Effects of changing rice cultural practices on C-band synthetic aperture radar backscatter using Envisat advanced synthetic aperture radar data in the Mekong River Delta

Nguyen Lam-Dao,[a,d] Thuy Le-Toan,[b] Armando Apan,[a] Alexandre Bouvet,[b] Frank Young,[a] and Trung Le-Van[c]

[a] University of Southern Queensland, Faculty of Engineering and Surveying, Toowoomba Queensland 4350, Australia
lamdao@usq.edu.au, apana@usq.edu.au

[b] Centre d'Etudes Spatiales de la Biosphère, 18 Avenue Edouard Belin, 31401 Toulouse Cedex 9, France
Thuy.Letoan@cesbio.cnes.fr, alexandre.bouvet@cesbio.cnes.fr

[c] HoChiMinh City University of Technology, Department of Geomatics, 268 Ly Thuong Kiet St., Dist. 10, Ho Chi Minh City, Vietnam
lvtrung@hcmut.edu.vn

[d] HoChiMinh City Institute of Resources Geography, GIS and Remote Sensing Research Center, 1 Mac Dinh Chi St., Dist. 1, Ho Chi Minh City, Vietnam
ldnguyen@vast-hcm.ac.vn

Abstract. Changes in rice cultivation systems have been observed in the Mekong River Delta, Vietnam. Among the changes in cultural practices, the change from transplanting to direct sowing, the use of water-saving technology, and the use of high production method could have impacts on radar remote sensing methods previously developed for rice monitoring. Using Envisat (Environmental Satellite) ASAR (Advanced Synthetic Aperture Radar) data over the province of An Giang, this study showed that the radar backscattering behaviour is much different from that of the reported traditional rice. At the early stage of the season, direct sowing on fields with rough and wet soil surface provides very high backscatter values for HH (Horizontal transmit – Horizontal receive polarisation) and VV (Vertical transmit – Vertical receive polarisation) data, as a contrast compared to the very low backscatter of fields covered with water before emergence. The temporal increase of the backscatter is therefore not observed clearly over direct sowing fields. Hence, the use of the intensity temporal change as a rice classifier proposed previously may not apply. Due to the drainage that occurs during the season, HH, VV and HH/VV are not strongly related to biomass, in contrast with past results. However, HH/VV ratio could be used to derive the rice/non-rice classification algorithm for all conditions of rice fields in the test province. The mapping results using the HH/VV polarization ratio at a single date in the middle period of the rice season were assessed using statistical data at different districts in the province, where very high accuracy was found. The method can be applied to other regions, provided that the synthetic aperture radar data are acquired during the peak period of the rice season, and that few training fields provide adjusted threshold values used in the method.

Keywords: rice crop, cultural practices, synthetic aperture radar data, processing, polarisation, mapping.

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1 INTRODUCTION

Rice is one of the world's major agricultural crops and is the staple food for more than half of the world population. In Asia, more than 2000 million people obtain 60 to 70% of their calories from rice and its products [1]. Food security has become a key global issue due to the Asian region's rapid population growth, extensive conversion of arable lands, and declining overall productivity in some areas because of climate effects (floods, water shortage, low or high temperature) and plant diseases. For this reason, there is a need to develop spatio-temporal monitoring system that can accurately assess rice area planted, crop vigour and health, and to predict crop yield.

In the past years, many research projects on rice crop monitoring have been carried out using remote sensing data. Among them, space-borne Synthetic Aperture Radar data available since the 1990s from ERS-1 and 2, and RADARSAT-1 were recognised as the most valuable data sources for the tropical and sub-tropical regions. At present, new radar technology and increased image data availability proved to be effective with the launch of new systems in 2002 (Envisat), 2006 (ALOS), 2007 (TerraSAR-X, RADARSAT-2), and 2009 (RISAT). More systems are scheduled in the near future, e.g. Sentinel 1.

Research on rice crop monitoring using satellite radar data has been conducted in various countries including Indonesia [2,3]; Japan [2,4,5]; Vietnam [6,7,8]; China [9,10,11,12,13,14]; Sri Lanka [15]; India [16]; and the Philippines [17]. These studies reported results, most of them based on C band (frequency = 5.3 GHz, wavelength = 5.6 cm) SAR data, on various aspects: i) experimental SAR data analysis as a function of rice biophysical parameters and their temporal change, ii) interpretation of the observations by theoretical modelling, iii) development and application of classification methods, iv) retrieval of biophysical parameters and v) interface with rice growth models for crop yield prediction.

Theoretical modelling has indicated that, at C band, the dominant scattering mechanism of HH and VV is the double bounce vegetation-water scattering [2,4,5]. The radar response of HH is higher than that of VV because of the stronger attenuation of VV by vertical stems.

Experimental results confirmed that a) the radar backscattering coefficients of rice fields have a characteristic increasing temporal behaviour resulting from the increase of double bounce scattering with plant biomass, b) similar variations of the radar backscattering coefficients were observed in different study areas when expressed as a function of rice biomass, and c) the backscattering intensity at C-band VV (ERS) or HH (RADARSAT) increases with increasing biomass during the vegetative phase (before reproductive phase) [2].

The analysis and modelling results have been used to derive methods of rice mapping and biomass retrieval based on intensity temporal change [2,18], or based on value of the ratio between HH and VV [11].

These mapping and retrieving methods have been widely validated in the past ten years. However, in recent years, changes in rice cultural practices have been observed in different regions of the world. The changes are caused by the rice demand pressure and water shortage, and exacerbated by the progress in technology and the decrease of available manpower.

