Rice mapping using ALOS PALSAR dual polarization data

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Abstract: Fine beam dual polarization data onboard Advanced Land Observing Satellite-Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) for Hai’an, Jiangsu, China acquired in 2008 were used to analyze rice backscatter features at L-band SAR for the development of rice mapping method. Similar temporal change trend of backscatter was observed at L-band SAR to that of C-band. With the dependence of HH backscatter on the spatial distribution structure of the rice canopy, Bragg resonance scattering has been observed in some mechanically planted fields due to extremely enhanced backscatter, making it difficult to map rice using L-band SAR. However, the HV polarization is not subject to Bragg resonance. Considering the Bragg resonance effect in HH polarization, a rice mapping method was proposed based on the temporal change characteristics of backscattering coefficient by the synergistic use of HH and HV polarization images of ALOS PALSAR. A mapping accuracy of about 88.4% was achieved.

Key words: ALOS, PALSAR, L-band, rice mapping, Bragg resonance

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1 INTRODUCTION

Rice plays an important role in the sustainable agriculture and rural area development in Asia (FAO, 2008). Rice production is important to China, a country famous for rice production. Facing the problem of a large and continuously increasing population, China’s government has paid great attention to how to make decisions on rice production policy and to solve the problem of food shortage. Therefore, it is crucial to know the rice area distribution and its changes. Regarding the global environment change, the knowledge of rice growing areas is important to estimate the fluxes of methane (CH₄) from irrigated rice fields to the atmosphere. Methane is the second in importance to CO₂ as a greenhouse gas. Changes in paddy rice cropland distribution and management intensity (multi-cropping, water management, fertilizer use, and cultivars) are projected to intensify over the coming decades. These changes in rice area and cultural practices can have a significant impact on the methane emission from rice paddies and on the global climate.

To monitor changes in the rice production area and cultivation intensity, satellite remote sensing data constitute a unique tool which can provide timely and consistent spatial and temporal coverage needed at regional to global scales. Among remote sensing methods, only radar imaging systems are not limited by cloud coverage in tropical and subtropical regions where most rice is grown. Many studies on rice mapping have been carried out using C-band SAR data. Kurosu, et al. (1995) demonstrated the relationship between the rice growth and multi-temporal ERS-1 SAR data. Theoretical studies using a coherent scattering model of rice canopy based on Monte Carlo simulations (Le Toan, et al., 1997; Wang, et al., 2005) have demonstrated that the co-polarized backscatter from rice fields covered by a water layer is dominated by the double bounce volume-ground interaction, with the dominant scatterers in the volume being the plant stems. Simulations of the temporal backscatter at HH and HV polarizations have shown a significant increase of the backscattering coefficient during the vegetative phase. The backscatter then decreases slightly during the reproductive phase until harvest. This temporal behavior was effectively reported and used for rice mapping and monitoring in a number of studies using ERS-1/2, ENVISAT ASAR and RADARSAT-1 data all around the world (Chakraborty, et al., 1997; Ribbes, et al., 1997; Panigravy, et al., 1999; Shao, et al., 2001; 2002; Chakraborty, et al., 2005; Dong, et al., 2005; Tan, et al., 2006; Ling, et al., 2007; Yang, et al., 2008; Wang, et al., 2008; Bouvet, et al., 2009). Backscatter was found to increase by more than 10 dB at HH and VV from the minimum value in the beginning of the growth cycle to the maximum value around the end of the vegetative phase. This unique temporal behavior has been exploited in rice mapping methods, in which this feature used for the classifiers are the temporal
changes of HH or VV backscattering.

Compared to co-polarized backscatter, much less effort has been put on the use of cross-polarized backscatter in rice mapping applications. ENVISAT ASAR data were used for rice mapping using a ratio between HH at one date at the end of the growth cycle and HV at another date at the beginning of the cycle (Chen, et al., 2007). Measurement of rice backscatter by multi-frequency and multi-polarization scatterometer showed that cross-polarization backscatter coefficients at C band and L band are well correlated with LAI and biomass of rice (Ioue, et al., 2002). However, backscatter at cross-polarization comes from the volume scattering of rice plants which is not unique to the rice plants. Therefore, more efforts should be carried out on rice mapping methods using cross-polarized data.

