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Rice monitoring with multi-temporal and dual-polarimetric TerraSAR-X data

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ABSTRACT

This study assesses the use of TerraSAR-X data for monitoring rice cultivation in the Sanjiang Plain in Heilongjiang Province, Northeast China. The main objective is the understanding of the coherent co-polarized X-band backscattering signature of rice at different phenological stages in order to retrieve growth status.

For this, multi-temporal dual polarimetric TerraSAR-X High Resolution SpotLight data (HH/VV) as well as single polarized StripMap (VV) data were acquired over the test site. In conjunction with the satellite data acquisition, a ground truth field campaign was carried out.

The backscattering coefficients at HH and VV of the observed fields were extracted on the different dates and analysed as a function of rice phenology to provide a physical interpretation for the co-polarized backscatter response in a temporal and spatial manner. Then, a correlation analysis was carried out between TerraSAR-X backscattering signal and rice biomass of stem, leaf and head to evaluate the relationship with different vertical layers within the rice vegetation.

HH and VV signatures show two phases of backscatter increase, one at the beginning up to 46 days after transplanting and a second one from 80 days after transplanting onwards. The first increase is related to increasing double bounce reflection from the surface–stem interaction. Then, a decreasing trend of both polarizations can be observed due to signal attenuation by increasing leaf density. A second slight increase is observed during senescence. Correlation analysis showed a significant relationship with different vertical layers at different phenological stages which prove the physical interpretation of X-band backscatter of rice. The seasonal backscatter coefficient showed that X-band is highly sensitive to changes in size, orientation and density of the dominant elements in the upper canopy.

1. Introduction

As a cereal grain, rice is one of the most important staple foods for a large part of the world. For this reason, monitoring its biophysical variables is valuable for agricultural management and yield prediction. In 2009, around 1.61 million square kilometre of the Earth's surface was used for rice cultivation with a global production estimated at 679 million tons (FAO, 2011).

Information extracted from remotely sensed data can assist in estimating key plant growth parameters such as biomass, crop height and leaf area index (LAI). Multispectral and hyperspectral optical imagery collect spectral information in a wide range of the electromagnetic spectrum. The visible and near infrared reflectance is sensitive to plant water content, pigment content and leaf structure (Kumar et al., 2003). To enhance the vegetation cover signal while minimizing the response of the background, vegetation indices (Schowengerdt, 2007), multivariate methods (Darvishzadeha et al., 2008) or physically based transfer models (Richter et al., 2009) were designed which enable a linkage of spectral signature with crop parameters. In the past, optical satellite data have been successfully used for rice plant parameter estimation (Tennakoon et al., 1992). For mapping rice cultivation in Asia, time series of vegetation indices (e.g., NDVI) derived from different sensors such as MODIS (Peng et al., 2011) were applied. However, operational crop monitoring and yield prediction based on optical remote sensing is hindered by unfavourable atmospheric conditions, which can lead to data gaps especially during critical growth stages.

As compared to optical sensors, spaceborne synthetic aperture radar (SAR) instruments can overcome inherent limitations of optical systems owing to its all-weather, day and night acquisition capabilities and sensitivity to surface characteristics (Kugler et al., 2010). This allows a more reliable and consistent rice monitoring

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during the growing season. Especially short wavelength SAR (X- and C-band) interacts with the upper part of the crop canopy, thus offering the potential to retrieve crop biophysical parameters (Ulaby et al., 1984). Longer wavelengths such as L- or P-band provide a deeper penetration into the vegetation depending on plant height and density (Brisco and Brown, 1998). To benefit from both optical and SAR data, there are investigations that use complementary information from both systems, e.g., for crop type mapping (Blaes et al., 2005) or crop condition estimation (Koppe et al., 2012).

A considerable number of research projects have been set up to investigate the capability of microwave data for agricultural monitoring since the first SAR satellites have been available for scientific and commercial use. Across all frequencies and crop types, the following aspects have been addressed: (a) soil moisture retrieval (Gherboudj et al., 2011; Koyama et al., 2010), (b) SAR backscatter analysis as a function of crop biophysical parameters and their temporal change (Bouvet et al., 2009; Shao et al., 2001), (c) development of methods for crop type mapping (Ribbes and Le-Toan, 1999a), (d) crop parameter estimation (Karjalainen et al., 2008; Jinsong et al., 2007) and (e) integration of SAR data in crop growth model for yield estimation (Ribbes and Le-Toan, 1999b). Results of the mentioned studies confirm that microwave backscatter is highly sensitive to different crop types and to changes in the crop canopy due to increasing biomass during the growing cycle. The degree of sensitivity is strongly dependent on the applied polarizations, as identified by quadpol analysis (Wu et al., 2011). Despite good results in crop monitoring, it has to be considered that the recorded SAR backscatter from a vegetated surface is a function of several physical properties. These are crop type, surface roughness, soil moisture, vegetation structure and plant moisture content as well as sensor configuration (e.g., frequency, polarization and incidence angle). Besides parameter estimation based on direct inversion from the recorded signal or integrating SAR into growth modelling, there also have been promising results by using repeat-pass SAR interferometric coherence data for vegetation biomass estimation (Blaes and Defourny, 2003). With the bistatic TanDEM-X mission, single pass polarimetric SAR interferometry for crop monitoring could be feasible (Hajnsek et al., 2010). Reasonable results have also been already achieved by using polarimetric SAR interferometry (POLInSAR) for rice biophysical parameter retrieval with indoor wide-band polarimetric measurements (Ballester-Berman et al., 2005).