Vietnam is the second largest world rice exporter since the mid-1990s and the Vietnamese people are among the world's top five rice consumers [19]. At the southern tip of Vietnam, the fertile Mekong River Delta accounts for more than half of the country's rice production [20]. This makes the rice growing areas of the Mekong River Delta a good example to study the changes from traditional to modern rice cultivation system, gradually adopted in the last ten years. The changes consist of a) increasing the number of crops from one or two, to two or three crops per year, b) changing from transplanting to direct sowing, c) using water-saving technology, d) using short-cycle seed varieties (85 to 105 days) and e) using fertilizer and pesticide more intensively. These changes in rice practices can have a significant impact on radar backscattering behaviour that may have an influence on remote sensing methods.

In the Mekong River Delta of Vietnam, the rainy season usually lasts seven months from May to November, and floods annually occur starting from August. A dike system has been built and intensified in recent years to block the floodway into the fields during the flood season in order to increase the number of crops during the wet season from one crop to two crops of rain-fed rice, named Summer Autumn (SA) and Autumn Winter (AW) crops. In the dry season, an irrigated rice crop, Winter Spring (WS) has been grown. As a result, two or three rice crops in a year have been planted, resulting in an increase in rice production from 12.8 million tons in 1995 to 19.3 million tons in 2005, i.e. raising 51% in ten years [20]. These multiple crops are made possible by the availability of short cycle rice varieties.

Besides increasing the number of crops a year, cultural practices have been changed in various ways. Whereas transplanting was a common practice few years ago, rice farmers are at present converting toward direct sowing as the dominant method for planting. Because of economic growth, increased labour demand puts upward pressure on wages or reduces the availability of labour for many farm operations. This has encouraged farmers to switch from transplanting, which requires 25-50 person-days per hectare, to direct seeding, which requires at most only about five person-days per hectare [21].

Concerning water management, the rice-based cultivation system is a major consumer of the freshwater resource. Saving water in the field is economically important for farmers and contributes to environmental protection. Therefore, a new water saving technology called alternative wetting and drying (AWD) was introduced and disseminated several years ago. Using the AWD technique with fewer pumping operations, the crop is not continuously flooded.

As indicated above, backscattering intensity at C-band increases with increasing rice biomass and the dominant scattering mechanism of HH and VV is the double bounce vegetation-water scattering for inundated rice. Due to modifications in rice cultivation system as previously indicated, subsequent changes in rice backscatter could be expected. These alterations in cultural practices therefore suggest the need to re-assess radar remote sensing methods developed previously for monitoring traditionally cultivated rice crop.

The study site is located in the An Giang province, where SAR data and ground data were acquired over a period of 12 months in the year 2007. The objectives of the study were to understand the relationship between radar backscatter coefficients and selected parameters (e.g. height and biomass) of rice crops over an entire growth cycle and to develop algorithms for mapping and monitoring rice cropping systems using time-series SAR imagery.

This paper describes an analysis of the effect of changing cultural practices on radar backscatter of C-band, HH, VV polarisations from Alternating Polarisation Precision (APP) data of Advanced Synthetic Aperture Radar (ASAR) instrument on Envisat satellite and discusses the possible applications of the derived new knowledge.

2 TEST SITE AND DATA

2.1 Test site

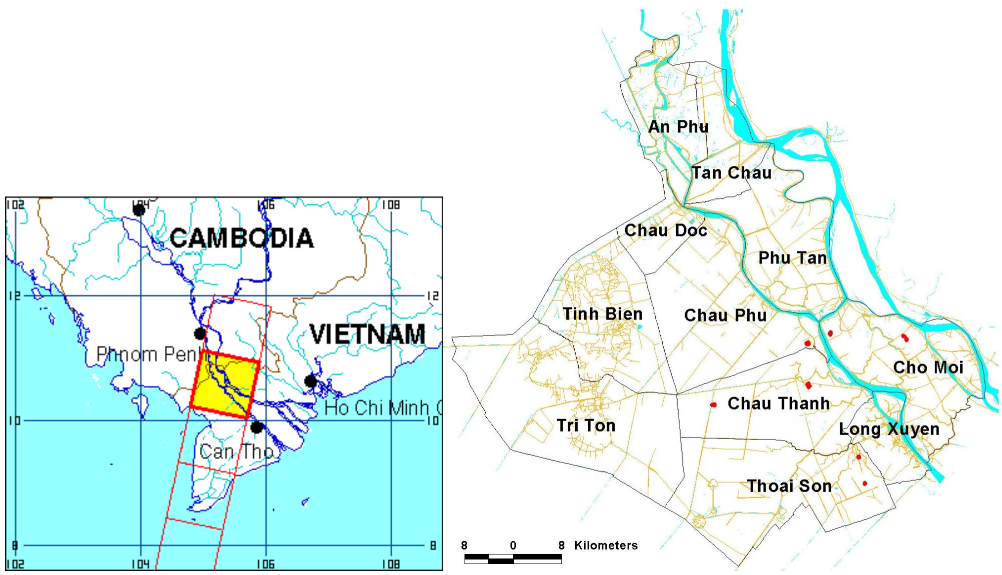
The climatic conditions in the Mekong River Delta are particularly favourable to agricultural production, such as high solar radiation and favourable high temperature. The Delta has a monsoon tropical semi-equatorial climate. Two seasons are distinguishable: the rainy season that lasts from May to November and constitutes approximately 90 percent of the total rainfall of 1600-2000 mm, and the dry season that lasts from December to April. The combination of hydrology, rainfall pattern, and availability of irrigation drives the variety of rice-based cropping systems (Table 1) practiced in the Mekong River Delta.

