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The use of radar satellite data from multiple incidence angles improves surface water mapping

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ABSTRACT

Satellite radar data has been employed extensively to monitor flood extents, where cloud cover often prohibits the use of satellite sensors operating at other wavelengths. Where total inundation occurs, a low backscatter return is expected due to the specular reflection of the radar signal on the water surface. However, wind-induced waves can cause a roughening of the water surface which results in a high return signal. Additionally, in arid regions, very dry sand absorbs microwave energy, resulting in low backscatter returns. Where such conditions occur adjacent to open water, this can make the separation of water and land problematic using radar. In the past, we have shown how this latter problem can be mitigated, by making use of the difference in the relationship between the incidence angle of the radar signal, and backscatter, over land and water. The mitigation of wind-induced effects, however, remains elusive. In this paper, we examine how the variability in radar backscatter with incidence angle may be used to differentiate water from land overcoming, to a large extent, both of the above problems.

We carry out regression over multiple sets of time series data, determined by a moving window encompassing consecutively-acquired Envisat ASAR Global Monitoring Mode data, to derive three surfaces for each data set: the slope β of a linear model fitting backscatter against local incidence angle; the backscatter normalised to 30° using the linear model coefficients (σ^0_{30}), and the ratio of the standard deviations of backscatter and local incidence angle over the window sample (SDR). The results are new time series data sets which are characterised by the moving window sample size.

A comparison of the three metrics shows SDR to provide the most robust means to segregate land from water by thresholding. From this resultant data set, using a single step water–land classification employing a simple (and consistent) threshold applied to SDR values, we produced monthly maps of total inundation of the variable south-western basin of the Aral Sea through 2011, with an average pixel accuracy of 94% (kappa = 0.75) when checked against MODIS-derived reference maps.

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1. Introduction

1.1. Mapping water using radar remote sensing

The mapping of water extents plays an important role across several fields. In recent years, much attention has been paid to the monitoring of wetland ecosystems, in which inundation patterns are formative in the study of biodiversity and greenhouse gas emissions (Aires, Papa, & Prigent, 2013; Bass et al., 2013; Bwangoy, Hansen, Roy, Grandi, & Justice, 2010; Dronova, Gong, & Wang, 2011; Haas, Bartholomé, Lambin, & Vanacker, 2011). Much research has turned to the use of radar remote sensing to map inundation (Arnesen et al., 2013; Frappart, Seyler, Martinez, León, & Cazenave, 2005; Gan, Zunic, Kuo, & Strobl, 2012; Hostache et al., 2009; Mason, Davenport, Neal, Schumann, & Bates, 2012; Schumann, Di Baldassarre, & Bates, 2009). Radar has several advantages over visual-infra red (VIR) data — being an active sensor system, it can acquire data independently from the position of the sun. Perhaps most importantly, radar can penetrate the cloud cover that prohibits, to varying degrees, the use of VIR data for continuous flood monitoring, or for timely production of flood maps for disaster response purposes. To take full advantage of radar data, much research has been concerned with the task of overcoming some difficulties in the interpretation of radar images. Flat, open water acts as a specular reflector of radar energy away from the sensor. For this reason, water under certain conditions is characterised by a low backscatter return. However, where structures such as vegetation, steep land forms and man-made features emerge through the surface of the water, multiple interactions between such structures and the surface of the water cause "double bounce" effects, which result in a very high return signal. Depending on the relative scale and density of these features with the pixel size of the data image, the result is either a mixed pixel mid-value aggregate of low and high backscatter returns, being hard to distinguish from dry land, or a very high backscatter value,

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which in turn can be very hard to distinguish from wet soil or vegetation. Consequently, some research has focussed on overcoming these effects, in terms of the optimal radar configuration (band, polarisation orientation, incidence angle, resolution, time series and data synergy) (Grings et al., 2009; Henderson & Lewis, 2008; Hess & Melack, 2003; Hess, Melack, Filoso, & Wang, 1995; Marti-Cardona, Lopez-Martinez, Dolz-Ripolles, & Bladè-Castellet, 2010; Martinez & Letoan, 2007; Quegan, Le Toan, Yu, Ribbes, & Floury, 2000; Ribbes, 1999). Another common problem with the identification of open water with radar data is caused by the waves induced on the surface of the water by winds over a particular speed. The phenomenon is the result of the roughened water surface reducing the proportion of energy reflected away from the sensor.

Research has identified the particular wind speeds and relative orientations that cause this effect, and the best radar configurations that may be used to minimise it (Liebe, van de Giesen, Andreini, Steenhuis, & Walter, 2009). However, the problem does persist, and in certain regions, can narrow the opportunity for water classification using radar data to an almost unusable level, as will be seen.

