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Microwave remote sensing of flood inundation

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ABSTRACT

Flooding is one of the most costly natural disasters and thus mapping, modeling and forecasting flood events at various temporal and spatial scales is important for any flood risk mitigation plan, disaster relief services and the global (re-)insurance markets. Both computer models and observations (ground-based, airborne and Earth-orbiting) of flood processes and variables are of great value but the amount and quality of information available varies greatly with location, spatial scales and time. It is very well known that remote sensing of flooding, especially in the microwave region of the electromagnetic spectrum, can complement ground-based observations and be integrated with flood models to augment the amount of information available to end-users, decision-makers and scientists. This paper aims to provide a concise review of both the science and applications of microwave remote sensing of flood inundation, focusing mainly on synthetic aperture radar (SAR), in a variety of natural and man-made environments. Strengths and limitations are discussed and the paper will conclude with a brief account on perspectives and emerging technologies.

Contents

1. Introduction

1.1. Background

It is well known that flooding affects societies, economies, and ecosystems worldwide and at certain times and places can have devastating impacts. By 2050, worldwide annual losses due to flooding are predicted to reach US $1 trillion (Hallegatte et al., 2013; Schumann et al., 2014) for coastal cities. The current period is said to be flood-rich for some countries compared with past records (Lane, 2009), so having a data-rich environment in terms of flood inundation observations is rather necessary. Useful information about flood extent and inundated area can be obtained in the field with dGPS or other suitable equipment along the wrack marks of a flood or with remote sensing platforms, either airborne or space-borne.

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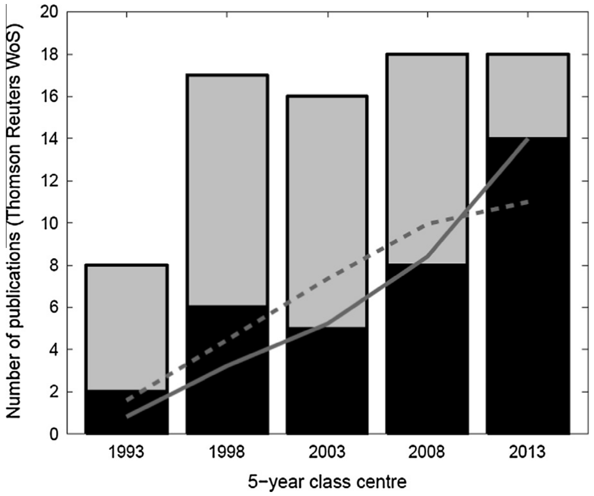

Fig. 1. Bar chart showing publishing trends of papers on flood detection from SAR imagery, split into conference proceedings (gray bars/dashed line) and full journal articles (black bars/solid line).

Deriving area and extent of permanent water bodies and flood inundation from remote sensing is generally more straightforward than deriving information about other variables in hydrology. Surface water area and associated change can be used in a variety of applications, ranging from simple mapping and monitoring of water bodies to more complex water quality assessments of lakes and reservoirs. Data on inundation area and extent are commonly used to assess the magnitude of a flood with the aim to support relief services and to calibrate and validate flood inundation (i.e. hydraulic) models. While the mapping of permanent water bodies may be done with most satellite imaging platforms at almost any time, obtaining the area and extent of a flood is rather opportunistic and certain conditions on both the Earth surface and atmosphere during an event (such as emergent flooded vegetation and persistent cloud cover) may restrict suitable data acquisition technology only to a few remote sensing instruments, such as microwave sensors. Moreover, given the rapid flood recession in small to medium sized catchments and weather conditions during events, flood detection is realistically only feasible with synthetic aperture radar (SAR) imagery.

The scientific literature of mapping surface water (i.e. detection of permanent water bodies and flooding) from SAR imagery is rapidly growing, and significantly so over the past decade (Fig. 1), which coincides more or less with recent launches of Earth-orbiting satellites carrying very high-resolution (<5 m pixels) SAR instruments (e.g. TerraSAR-X, COSMO-SkyMed, Radarsat-2, Sentinel-1).