Table 1 summarises the major rice cropping systems practiced in the Mekong River Delta. The double cropping system may be the WS – SA or the SA – AW system. As the WS crop grows during the dry season, the WS – SA cropping system is practiced in areas that receive irrigation water. The SA – AW system is practiced under predominantly rain-fed conditions. The crop calendar varies each year, depending on the onset of the rainy season at the start of the Summer Autumn crop.

Table 1. Main rice-based cropping systems in the Mekong River Delta.

Rice-based cropping system	Rice season
Single rice crop	Traditional rice (rain-fed)
Double rice crop	Summer Autumn – Autumn Winter (rain-fed)
	Winter Spring – Summer Autumn (irrigated)
Triple rice crop	Winter Spring – Summer Autumn - Autumn Winter

The study area is the An Giang province (Fig. 1), extending from 10° 12' to 10° 57' N latitude and 104° 46' to 105° 35' E longitude and is covered by the entire 100 x 100 km Envisat ASAR scene IS2 mode (Fig. 1(a)). Located at the border of Cambodia, about 190km from Ho Chi Minh City, An Giang has an area of 3 536.8 square kilometres, with a population of about 2 231 000 people [22].



(a) (b)

Fig. 1. The An Giang province: (a) Location of the frame of Envisat ASAR APP scene on the study site; (b) Administrative boundary map of An Giang province, with locations (red dots) of the sampling areas.

Table 2. Main rice seasons in An Giang, Mekong River Delta.

Rice crop		Planting	Harvesting
English name	Local name		
Winter Spring	Dong Xuan	Nov./Dec.	Mar./Apr.
Summer Autumn	He Thu	Apr./May	Jul./Aug.
Rainy season	Thu Dong (Autumn Winter)	Jul./Sep.	Oct./Dec.
	Mua (Traditional rice)	Jul./Sep.	Nov./Jan.

In An Giang province, agricultural land covers the largest area (280 494 ha), of which 93.6% (262 649 ha) is dominated by rice farms [23]. The main rice seasons in the province are listed in table 2.

2.2 SAR Data

This study used Envisat ASAR APP data at HH and VV polarisation, IS2 (Image Swath 2, corresponding to incidence angle range of 19.2^{O} – 26.7^{O}) at 35-day repeat interval. The APP images have a nominal spatial resolution of 30 m x 30 m and pixel size of 12.5 m x 12.5 m, with a swath width of about 100 km. The data under study have been acquired at ten dates in 2007 covering three rice crops (Table 3).

The steps used to pre-process the SAR data consisted of a) image calibration or conversion of the data into the radar backscattering coefficient sigma nought (σ^o); b) image geo-correction; and c) image spatial filtering.

Image calibration consisted of correcting SAR images for incidence angle effect and for replica pulse power variations, to derive physical values. This transformed SAR precision images into intensity images expressed in σ^o. Image geo-correction was performed to reproject the calibrated images to the selected cartographic projection, i.e. UTM, ellipsoid WGS-84. Spatial filtering was then done to reduce the speckle effect in the image. In this work, the enhanced Frost spatial filter has been applied to each image [24,25]. The software BEST (Basic Envisat SAR Toolbox) and ENVI have been used for these processing steps.

Table 3. List of Envisat ASAR data used.

Sensor	Observation date	Rice crop
Envisat ASAR Narrow Swath	January 13, 2007 February 17, 2007 March 24, 2007	Winter Spring
	April 28, 2007 June 02, 2007 July 07, 2007	Summer Autumn
	September 15, 2007 October 20, 2007 November 24, 2007 December 29, 2007	Rainy season

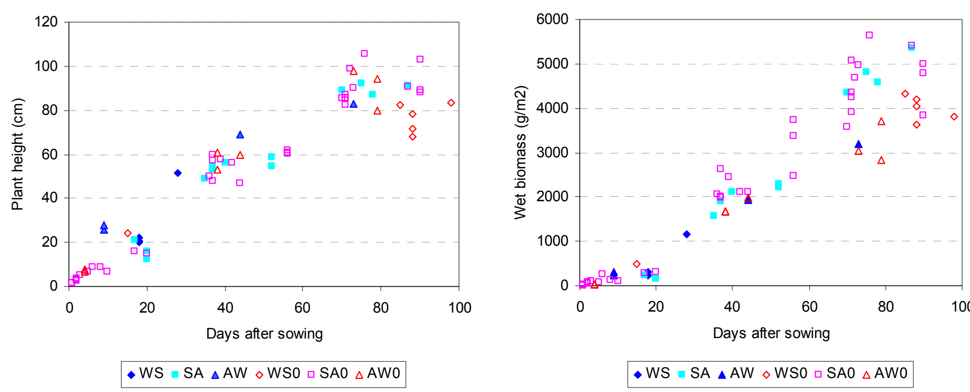
2.3 Ground and survey data

Seven sampling areas which are located in Chau Phu, Chau Thanh, Thoai Son and Cho Moi district (Fig. 1(b)) were selected to meet the research objectives. The main criteria used for the selection of sampling areas were representativeness of rice growing regions in terms of physiographic stratification, variety of crop type and cultural practices, and accessibility of the area for ground data collection [26]. The measurements were done on five rice fields in each of the seven sampling areas. The size of fields was ranging from 0.2 to 1.7 ha. The parameters measured for each field include general parameters (rice variety, method of planting, sowing/transplanting and harvesting date, plant phenological stage, water layer height, yield), plant parameters (number of plants per square meter, plant height, height uniformity, number of stems per plant, wet and dry weight per plant), leaf parameters (number of leaves per stem, leaf length and width) and panicle parameters (number of panicles per plant, number of grain per panicle and moist weight of panicle). Each parameter of plant, leaf or panicle was estimated over 3 to 5 sampling plots of 0.50 x 0.50 m within the fields (according to the field uniformity). All field work was conducted during or near the time of the satellite pass. Location of rice fields were identified on the reference map scale of 1:50,000 and measured on the ground using hand-held GPS receivers with a location accuracy of approximately 10 meters.

