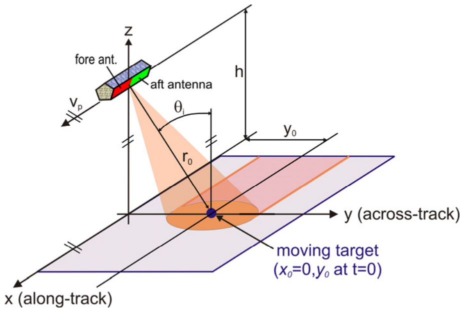

Figure 1 Two-channel side-looking radar geometry.

In [1] it is shown that even small across-track accelerations can bias the along-track velocity estimation. Since we want to monitor complex traffic scenarios with a future traffic monitoring system like TRAMRAD [2], we must know with which vehicle accelerations we have to deal in reality and with which estimation errors we have to cope with if these accelerations are neglected. For this reason an experiment to measure accelerations of a common passenger car during rush hour traffic was conducted. Before we present and discuss the acceleration measurement results, we will recapitulate the problem of reliable along-track velocity estimation.

2 Along-Track Velocity Estimation Error

For the following investigations the Cartesian radar geometry shown in Figure 1 is considered. The instantaneous motion parameters of the moving point target at broadside time $t = 0$, where the target is located at ($x = 0$, $y = y_0$, $z = 0$), are: along-track velocity v_{x0}, across-track velocity v_{y0}, along-track acceleration a_{x0} and across-track acceleration a_{y0}. The target doesn't move in z-direction.

Assuming that nowadays it is principally possible to estimate the across-track velocity v_{y0} of a moving vehicle and additionally the Doppler slope k_a of the corresponding signal with high accuracy, there still remains the problem of reliable along-track velocity estimation. Following the derivation in [1] and also ignoring across-track acceleration and velocity, the along-track velocity can be computed by exploiting the estimated Doppler slope $\hat{k}_a$ in the following way:

$$\hat{v}_{x0} = v_p - \sqrt{-\frac{1}{2}\hat{k}_a \lambda r_0}, \qquad (1)$$

where v_p is the SAR platform velocity in along-track direction, λ the wavelength of the carrier frequency and r_0 the distance to the target at broadside time $t = 0$. Under the assumption that the Doppler slope can be estimated exactly (i.e. $\hat{k}_a \equiv k_a$) equation (1) can also be written as:

$$\hat{v}_{x0} = v_p - \sqrt{\left(v_{x0} - v_p\right)^2 + v_{y0}^{\;2}\left(1 - \frac{y_0^{\;2}}{r_0^{\;2}}\right) + y_0\, a_{y0}}\,. \qquad (2)$$

The along-track velocity error or bias, respectively, is then given by:

$$\Delta v_{x0} = \hat{v}_{x0} - v_{x0}. \qquad (3)$$

It can be shown that for SAR systems where $v_p >> v_{x0}$ and $v_p >> v_{y0}$ the following simple approximation describing the along-track velocity estimation error can be used (we also have verified this equation by using a ground moving target SAR simulator developed at DLR's Microwaves and Radar Institute):

$$\Delta v_{x0} \cong -\frac{y_0}{2\,v_p} a_{y0} = -\frac{r_0 \sin\theta_i}{2\,v_p} a_{y0}, \qquad (4)$$

where θ_i is the incidence angle.

Considering a SAR system operating in low-earth-orbit (LEO, Cartesian geometry shown in Figure 1 assumed) with v_p = 7300 m/s and y_0 = 514 km, an across-track acceleration of 0.25 m/s² causes an along-track velocity estimation error of about -32 km/h (Figure 2). Such high along-track velocity estimation errors are not tolerable for traffic monitoring systems.

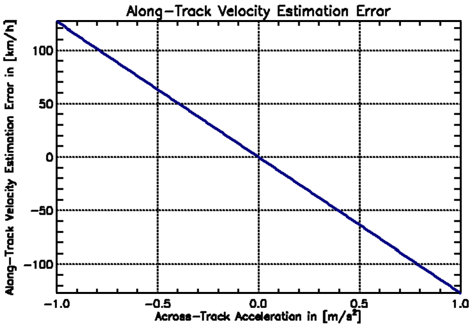

Figure 2 Along-track velocity estimation error as a function of moving target's unconsidered across-track acceleration (v_p = 7300 m/s, y_0 = 514 km).