For operational rice monitoring, the detailed understanding of the interaction between backscattered energy and crop canopy as a function of acquisition parameters such as frequency, polarization and incidence angle is essential for interpreting the SAR signal and for developing methods to retrieve crop biophysical parameters. In terms of rice monitoring by microwave remote sensing, the scattering process and penetration depth into the canopy is highly dependent on the wavelength and the incidence angle (Lim et al., 2007). Inoue et al. (2002) identified typical multi-temporal backscatter signatures of rice for frequencies at around 35 (K_a-band), 15 (K_u-band), 10 (X-band), 5 (C-band) and 1 (L-band) GHz and at different incidence angles. Results outlined, that the shorter wavelengths K- and X-band showed high dynamic range at the beginning of the growing season, but also an early peak in backscatter. The longer wavelengths C- and L-band maintained the increasing trend in backscatter with increasing biomass until heading, and hence were most highly correlated with biomass. The electromagnetic interaction between microwaves and canopy, the received radar backscatter is a sum of three main components, including volume scattering, the double bounce scattering from the vegetation–surface interaction and the contribution from the surface itself. At the X-band, experiments conducted by Kim et al. (2000) using ground-mounted scatterometer data have demonstrated that the co-polarized backscatter from a paddy rice field at the beginning of the growing season is dominated by double bounce scattering from the stem–surface (water) interaction. With increasing plant density, the double bounce scattering is replaced by a random scattering from the upper canopy. Inoue et al. (2002) mentioned a typical dual-peak trend for higher frequencies; the first peak at the maximum of double bounce scattering and the second peak with appearance of the top leaf and the heads in top layer of the canopy.

For rice crops, the temporal backscattering behaviour has been extensively reported and understood in a number of studies based on spaceborne C-band data mentioned above. Comparatively to C-band data, much less effort has been put on the use of spaceborne X-band data in rice monitoring applications. This is mainly due to lack of spaceborne X-band systems in the last decades. With the launch of TerraSAR-X and Cosmo Skymed in 2007, X-band data gained interest for rice monitoring. Lopez-Sanchez et al. (2010) adapted an electromagnetic model to simulate X-band backscatter from rice field. It was used for interpretation of dual-polarized TerraSAR-X images over rice fields in Spain. Suga and Konoshi (2008) investigated the temporal change of SAR backscatter during the rice growing cycle.

In this work, we present results from a dual polarimetric time series analysis of TerraSAR-X data. The underlying hypothesis of this study is that X-band SAR data is well suited to detect changes in the phenological development of rice due to a clear backscatter signature as a function of rice development stage. To understand the scattering behaviour of rice, the first objective of this investigation was to quantitatively describe polarimetric X-band SAR backscattering of rice canopy as a function of phenologic stage. In this investigation, six co-polarized TerraSAR-X High Resolution SpotLight scenes and five single polarized StripMap scenes of the rice cultivation were utilised. To support the interpretation of backscattered X-band signal, a second objective was to investigate the relationship between the SAR signal (HH and VV) and biomass of the different scattering layers (stem, leaf, and head). The correlation coefficients indicate the interaction of SAR signal with different vertical layers at a certain phenologic stage and can give information about penetration depth, signal attenuation and scattering mechanism.

2. Methods

2.1. Satellite data and processing

A time series of six dual polarimetric and five single polarimetric TerraSAR-X data were acquired during the growing season in 2009. TerraSAR-X satellite operates at a frequency of 9.6 GHz and provides high resolution SAR images in SpotLight, StripMap and ScanSAR modes with varying spatial resolution between 1 and 18 m (Fritz and Eineder, 2010). Six High Resolution SpotLight (HS) images were acquired with an incidence angle of about 39° in ascending orbit direction. In addition to the HS data, five StripMap (SM) data with an incidence angle of about 36° in descending orbit direction were acquired to cover the complete test area. The dual-pol HS images have a ground range resolution of around 2.2 m for the incidence angle of 39° whereas the single-pol SM images have a coarser ground range resolution of 3.5 m for an incidence angle of 36° (Fritz and Eineder, 2010). The HS and SM data were acquired in repeat pass with 11-day intervals in order to obtain a multi-temporal data stack with similar acquisition parameters (see Table 1). Image data acquisition timeline for both image modes is shown in Fig. 3.

TerraSAR-X level 1b complex data were converted to intensity (squared amplitude) since multi-temporal backscatter analysis and regression analysis with crop parameters was based on intensity values. In order to extract plot-level specific crop information from imagery, the images were geo-referenced and location accuracy