For WS, SA and AW crops, the farmers used various seed varieties of short cycle ranging from 86 to 106 days with a mean of 97 days. In the sampling fields, the dominant varieties grown were Jasmine (34%) and IR 50404 (21%). Direct sowing method was dominant at about 80% of the selected fields. In each sampling area, the sowing/transplanting dates differ between the sampling fields from 0 to a maximum of 9 days.

The height of rice plant (plotted in Fig. 2(a)) was measured at the SAR acquisition date. Two categories were distinguished: inundated fields with standing water (noted WS, SA and AW), and fields without standing water (noted WS0, SA0, and AW0). The height was measured from the top of the plant to the ground or water level. Since the water layer, when present, ranged from 1 to 9 cm thick (with an average of 3.2 cm), the difference between plant height with and without water does not seem significant, except at early stage. The plant height increases to reach 80 - 100 cm, at about 70 days, whereas the maximum height is reached at 100 days for long cycle rice [2].

The plant densities of sampling fields measured at the middle of the season have average values of 928, 850, 750 stems per square meter in WS, SA and AW crops, respectively, whereas plant density of about 200 stems per square meter was observed in traditional practiced rice fields at the same stage [2].

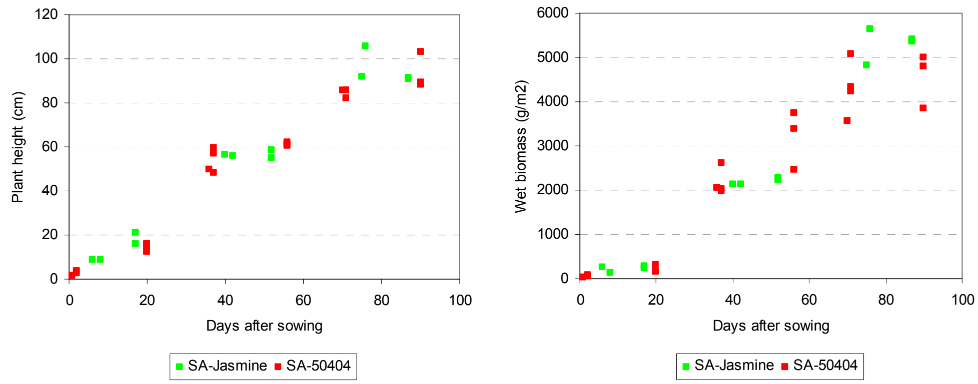


(a) (b)

Fig. 2. Temporal variation of (a) plant height; (b) biomass in WS, SA, and AW crops.

During the Summer-Autumn crop, the rice biomass increased steadily during the vegetative stage and the reproductive stage and reached the maximum value of about 5000 g/m^2 or more at the final stage (harvest) (see Fig. 2(b)). For the Winter-Spring and Autumn-Winter rice crops, a maximum value of 4000 g/m^2 was observed. In comparison, the plant wet biomass in Akita, Japan [4] and in Semarang, Indonesia [2] showed an increase only until the reproductive phase. The maximum biomass value obtained from these two test sites was around 3500 g/m^2, which is lower than that of the fields cultivated by modern practices. This could be explained by the higher plant density, the use of fertilizer, and the rice varieties of higher yield.

The plant height and rice biomass of the two dominant rice varieties i.e. Jasmine and IR 50404 in the same crop season Summer Autumn were analysed (Fig. 3). While the temporal increase of the height was similar, the rice biomass showed some differences between the two varieties. Jasmine attained more than 5000 g/m^2, whereas IR 50404 biomass appears lower than 5000 g/m^2 at the final stage of the SA season, however biomass values are dominated by inter-field variation.



(a) (b)

Fig. 3. Temporal variation of (a) plant height; (b) biomass in SA crop of Jasmine and IR 50404.

3 ANALYSIS OF THE RADAR BACKSCATTER

Twenty five sampling fields were retained for detailed analysis of their radar backscatter: five fields grown in Winter Spring, 16 in Summer Autumn, and 4 in Autumn Winter crop. The other fields were not chosen because: a) the radar response of some fields was not homogenous in term of backscatter, and b) the sampling fields grown in Autumn Winter crop were only in Cho Moi district.

3.1 Effect of water/no water in the field

Since 2005, the Water-Saving Work Group of the Irrigated Rice Research Consortium (IRRC) has established activities on water management and water-saving practices for rice in the Mekong River Delta in collaboration with Vietnam's Plant Protection Department. The farmers have, on average, two to three fewer pumping operations during the season to irrigate their fields than the past regular practice of continuous flooding.

With the traditional method, the fields are flooded at the onset of the rains or with the arrival of irrigation water, in order to prevent weeds and pests. The water depth varies from 2 to 15 cm, with an average of 10 cm. The rice plants are sown in nurseries before transplantation. After 25 to 35 days depending upon labour availability, the plants are transplanted in clusters of one to ten plants and planted in line (ten to twenty clusters per square meter).

Fig. 4. Example of one sampling field a week after sowing (no water, very wet soil with some surface roughness).

Table 4. Effect of water on radar backscattering at early stage in Winter-Spring crop.