3 Acceleration and Vibration Measurements

From data sheets of common passenger cars it is known that maximum reachable average accelerations (to accelerate from 0 to 100 km/h) lie somehow between 1.7 and 3.5 m/s². Extreme values of decelerations are strongly dependent on road conditions. They reach from about 1.0 m/s² (black ice) to 7.5 m/s² (dry asphalt). However, the just mentioned values are extreme values which are rare in reality.

To find out which vehicle accelerations we have to handle in complex traffic scenarios generally, an experiment to measure accelerations was conducted in cooperation with the DLR Institute of Transport Research in Berlin in July 2005. For measuring the acceleration components in all three spatial dimensions a common passenger car has been equipped with a calibrated inertial measurement system (IMU) and DGPS. The acceleration measurement sensors were bound up with the car body under the front passenger seat. Data were acquired half an hour long with a sampling frequency of 200 Hz. The measurement route led along a major road and an autobahn during afternoon rush-hour traffic. In the next two subsections the evaluation of the acceleration measurement results, which we have divided into the two parts "Acceleration Statistics" and "Temporal Behaviour and Vibrations", will be presented.

3.1 Acceleration Statistics

For the data evaluation presented in this section the moving average filtered measurement values were used (filter window width w was set to 11 samples or 0.055 s, respectively). The histogram of the passenger car accelerations is shown in Figure 3.

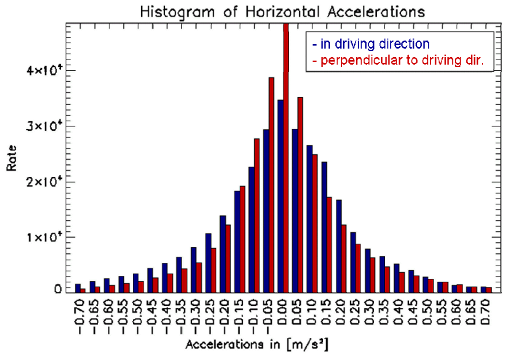

Figure 3 Histogram of measured horizontal accelerations.

Considering the whole dataset, the determined standard deviation of the acceleration component in driving direction was 0.45 m/s² and perpendicular to driving direction 0.61 m/s² (see also Table 1 where v_{car} is the vehicle velocity, $a_{x,car}$ the acceleration in driving direction, $a_{y,car}$ the acceleration perpendicular to driving direction and $a_{z,car}$ the vertical acceleration).

Whole dataset		min.	max.	mean	std. dev.
	v_{car}	0.00	115.31	66.56	26.79
	$a_{x,car}$	-4.59	3.75	0.01	0.45
	$a_{y,car}$	-3.11	5.21	0.07	0.61
	$a_{z,car}$	-5.55	6.18	-0.01	0.37

Table 1 Statistical values of whole dataset. The units are [km/h] for velocities and [m/s²] for accelerations.

Alone the magnitudes of the standard deviations and hence the large expected along-track velocity estimation error imply that across-track accelerations must not be neglected in the along-track velocity estimation step. The minimum and maximum values of the measured accelerations are of less interest since their occurrence in the measurement data is temporally limited. For a more detailed analysis we have picked out some regions of interest from the dataset:

- Region 1: Acceleration from 0 to 100 km/h.
- Region 2: Deceleration from 100 to 48 km/h.
- Region 3: Vehicle moves with nearly constant velocity along an autobahn construction site.

Statistical values regarding these regions can be found in Table 2. Even in region 3, where the vehicle has moved with nearly constant velocity, acceleration standard deviations in and perpendicular to the driving direction of 0.11 and 0.08 m/s² were determined.

		min.	max.	mean	std. dev.
Region 1	v_{car}	0.11	100.58	66.73	29.33
	$a_{x,car}$	-1.35	2.44	0.68	0.61
	$a_{y,car}$	-0.84	4.08	0.32	0.89
	$a_{z,car}$	-2.44	4.13	-0.01	0.42
Region 2	v_{car}	48.26	100.08	83.81	12.98
	$a_{x,car}$	-1.41	0.38	-0.27	0.28
	$a_{y,car}$	-0.78	1.83	0.34	0.58
	$a_{z,car}$	-2.60	2.22	-0.02	0.43
Region 3	v_{car}	53.32	56.21	54.65	0.84
	$a_{x,car}$	-0.27	0.31	0.01	0.11
	$a_{y,car}$	-0.38	0.29	0.01	0.08
	$a_{z,car}$	-1.21	0.99	0.00	0.19

Table 2 Statistical values of selected regions. The same units as in Table 1 are used.

