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Traffic monitoring with spaceborne SAR—Theory, simulations, and experiments ☆

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Abstract

This paper reviews the theoretical background for upcoming dual-channel radar satellite missions to monitor traffic from space and exemplifies the potentials and limitations by real data. In general, objects that move during the illumination time of the radar will be imaged differently than stationary objects. If the assumptions incorporated in the focusing process of the synthetic aperture radar (SAR) principle are not met, a moving object will appear both displaced and blurred. To study the impact of these (and related) distortions in focused SAR images, the analytic relations between an arbitrarily moving point scatterer and its conjugate in the SAR image have been reviewed and adapted to dual-channel satellite specifications. Furthermore, a specific detection scheme is proposed that integrates complementary detection and velocity estimation algorithms with knowledge derived from external sources as, e.g., road databases. Results using real SAR data are presented to validate the theory.

Keywords: Vehicle detection; Velocity estimation; Spaceborne synthetic aperture radar; Along-track radar interferometry

1. Motivation

Increasing traffic appears to be one of the major problems in urban and sub-urban areas. Both components, the increase of transport safety and transport efficiency, as well as the reduction of air and noise pollution are the main tasks to solve in the future. Automated traffic monitoring has consequently evolved to an important research issue during the past years.

Nowadays, sensors like induction loops, bridge sensors and stationary cameras acquire the traffic flow on some main roads, while traffic on smaller roads, which represent the main part of road networks, is rarely collected. However, when gathering traffic information of the complete network, the drivers could be provided with much more valuable information like, for instance, precise estimates for the current travelling time for various routes from point "A" to point "B" in the road network. Hence, area-wide images of the entire road network are required to complement these selectively acquired data.

A number of approaches have recently been developed to automatically detecting vehicles or vehicle rows in optical satellite imagery—mainly pushed by the launch of the new 1-m class optical satellite systems as Ikonos and QuickBird (see e.g. Refs. in [1,2]). Traffic monitoring based on optical satellite systems, however, is only possible at daytime and cloud-free conditions, while spaceborne SAR (Synthetic Aperture Radar) systems are not affected by these limitations. Yet there are other difficulties inherent in the SAR imaging process that must be overcome to design a reasonably good approach for traffic monitoring using spaceborne radar.

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Table 1
Parameters of the TerraSAR-X satellite

Orbit height	h	515,000 m
Wavelength	λ	0.0311 m
Satellite velocity	v_{sat}	7600 m/s
Beam velocity on ground	v_{B}	7105 m/s
Range (@ 40°)	R_0	670,000 m
FM rate	FM	−5183 Hz/s
Processed Doppler bandwidth	PBW	3000 Hz
Processed synthetic aperture	T_{A}	0.5788 s
Pulse repetition frequency	PRF	4000 Hz
Ground sampling distance		1–3 m

Note. The distinction between v_{sat} and v_{B} can be usually neglected for airborne platforms. In the case of space-borne SAR both values differ significantly due to the curved orbit and the influence of the earth rotation.

In this paper, special emphasis is put on a thorough analysis and validation of the effects of moving objects in SAR images. Based on this, a detection strategy is derived that accommodates for the restrictions of *civilian* SAR satellite systems. To validate the theory, we use the sensor and orbit parameters of the upcoming TerraSAR-X mission (see Table 1). Its high resolution synthetic aperture radar sensor will operate in X-band and deliver images of 1–3 m resolution. The system allows to splitting-up the antenna into two parts on receive so that two high resolution SAR images of the same scene can be acquired within a small time frame.

This paper focuses on the *theory* of moving object detection in these images. It is thus the basis for the follow-on paper [3], where a comprehensive *performance analysis* for the adaption of the detection approach to TerraSAR-X can be found.

After a brief overview of related work in Section 2 we review the theoretical background of influences caused by moving objects in one- and dual-channel SAR images in Section 3. Then, Section 4 outlines theory and simulations of a detection and velocity estimation algorithm, that integrates (uncertain) a priori knowledge on location and movement of vehicles. Experiments and validations using real images are presented and discussed in Section 5 before concluding with an outlook in Section 6. 'Real' images have been acquired during flight campaigns in which the radar instrument has been parameterized such that the resulting data correspond approximately with the expected data of TerraSAR-X.

2. Background and related work

In military research the task of detecting moving vehicles with SAR sensors is well known as ground moving target indication (GMTI). GMTI approaches are commonly based on a SAR sensor with at least 3 channels and use space-time adaptive processing (STAP) for target detection, see e.g. [4–6] for more details. However, civilian spaceborne SAR systems with 3 or more channels are currently not available.

The upcoming TerraSAR-X mission as well as the Canadian RADARSAT-2 mission will be equipped with a single channel SAR that can be switched to an experimental mode with only 2 channels. These spaceborne SAR systems are thus by far not optimal for the task of traffic monitoring. Although some investigations are currently under way, whether a further splitting of 1 phased array antenna in 3 or more sub-antennas will support such kind of applications [7], this question cannot be answered clearly up to now. The benefit of reducing clutter by the use of 3 or more sub-antennas might be compensated by the loss of radiometric quality due to the worse signal-to-noise-ratio (SNR) caused by the smaller area of each sub-antenna.

The classical approach for detecting moving points in images of a two-channel system is the displaced phase center array (DPCA) method. When certain assumptions on the statistical distribution of the involved backscattered signals are met, DPCA can be shown to be the optimal detector for two-channel images [8]. While DPCA exploits primarily the phase information of the two images, along track interferometry (ATI) includes also the amplitude information. The issue of detecting moving targets using ATI is discussed, for instance, in [9,10]. In [11], special emphasis is put on the probability density functions associated with this detection, and the influence of vehicle acceleration is discussed in [12,13]. Traffic monitoring from space is quite rare so far. But as shown in [14–16] first endeavors have already been carried out.

Although civilian SAR systems are less specialized for moving object detection than military systems, there are other advantages that can be exploited. In contrast to military applications, civilian applications include more constraints regarding the objects to detect. In the traffic monitoring case, we can assume that vehicles travel on roads of a known road-network, which might not be true in military GMTI. Such knowledge provides a priori information that can be effectively used for detection. It is one of the objectives of this paper to develop a detection strategy that incorporates this kind of a priori information.

3. Moving objects in SAR images

We briefly review the SAR imaging process for stationary objects in Section 3.1, before deriving the theory for moving objects in SAR images in Section 3.2. Finally, Section 3.3 quantifies the theoretical findings for selected cases. We assume the SAR system operating in strip map mode for all the following derivations. The squint angle of the SAR system is assumed to be zero.

3.1. SAR image formation

Let the position of a radar transmitter on board a satellite be given by $P_{\mathrm{sat}}(t) = [x_{\mathrm{sat}}(t), y_{\mathrm{sat}}(t), z_{\mathrm{sat}}(t)]$ with x being the along-track direction, y the across-track ground range direction and z being the vertical. A point scatterer is assumed to be at position $P_{\mathrm{object}} = [x_{\mathrm{object}}(t), y_{\mathrm{object}}(t), z_{\mathrm{object}}(t)]$. The