Sample name	**Age (day)**	**Water height (cm)**	**σ^o_{HH} (dB)**	**σ^o_{VV} (dB)**
WS1	19	7.0	-9.1	-14.9
WS2	19	5.0	-9.1	-13.6
WS3	19	2.0	-7.2	-11.6
WS01	16	no water	-3.3	-6.3

With the present technique of direct sowing, the grains are sown at a high density directly in wet soil (Fig. 4). At the early stage of the rice crop cycle, the fields in the test region were wet soil. After 10-20 days, the fields were filled with water. Table 4 shows values of backscatter at HH and VV at the dates around 15-20 days. For fields not yet irrigated, such as field WS01, the radar backscattering coefficient is high, with values ranging from -7 dB to -2 dB in both HH and VV polarisation. This high backscatter results from scattering by wet and rough soil surface. When the fields are flooded as seen in Fig. 5 (e.g. fields WS1, WS2, WS3), the backscatter decreases significantly, with HH ranging from -7 to -9 dB and VV from -11 to -15 dB (see Fig. 6). The low backscatter results from the backscattering from water surface, attenuated by the plant. VV is more attenuated by vertical stem and has lower values than HH.

Fig. 5. Field sample with standing water at about 20-day after sowing.

Backscatter temporal variations of HH and VV polarisation data for the three rice crops WS, SA, and AW in the year 2007 are presented in Fig. 6 and described as follows:

1) At the beginning of the rice season (20 days after sowing), i.e. the first half of the vegetative stage, flooded and non-flooded rice fields have low and high backscatter, respectively (with the exception of two data points, maybe due to field observation performed before the exact flooding time),

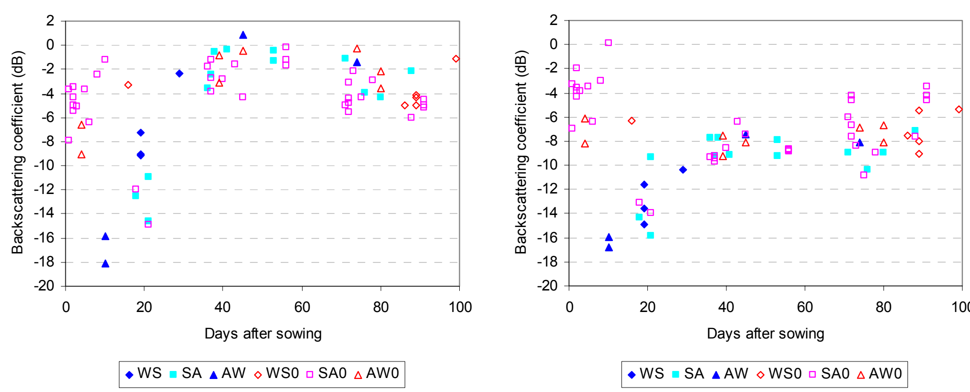
2) During the period of 20-70 days, i.e. the second half of the vegetative stage and the reproductive stage, flooded and non-flooded fields have similar high backscatter response.

It was expected that in flooded fields the plant- water double bounce interaction should be dominant, thus the backscatter of flooded fields should be higher than that of drained fields. A possible explanation of the similar backscatter response could be due to the high density of the plants (as explained in section 2.3), causing important contribution of volume scattering and multiple plant–ground scattering. HH>VV is as expected, linked to attenuation of the waves by the vertical plant elements. However, the most surprising feature is the very high value of HH (0 to -2 dB), not often seen in natural surfaces.

3) During the period from 0 to 70 days, i.e. from sowing to heading, the plant structure remained mostly erectophile. The stems were quasivertical and the leaves had a small insertion angle (5-20^o) [27]. The temporal increase of SAR backscatter at two consecutive data acquisition dates (e.g. 35 days with Envisat) is high if the fields are flooded at both dates, i.e. 18 dB at HH and 11 dB at VV as the maxima observed. In contrast, if the field is not flooded at the first date, a variable increase is observed at HH (0 to 8 dB), and a variable decrease (0 to 6 dB) at VV. As a consequence, the backscatter temporal change is no longer a robust rice classifier.

4) After the age of 70 days, i.e. the ripening stage, the growth (height and biomass) stopped and the leaves changed their orientation to be no more erectophile (i.e. their insertion angles were typically 30-40 ^{o}) [27]. Although inter-field variation is observed, it can be seen that most backscattering coefficient values of the rice fields without water are slightly lower in HH and higher in VV compared to that of fields with standing water (Fig. 6).

5) The polarisation ratio (HH/VV or HH in dB – VV in dB) is presented in Fig. 7. In general, the ratio increases until the period 30-70 days, then decreases until harvest. The most striking observation is the high value of the ratio (4.6 to 7.8 dB for flooded fields). However, fields without water at the SAR overpass have large dispersion of the ratio values, varying from -1.4 to 6.5 dB.



(a) HH (b) VV

Fig. 6. Backscatter temporal variation of (a) HH; (b) VV in WS, SA, and AW crops of the fields with water and without water.

