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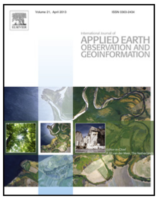

Detection of flooded urban areas in high resolution Synthetic Aperture Radar images using double scattering☆

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ABSTRACT

Flooding is a particular hazard in urban areas worldwide due to the increased risks to life and property in these regions. Synthetic Aperture Radar (SAR) sensors are often used to image flooding because of their all-weather day–night capability, and now possess sufficient resolution to image urban flooding. The flood extents extracted from the images may be used for flood relief management and improved urban flood inundation modelling.

A difficulty with using SAR for urban flood detection is that, due to its side-looking nature, substantial areas of urban ground surface may not be visible to the SAR due to radar layover and shadow caused by buildings and taller vegetation. This paper investigates whether urban flooding can be detected in layover regions (where flooding may not normally be apparent) using double scattering between the (possibly flooded) ground surface and the walls of adjacent buildings. The method estimates double scattering strengths using a SAR image in conjunction with a high resolution LiDAR (Light Detection and Ranging) height map of the urban area. A SAR simulator is applied to the LiDAR data to generate maps of layover and shadow, and estimate the positions of double scattering curves in the SAR image.

Observations of double scattering strengths were compared to the predictions from an electromagnetic scattering model, for both the case of a single image containing flooding, and a change detection case in which the flooded image was compared to an un-flooded image of the same area acquired with the same radar parameters. The method proved successful in detecting double scattering due to flooding in the single-image case, for which flooded double scattering curves were detected with 100% classification accuracy (albeit using a small sample set) and un-flooded curves with 91% classification accuracy. The same measures of success were achieved using change detection between flooded and un-flooded images. Depending on the particular flooding situation, the method could lead to improved detection of flooding in urban areas.

1. Introduction

Flooding is a major hazard in both rural and urban areas worldwide, but it is in urban areas that the risks to people and the economic impacts are most severe. In the UK, for example, over 2 million properties, the majority of them in urban areas, are located in floodplains. An estimated 200,000 of these properties are classified as at risk because they do not have protection against a 1 in 75 year flood event (Evans et al., 2004). This figure may rise further with climate change, especially as the observed increase in the intensity of heavy rainstorms with temperature rise is larger than that predicted (Allan and Soden, 2008).

Nowadays, imaging of flooding is carried out routinely using both satellite and airborne sensors. Synthetic Aperture Radar (SAR) sensors are preferred for flood detection rather than visible band sensors because of their ability to penetrate the cloud that is often present at times of flood, and to image at night-time as well as during the day. A number of active SARs with spatial resolutions as high as 3 m or better have recently been launched that are capable of detecting urban flooding. They include TerraSAR-X, RADARSAT-2 and the four satellites of the COSMO-SkyMed constellation. The latter is particularly useful because it allows image sequences of urban flooding to be built up with 12- or 24-hour revisit intervals. In the absence of significant wind, rain or turbulent surface currents, flooded urban areas generally appear dark in a SAR image

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due to specular reflection from the water surface. Roads and tarmac areas also exhibit low backscatter, though not as low as undisturbed water.

There are two main reasons why SARs are important for the detection of urban flooding. Firstly, the ability to obtain a synoptic overview of the extent of urban and rural flooding both day and night even if cloud is present could be a useful tool for operational flood relief management. The Pitt Report (2008) set out to consider what lessons could be learned from the UK floods of 2007. Among its many recommendations was the need to have real-time or near real-time flood visualisation tools available to enable emergency responders to react and manage fast-moving events, and to target their limited resources at the highest priority areas. It was felt that a simple GIS that could be updated with timings, water levels and extents of flooding during a flood event would be a useful system to keep the emergency services informed. Mason et al. (2012a) describe a prototype near real-time flood detection algorithm for urban and rural areas using high resolution SAR images. The method assumes that a processed multi-look geo-registered SAR image can be delivered to the user in near real-time. Whilst this is not yet possible for newer high resolution SARs such as TerraSAR-X and COSMO-SkyMed, the technology already exists in ESA's FAIRE system for medium resolution ASAR data (Cossu et al., 2009), and processed SAR images from the future Sentinel-1 mission are planned to be available one hour after image reception at the ground station.