Vertical accelerations occur mainly due to car body vibrations. Their impact on SAR imagery will be investigated in the next section.

3.2 Temporal Behaviour and Vibrations

Depending on the synthetic aperture time temporal motion parameter changes can influence the impulse response and furthermore the accuracy of different parameter estimators.

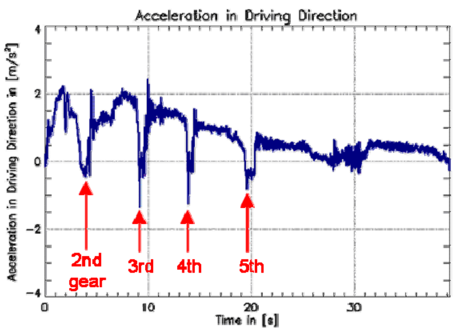

Figure 4 Measured accelerations in driving direction of region 1 (moving average filtered with $w = 11$).

In Figure 4 the measured accelerations in driving direction of region 1 are shown. The points in time where the driver changes the gear can clearly be identified. At every time point where the gear is changed the driving force drops to zero and the vehicle decelerates slightly due to friction, air resistance and so on.

The occurrence of significant accelerations perpendicular to driving direction (radial accelerations) is shown in Figure 5. The instantaneous velocity of the car where the maximal acceleration has occurred was about 30 km/h. A later change of the lane on a straight road section has led to radial accelerations of about ± 0.5 m/s² (the velocity of the car in this case was 80 km/h).

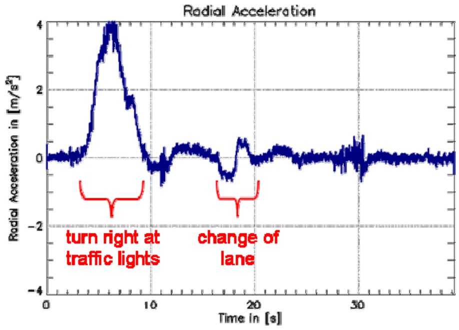

Figure 5 Measured radial accelerations of region 1.

Considering the whole dataset, the measured accelerations in driving direction and the radial accelerations generally changes only slowly with time, apart from some particular extreme cases as e.g. the gear switching shown in Figure 4. High accelerations in the order of 4 m/s² are rare in reality. Nevertheless, we recommend that at least accelerations in the order of the measured standard deviations should be considered in the along-track velocity estimation steps.

We assume that the main part of the reflected signal energy comes from the car body and from the road surface due to double bounce [2]. From the field of vehicle dynamics it is known that the eigen frequencies of the car body of a typical passenger car along the vertical axis lie between 0.7 and 2 Hz [3]. Indeed, significant vibration frequencies in the range from 1 to 2 Hz were observable in the spectrogram of the measured vertical accelerations. The vibration amplitudes or car body deflections, respectively, depend mainly on the road unevenness. For example a road declared as "bad road" can have average road unevenness amplitudes of up to 2.5 centimetres [3]. The largest measured car body deflection during the measurement drive was about 3 centimetres, where the vehicle has probably hit a chuckhole.

To investigate the influence of vibrating point targets on SAR imagery simulations have been performed. Harmonic point target vibrations along the vertical axis were modelled by using for the z-coordinate of the target the following time dependent expression:

$$z = z(t) = A_z \cos(2\pi f_z t + \varphi_z), \qquad (5)$$

where A_z is the peak amplitude of the vibration, f_z the frequency and φ_z an initial phase shift. In Figure 6 the simulated impulse responses of a vibrating point target with low frequency are shown. Especially at short integration times (e.g. at LEO systems) the shape of the impulse response is also influenced by the initial phase φ_z since here the integration time is in the order of the vibration period.