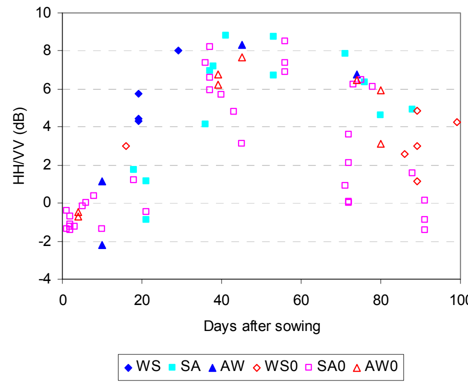
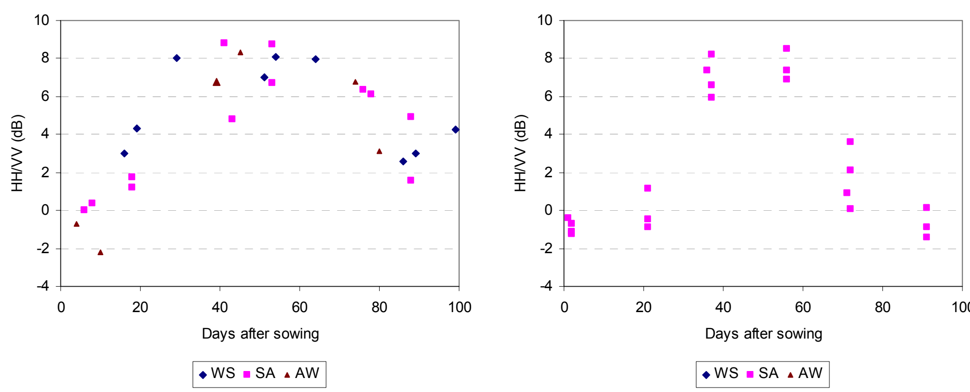


Fig. 7. Temporal variation of HH/VV ratio in WS, SA, and AW crops of the fields with water and without water.

3.2 Effect of plant structure and seed varieties

Plant structure and different rice varieties can have impact on radar response [28]. HH/VV can have lower values when the plant structure deviates from vertical. For example, for plants affected by wind, the decrease could be 2 dB (see Fig. 8(a) and 8(b) at the ripening stage). This could be due to plants becoming lodged (rice plants falling over) as recorded in field samples. Nine sampling fields grown from IR 50404 variety in Vinh Chanh and Phu Hoa districts were measured with stem inclination of 10^o – 45^o (28^o in average value) at the ripening stage (Fig. 9 (b)). In comparison, stem inclinations ranging from 5^o to 15^o with mean of 9^o were observed at the same stage from seven other fields where Jasmine seed were planted (Fig. 9(a)). The radar response of those plants decreased in comparison with vertical rice plants in HH (below -4.5 dB), and increased in VV polarisation (above -6.0 dB) (see Fig. 6) because rice stems are not vertical at the maturation stage.



(a) Jasmine (b) IR 50404

Fig. 8. Temporal variation of HH/VV ratio of (a) Jasmine; (b) IR 50404 varieties in WS, SA, and AW crops.

The differences in plant structure are also related to rice varieties. As plotted in Fig. 8b, most of IR 50404 rice variety (grown in SA crop only) is characterised by a very low HH/VV (below 1 dB) at the end of the rice crop, whereas Jasmine species with a quasi-vertical structure has higher ratio (Fig. 8a) at the same stage of the rice season.

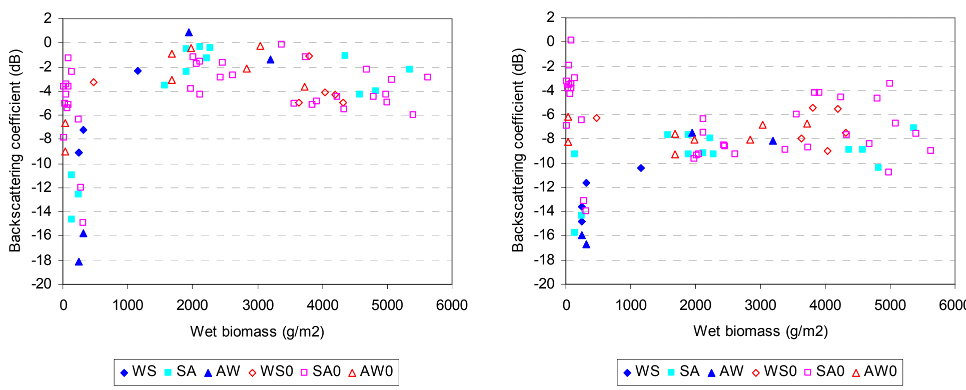
(a) Jasmine (b) IR 50404

Fig. 9. Sampling fields with plants in (a) quasi-vertical structure and (b) lodging at the end of SA crop.

3.3 Radar backscatter and rice biomass

In traditional rice cultivation system, radar backscatter was found to be strongly correlated to rice parameters i.e. plant height and biomass [2]. Backscatter of rice fields increases steadily during the growing stage and then reaches a saturation level. This temporal variation of radar response has proved to be effective for rice crop monitoring. Radar backscatter can increase by more than 10 dB from the beginning of the crop (flooded fields) to the saturation level [2,4,29,30].

In the study of Ribbes and Le-Toan [3], the rice growth model ORYZA1 was used to simulate rice growth with the sowing date and rice biomass values retrieved from ERS and RADARSAT SAR data as input parameters. The coupling of SAR data and ORYZA model gave good results for rice yield estimation. Choudhury et al. [30] recently used dual polarisation ASAR data in the case of regular practice in the Bardhaman, India. A linear relation between polarisation ratio (HV/HH) and fresh biomass indicated that even though Envisat data were acquired during vegetative stage, rice biomass could be retrieved with good confidence, as HH alone shows saturation before maturity stage.



(a) HH (b) VV

Fig. 10. Radar backscattering of (a) HH; (b) VV versus plant wet biomass in WS, SA, and AW crops.