1.2. The use of multiple incidence angle, low spatial–high temporal-resolution radar data

Backscatter values over multitemporal time series of satellite radar data have been used as a tool to detect land use, by analysis of the variation of backscatter with respect to time, and to changes in, for example, plant phenology and biomass. Le Toan et al. (1997) model the interaction of C-band radar with rice and water at various stages of crop development, in order to monitor rice farming on a large spatial scale. Their research is extended by Ribbes (1999), who analyse observed backscatter values from RADARSAT against rice height, biomass and age, for the same purpose. Quegan et al. (2000) recognised the potential of using the relatively low temporal variability of backscatter values in forest compared with other land cover types as a forest segregation technique. Martinez and Letoan (2007) incorporated the temporal variation of L-band JERS-1 data into their classification technique when mapping flood patterns and vegetation in the Amazon floodplain. Their time series is used to increase the effective number of looks in the calculation of a mean backscatter coefficient, which is coupled with a temporal change estimate, derived over the time series, to classify flood conditions as *never*, *occasionally* and *always flooded*, together with broad vegetation types. Specific analysis of the comparative response of C-band radar to water at low and high incidence angles was made by Töyrä et al. (2001), who advise that at high incidence angles, wave-induced effects are overcome, and that at low angles, the return signal from water has similar values to those for dry land. For our purposes, it is this very quality that offers a potential means for better classification of water. The diffuse reflections from dry land at low incidence angles are not expected to reduce significantly at higher angles, and the low backscatter values returned from dry sand are not expected to increase significantly at lower angles, thus distinguishing both surface conditions from water. For this reason, a time series of radar data acquired at multiple incidence angles is desirable.

Some research has focussed on the advantages of the high temporal frequency of the systematically-acquired C-band radar data from the European Space Agency's (ESA) Advanced Synthetic Aperture Radar (ASAR) on the Envisat satellite, operating from March 2002 until April 2012, when full operation of the satellite was lost (Baup et al., 2007; Mladenova et al., 2010; O'Grady, Leblanc, & Gillieson, 2011; O'Grady, Leblanc, & Gillieson, 2013; Park et al., 2011). In ASAR's Global Monitoring (GM) mode, the sensor systematically acquired data at times when the other modes were not required, providing high repeat coverage ($\approx 0-4$ times per week) across much of the globe (O'Grady et al., 2011). The data covered the full orbit width across the whole swath of incidence angles (14–44°), with a pixel size of 500 m and a nominal spatial resolution of 1 km. Such a coarse spatial resolution obviously limits the scale of use to which GM data may be put. One application, as was originally envisaged by ESA, is the monitoring of sea ice (Zink et al., 2001). Others have drawn much information on

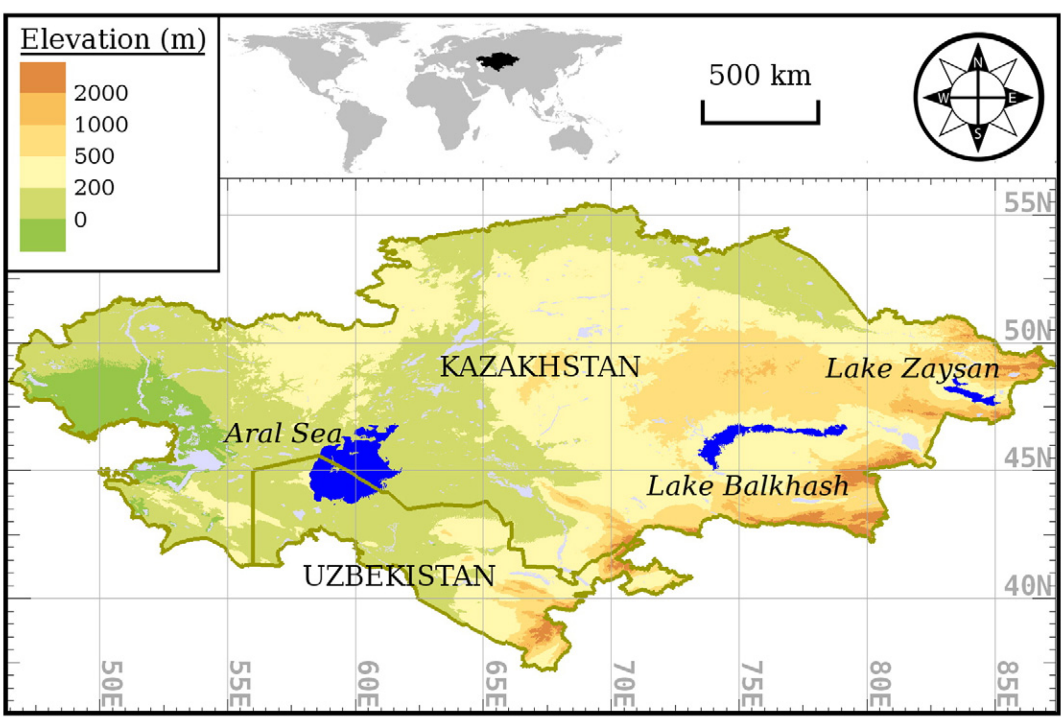

Fig. 1. Map of regions under study: the Aral Sea in Kazakhstan/Uzbekistan, and Lakes Balkhash and Zaysan in Kazakhstan. Map produced from an SRTM90 DEM downloaded from the Consortium for Spatial Information (Jarvis et al., 2008).

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