1.2. Main principles of SAR remote sensing of surface water

Many SAR image-processing techniques exist to successfully derive flood area or extent, including simple visual interpretation (MacIntosh and Profeti, 1995; Oberstadler et al., 1995; Brivio et al., 2002), image histogram thresholding (e.g. Brivio et al., 2002; Matgen et al., 2004; Schumann et al., 2005), automatic classification algorithms (e.g. Hess et al., 1995; Bonn and Dixon, 2005), image texture algorithms (Schumann et al., 2005), multi-temporal change detection methods (e.g. Calabresi, 1995; Laugier et al., 1997), of which extensive reviews are provided in Liu et al. (2004) and Lu et al. (2004). Complex auto-logistic regression (Atkinson, 2000) and principal component analysis (Matgen et al., 2006) may also be applied. Image statistics-based active contour models have been used by Bates et al. (1997), Horritt (1999), De Roo et al. (1999), Horritt et al. (2001) and Schumann et al. (2005). Classification accuracies of flooded areas (most of the time defined as a ratio of the total area of interest where classification errors are omitted) vary considerably and only in rare cases do classification accuracies exceed 90 percent.

Image classification or interpretation errors (i.e. non-flooded areas mapped as flooded and vice versa) may arise from a variety of sources: inappropriate image processing algorithm, altered backscatter characteristics, unsuitable wavelength and/or polarizations, unsuccessful multiplicative noise (i.e. speckle) filtering, remaining geometric distortions, and inaccurate image geo-coding. Horritt et al. (2001) state that wind roughening and the effects of protruding vegetation, both of which may produce significant pulse returns, complicate the imaging of the water surface, although the effects of vegetation are probably easier to estimate (using land cover maps for instance) than wind effects. Moreover, due to the corner reflectors (i.e. where the structure of rectangular surfaces, e.g. buildings, is such that the wave is returned to the SAR antenna and thus causes complete sensor saturation resulting in white image pixels (Rees, 2001)) or dihedral corner reflectors (i.e. a corner reflector of two sides creating signal bounce) in conjunction with often inadequate spatial resolution, it is currently very challenging to extract flooding from urban areas, which for obvious reasons would be desirable when using remote sensing for flood management. However, it is worth noting that similar to using the double-bounce in flooded vegetation, some studies have used dihedral corner reflection to assist flood detection in urban areas (see Section 4).

The magnitude of the deteriorating effects in a SAR (flood) image is a function of wavelength, incidence angle and polarization. Incidence angle refers to the angulat deviation of the incident signal from nadir while polarization describes the direction at which materials reflect signals and SAR sensor receive these signals (Ulaby et al., 1982). Both these properties impact on the ability to discriminate features or conditions of the Earth's surface.

Despite their importance, only relatively few studies have looked in detail at sensitivities of polarization and incidence angle for mapping flooded surfaces, with the notable exception of Lang et al. (2008) and Manjusree et al. (2012). Manjusree et al. (2012) examined backscattering sensitivities for flood mapping from higher incidence angles (20–49°). Although they found that all polarization modes can be employed for flood mapping, there is better land–water surface discrimination in HH polarization (see also Henry et al. (2006)). They demonstrate that at near to far range, −8 to −12 dB, −15 to −24 dB, and −6 to −15 dB can be used as optimum ranges for the classification of flood water in HH, HV, and VV polarizations. Lang et al. (2008) examined the same range of incidence angle to determine sensitivities in C-band HH SAR backscatter from flooded and non-flooded forests. They found little differences in the ability to detect flooding between incidence angles and also little influence of leaf on or off conditions, possibly suggesting a better than expected all-year round use of SAR images for detecting flooding under forest canopy at high incidence angles.

Fig. 2 illustrates a schematic of the basic backscatter properties for the most commonly employed SAR bands during non-flooded and flooded conditions in a number of environments.

The following sections provide a concise review of flood inundation mapping from microwave imagery in a variety of environments, including river floodplains and coasts, wetlands and forest, as well as urban areas. The paper then concludes with an outlook section on perspectives and emerging technologies.

2. Mapping floodplain inundation and coastal shorelines

This section provides a general overview of progress in microwave remote sensing of floodplain inundation focussing primarily