An analysis of the relationship between radar backscatter and rice biomass in the study site of An Giang was carried out. Fig. 10 shows the HH and VV data as a function of biomass. HH and VV polarisation data increase strongly until the plant fresh biomass reaches 1000 g/m^2 (at 30 days after sowing). However, for non-flooded fields, the increase in HH is smaller and VV even decreases. A saturation level of backscatter is reached at around 2000 g/m^2 at the middle of crop cycle (during the second half of the vegetative stage and the first half of the reproductive stage). After saturation level, radar backscatter remains stable and slightly reduces for HH and rises for VV until biomass gets to maximum values. Fig. 11 shows the polarisation ratio (HH/VV) as a function of rice biomass. Only the increase of HH/VV at the beginning of the season is clearly observed; however, this increase is restricted to the first month or a limit of 1000g/m^2. After this date, the backscatter of non-flooded fields has a large dispersion with respect to biomass. Fig. 10 and 11 show that retrieving rice biomass using HH, VV or HH/VV is not applicable to modern rice practices.

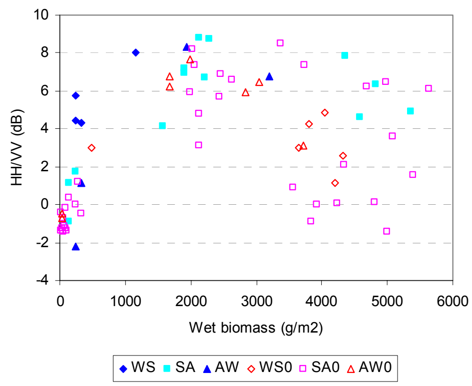


Fig. 11. Polarisation ratio versus plant wet biomass in WS, SA, and AW crops.

4 RICE MAPPING

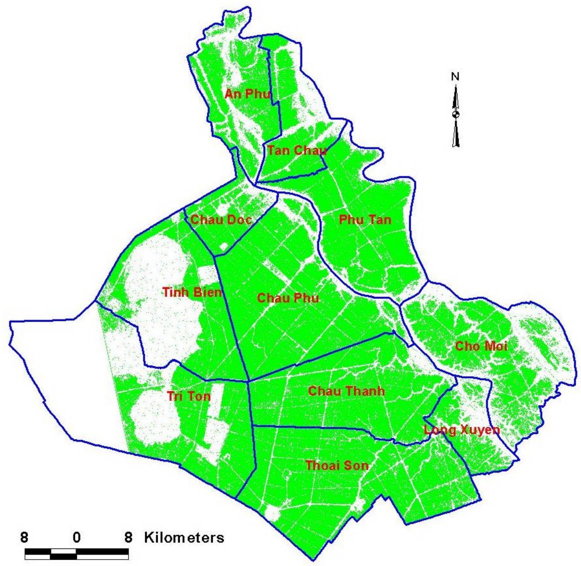
The analysis results of the section 3 have shown that: a) methods using the temporal change of HH and VV will not work for fields which are not inundated at the beginning of the season, and b) the ratio HH/VV is a good classifier during the period of 30 days to 60 days after seeding, i.e. during the second half of the vegetative stage and the first half of the reproductive stage for 100-day cycle rice varieties.

A classification method based on the HH/VV ratio was tested on the image taken in the middle of Winter Spring crop cycle (i.e. February) to map rice and non-rice. The principle inherent in this method was to threshold the maximum or minimum values of the HH/VV image to identify image pixels with backscatter coefficients consistent with a rice signal. A minimum threshold, X, was imposed as follows:

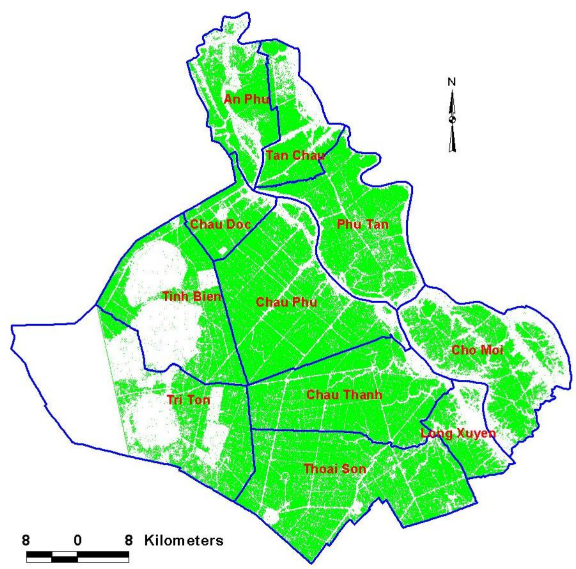
$$DN_{i,j} = \text{Rice if } \sigma^o \geq X \text{ dB else } DN_{i,j} = \text{Non-rice} \quad (1)$$

where $DN_{i,j}$ is a pixel value in the output image.

A threshold of HH/VV (Ra) value = 3dB is determined to segment rice and non-rice areas based on the temporal variation of HH/VV ratio in WS, SA, and AW crops of the fields with water and without water (see Fig. 7). In addition, during the middle period of crop season, the radar backscattering of sampled rice fields always attained values of -6 dB or less in VV polarisation and of -6 dB or more in HH polarisation (see Fig. 6). In order to reduce the confusion of rice with other non-rice classes having high HH/VV ratio values (e.g. reed or marshland with vertical plant structure, other crops, etc.), an additional criterion was added: $\sigma^o(VV) \leq -6$ dB. This threshold was chosen, after comparing between the accuracies of classified images segmented by using various combinations of thresholds, i.e. Ra ≥ 3 dB, σ^o(HH) ≥ -6 dB, and σ^o(VV) ≤ -6 dB. Since these threshold values apply to flooded and drained rice fields having different rice varieties and plant number density, the method is expected to be robust for the Mekong Delta. The method was applied to Envisat ASAR image taken in the middle of crop cycle of Summer Autumn, i.e. in June.