Secondly, SAR data may be used as calibration, validation and assimilation data for urban flood inundation models. Such models are important tools for the prediction of risk from flooding in urban areas. They are hydraulic models that solve the shallow water equations at each node of a regular or irregular grid covering the river channel and floodplain, subject to boundary conditions that include the input flow rate to the domain (e.g. Bates et al., 2006). Flood modelling in urban areas is more complicated than in rural areas, as the interaction of flows with the built environment must be modelled. Surface flows are affected not only by ground topography and vegetation, but also by buildings and other man-made features (walls, roads, kerbs, parked vehicles, etc.) (Hunter et al., 2008). Subsurface flows in storm water drainage systems must also be modelled, and coupled with surface flows. Two-dimensional urban flood models need considerable data for their parameterisation. LiDAR data at sub-metre spatial resolution are used to provide highly resolved Digital Surface Models of the urban environment. The other main parameters are the bottom friction factors for the channel and floodplain, with the floodplain friction differing for different surface types (vegetation, roads, etc.). The calibration approach involves adjusting these parameters to minimise the difference between the SAR-observed and modelled flood extents (e.g. Aronica et al., 2002). In addition, assimilation may be used to correct the model state and improve estimates of the model parameters and external forcing. Distributed water levels may be estimated along the SAR flood extents by intersecting them with the floodplain topography, and the water levels at various points along the modelled reach may be assimilated into the model run (e.g. Giustarini et al., 2011; Garcia-Pintado et al., 2013; Mason et al., 2012b).

A difficulty of urban flood detection using SAR is that, due to its side-looking nature, substantial areas of urban ground surface may not be visible to the SAR due to radar shadowing and layover caused by buildings or taller vegetation. For example, Soergel et al. (2003) found that, in airborne SAR data of Karlsruhe, only one-third of the total road surface was visible to the SAR. This makes SAR less effective at detecting urban flooding than it might otherwise be. Consider the case of a road between two buildings as in Fig. 1, with the SAR azimuth direction normal to the paper. Ground (CD) will be in radar shadow as it is hidden from the radar by an adjacent intervening building. The shadowed area will appear dark, and may be misclassified as water even if it is dry. In contrast, an area of flooded ground (AB) in front of the wall of a building may be allocated to the same range bin as the wall, causing layover which generally results in a strong return, and a possible misclassification of flooded ground as un-flooded. Soergel et al. (2003) showed that an object on the road (Y) will only be sensed properly if a condition for the road width w_s holds:

$$w_s > CD + AB = h_2 \quad \tan\theta + h_1 \quad \cot\theta \tag{1}$$

where θ is viewing angle and h_1 and h_2 are building heights. Assuming $\theta = 20^\circ$ and $h_1 = h_2 = 10$ m, a road narrower than 30 m will thus be totally in shadow/layover.

This loss of visibility in flood detection has been quantified in a study by Mason et al. (2010) that used a TerraSAR-X image containing urban flooding together with contemporaneous aerial photography for validation of the TerraSAR-X result. This employed a SAR simulator in conjunction with a LiDAR Digital Surface Model (DSM) to estimate regions of the image in which water would not be visible due to shadow or layover caused by buildings and taller vegetation. Fig. 2 shows the LiDAR DSM of the Tewkesbury area, while Fig. 3 shows those parts of the image not visible to the SAR due to radar shadow and layover. The study found that 76% of the urban water pixels that were actually visible to TerraSAR-X were correctly detected. However, if all the urban water pixels

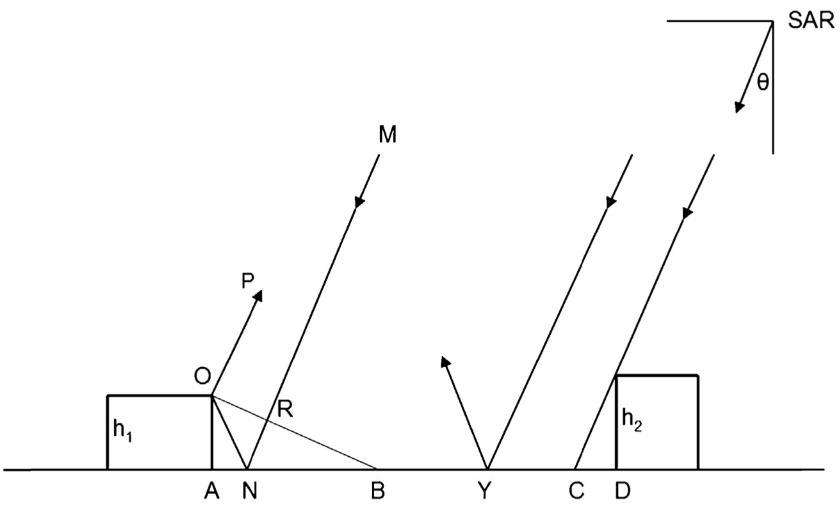

Fig. 1. Layover (AB) and shadow (CD) regions in a flooded street (AD) between adjacent buildings of height h_1 and h_2 (θ = incidence angle).