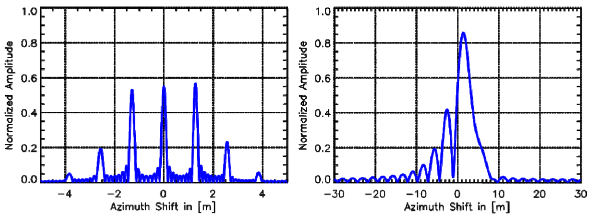

Figure 6 Impulse responses of a vibrating point target with f_z = 1.5 Hz, A_z = 5 mm and φ_z = -90° (left: airborne system, integration time T_{SA} = 5.7 s; right: LEO system, T_{SA} = 0.64 s).

Beside the low frequencies of up to 2 Hz in the original (not filtered) dataset also frequencies in the order of 10 Hz and 30 Hz were measured, but only with negligible small amplitudes (from the physical point of view at high frequencies only small deflections of the car body can occur due to inertia). These frequencies can be assigned to wheel vibrations [3], to engine vibrations and to the internal control loop of the IMU. However, such high frequencies in combination with the small amplitudes have no significant influence on target's impulse response. Although the influence on SAR imagery of vibrating point targets with low frequency clearly can be observed in the simulation results, these results cannot be transferred par to par to real vibrating vehicles, since no double bounce effects were simulated and since real vehicles are assumed to be not point like [2]. Further investigations and measurements are necessary before clear statements regarding vibrations of real vehicles can be made. Vibrations could potentially be exploited to gather information about road conditions.

4 Reliable Along-Track Velocity Estimation

The easiest way to separate across-track acceleration and along-track velocity, if no tracking should be performed, is the additional use of a road database. Once the across-track velocity and the azimuth displacement Δx of the vehicle have been estimated, the vehicle can be assigned to a certain road, whereas the road direction α can be gained from a road database (Figure 7, left part).

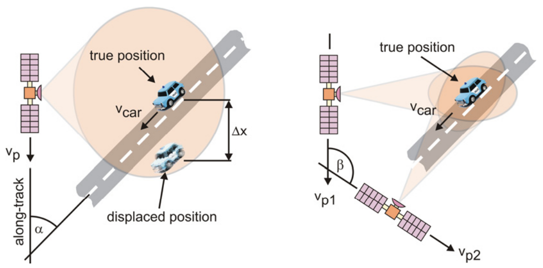

Figure 7 Possible configurations for resolving both ground velocity components of a moving vehicle (left: two- or multi-channel system integrated on a single platform; right: multi-static system).

With the knowledge of the across-track velocity and the angle α the along-track velocity can be computed. The Doppler slope information now can be used for focusing the moving vehicle as well as for computing the across-track acceleration. However, the accuracy of the along-track velocity estimate depends strongly on the accuracy of the across-track velocity and on the magnitude of α. Nevertheless, this method is inexpensive since no additional hardware is required and since for a traffic monitoring system anyhow a road database is necessary.

Another method allowing the estimation of the velocity vector is the use of a multi-static system as shown in the right part of Figure 7. The beams of two or more radar satellites can be steered to a region of interest. Each satellite sees the vehicle moving with a different "across-track velocity", thus estimation of the vehicle velocity vector becomes feasible. Furthermore the detection probability is increased in contrast to a single-satellite system since most likely at least one "across-track velocity" exceeds the minimum-detectable velocity limit. Also a highly squinted geometry can be used where two satellites fly in a tandem configuration with large distance from each other (i.e. the angle β in Figure 7 is increased to 180°).

5 Conclusions

The measurement results imply that acceleration standard deviations of up to 0.6 m/s² are not uncommon in real traffic scenarios. Using typical LEO systems even an unconsidered across-track acceleration of 0.25 m/s² leads to an along-track velocity estimation error of about -32 km/h. Having only a single- or two channel SAR system integrated on a single platform, additional information, e.g. from a road database, is needed to estimate the along-track velocity with high accuracy. The along-track velocity indeed is one important design driver for a radar based traffic monitoring system. Further investigations are necessary before such a system can be designed and realized.

References

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[3] M. Mitschke, "Dynamik der Kraftfahrzeuge - Band B: Schwingungen," 2. Auflage, Springer-Verlag, 1984.