(a)



(b)

Fig. 12. Rice and non-rice maps (rice in green) of (a) WS; (b) SA crop.

The method is briefly described as follows:

1. An ASAR APP image acquired in the middle of the crop season is selected;

2. Image pre-processing steps were implemented: a) image calibration or conversion to the radar backscattering coefficient sigma nought (σ^o), b) image geo-correction, and c) image spatial filtering;
3. A polarisation ratio image was created;
4. Thresholding method was applied to the polarisation ratio and VV images in order to segment rice and non-rice classes;
5. A post-classification step was conducted by using majority filter to the classified image; and
6. A rice and non-rice map was finally produced.

Fig. 12 shows the pixel-based mapping results.

Table 5. Difference of rice acreages in WS crop produced by ASAR data and statistical data.

District name	Area_GIS (Ha)	Statistical data (Ha)	Rice from ASAR (Ha)	Percentage error in WS crop (%)
Phu Tan	32753	23041	24546	6.5
Chau Phu	45045	34383	36556	6.3
Tri Ton*	59867			
Tinh Bien	35634	14952	14999	0.3
Chau Doc	10452	7148	6965	-2.6
Long Xuyen	11533	5591	5244	-6.2
Thoai Son	46906	36691	39112	6.6
Tan Chau	16988	11420	10114	-11.4
An Phu	21864	14443	12377	-14.3
Cho Moi	36942	17887	17235	-3.6
Chau Thanh	35440	27686	28702	3.7
Province	353424	193242	195850	1.3

*Outside of the SAR image coverage

Table 6. Difference of rice acreages in SA crop produced by ASAR data and statistical data.

District name	Statistical data (Ha)	Rice from ASAR (Ha)	Percentage error in SA crop (%)
Phu Tan	22968	22471	-2.2
Chau Phu	33959	34612	1.9
Tri Ton*			
Tinh Bien	15164	14689	-3.1
Chau Doc	7123	7220	1.4
Long Xuyen	5433	5227	-3.8
Thoai Son	35990	35223	-2.1
Tan Chau	10908	9687	-11.2
An Phu	12856	11699	-9.0
Cho Moi	16324	16827	3.1
Chau Thanh	27629	27659	0.1
Province	188354	185314	-1.6

*Outside of the SAR image coverage

The accuracy assessment of the classified rice pixels in the Winter Spring and Summer Autumn crops has been produced (Table 5 and 6) based on the statistical data published by An Giang Statistical Office (AGSO) in the Statistical Yearbook 2007 An Giang province [31]. The difference between rice area by district from classified image and the statistics was between -14.3 to 6.6% (Table 5) and -11.2 to 3.1% (Table 6) for Winter Spring and Summer

Autumn crops, respectively. Errors were highest in the Tan Chau and An Phu districts, in comparison with other districts. At the province scale, however, the errors in rice grown acreage were only 1.3% for Winter Spring crop and -1.6% for Summer Autumn crop. These results suggest that rice fields in these cropping systems can be mapped over the An Giang province with reasonable accuracy using these methods. Most classification accuracies obtained for two rice crop seasons in this study were higher than that of the previous studies [10,11,17]. The results appear encouraging to map rice fields at different conditions in the province of An Giang.

In the case of changing cultural practices in the future, the method can also be used by adjusting the threshold values of polarization ratio and VV using training plots. It is expected that for larger regions, e.g. the Mekong delta, it is possible that SAR data need to be acquired at more than one date to cover the peak period of rice crops prevailing in the main agricultural regions.

5 CONCLUSION

Radar imagery consisting of multi-temporal, dual polarisation HH and VV Envisat ASAR APP data have been analysed for selected rice cropping areas in An Giang, Mekong River Delta. As a consequence of changes brought by modern cultural practices, the radar backscattering behaviour is much different from that of the traditional rice plant previously reported in scientific literature. At the early stage of the season, direct sowing on fields with rough and wet soil surface provided very high backscattered values for both HH and VV data (about -7 to -2 dB). Around 10 – 20 days after sowing, rice plants attained more or less 20 cm high and field flooding decreases dramatically the backscatter to -18 to -12 dB. The backscatter then increases and reaches a saturation level (-2 to 1 and -9 to -7 for HH and VV, respectively) in the middle of crop cycle.

The very high value of HH and the similar response of flooded and non-flooded fields are explained by the high plant density. HH, VV and HH/VV are not strongly related to plant biomass as in the reported traditional rice results. This is explained by the effect of water management, plant density and structure. As a result, retrieving rice biomass using HH, VV or HH/VV is not applicable to modern rice growing practices that prevail in the study area, and backscatter temporal change of HH and VV is not a robust rice classifier. However, the polarisation ratio and VV data of rice fields during a long period of the rice cycle could be used to derive the rice/non-rice mapping algorithm. The result using Envisat ASAR APP data acquired at a single date provided a high accuracy of planted rice area for the first crop (the percentage error at provincial scale is of 1.3% when compared to the official statistics) and the algorithm have been validated for the second crop season of the year 2007 with the difference of 1.6% between rice acreage extracted from ASAR APP data and that from published statistical yearbook.

In summary, a method for rice crop inventory in the province before harvest was developed by using single-date ASAR APP data taken in the mid-crop season. For operational purposes, this rice mapping algorithm need to be further investigated for other provinces in the Mekong River Delta.

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