Regarding the aspect of rice monitoring using L band SAR, Ronsenqvist (1999) and Ouchi, et al. (1999, 2006) showed the Bragg resonance scattering phenomena in some mechanically planted rice fields on JERS-1 SAR HH images. The backscatter is subject to the planting structures (line orientation and spacing interval) and microwave incidence angle. Extremely enhanced backscatter can be observed when the Bragg scattering conditions are satisfied. Ishitsuka (2007) showed some different backscatter behaviors of rice fields at L band from that at C band based on the analysis of ALOS PALSAR. Wang, et al. (2009) demonstrated that L-band HH backscatter is more sensitive to rice’s structural variation than the VV backscatter and may therefore be more useful in rice mapping and modeling studies. ALOS PALSAR is the first L-band multi-polarimetric satellite SAR sensor in the world. However, its full polarimetric imaging is limited to certain experimental test sites, and the conventional operation mode is imaging with dual polarization, namely HH and HV. The swath and revisit time can satisfy the requirements of rice mapping. Ouchi, et al. (2006) concluded that L band SAR is not suitable for monitoring rice plants, in particular, machine-plantated rice plants, because of the strong Bragg scattering effect, based on the study of JERS-1 SAR with only HH polarization. Compared to the only HH channel of JERS-1 SAR, the HV channel of ALOS PALSAR provides a potential solution to the Bragg resonance scattering effect on the rice fields. Therefore, it is important to explore ALOS PALSAR dual-polarization data for rice mapping.

It is critical to acquire the SAR image at rice’s early growth stage for rice mapping with the temporal backscatter changes at C band. However, the acquisition time for the first image at rice’s early growth stage is not so strict for L band SAR while using the same mapping method because a rough surface at C band can be regarded as smooth due to longer wavelength. Thus, rice fields have low backscatter coefficient for L band in a wider period of early growing period than that for C band, which makes L band SAR more practical and suitable for rice mapping in a sense. In this paper, we analyzed the backscatter behavior of rice fields at L band SAR, as well as the mapping method using ALOS PALSAR dual-polarization data acquired in 2008 of Hai’an, Jiangsu province. First, the study site and the data were introduced and described. Second, the temporal and polarimetric behaviors of rice fields at L band was discussed, with an emphasis on the Bragg resonance scattering phenomena and its causes. In the end, we proposed a rice mapping method using the combination of HH and HV polarization images of ALOS PALSAR.

2 TEST SITE AND DATA

The test site used for this investigation is the Hai’an county (32°32’N—32°43’N, 120°12’E—120°53’E) in Jiangsu province, China. The annual average temperature is around 14.5°C, with the minimum of 1.7°C in January and the maximum of 27°C in July and August. The annual average precipitation is about 1025 mm. With warm climate and abundant precipitation, Hai’an is an important area of rice production in Jiangsu province. Following winter wheat or rapeseed, rice is planted as the second crop for over 90% of the local areas. All varieties, having 135-day growth period, are transplanted in early June and harvested in the middle of October. Young rice plants are transplanted into the fields by hand, throw or machine. Mulberry tree is another dominant crop during the rice season.

Table 1 shows the ALOS PALSAR data of the test site, as well as the parameters for the sensor. In wetland rice cultivation, five main periods can be distinguished: transplanting period, seedling development period, tillering period, head sprouting period and ripening period. The images acquired on June 30, August 15 and September 30 were corresponding to the periods of seedling development, tillering and ripening. Three scenes of TerraSAR-X images (3 m, HH/HV) and one ALOS AVNIR-2 image (10 m) were used for validation, together with GPS measurements from field surveys.

3 DATA PREPROCESSING

The preprocessing procedure involves (1) calibration, (2) image-to-image coregistration, (3) multilooking, (4) multichannel filtering (Quegan & Yu, 2001) and (5) geocoding. The spatial sampling is 10 m for the output.

The following formula provided by The Japan Aerospace Exploration Agency(JAXA) was used for radiometric calibration (Shimada, et al., 2009):

\[
\sigma_0 = 10\log(P + Q) + CF - 32.0
\]

where I is the in-phase component of the complex data, Q is the quadrature component, and CF is the calibration constant, which is –83.2 and –80.2 for HH and HV, respectively.

4 TEMPORAL BEHAVIOR OF RICE BACKSCATTER

Rice showed the same great temporal variations in backscatter on L-band HH images as that in C band. At the early growing stage of rice, low backscatter was observed due to specular reflection.
from the water surface, as shown by the rice backscatter for June 30 (2008-06-30) in Fig. 1. The dihedral structure formed by the water surface and the vertical plants becomes the dominant scatter element with the growth of the rice. The water content also increases with the development of the rice plants. The dihedral structure and the increase of the water content would combine to cause the increase of the radar backscatter, reaching the climax at the end of growing period, as shown by the rice backscatter for August 15 (2008-08-15) in Fig. 1. In reproductive stage, the top part of the plants contains more elements (panicle, grains, leaves etc.) than in vegetative phase. The elements are horizontally oriented and bent, leading to more scattering at this layer than the water-plant dihedral structure. The backscatter decreases with the increase of the attenuation by the horizontally oriented elements, as shown by the rice backscatter for September 30 (2008-09-30) in Fig. 1. The backscatter of rice in HV polarization increases continuously with the growth of the rice plants, making the temporal change trend of rice backscatter different from that in HH polarization (Fig. 1 (b)). The temporal change difference of rice backscatter between HH and HV originates from the change in the spatial orientation of the rice plants at different growth stages. On June 15 and August 30, when the data were acquired, rice plants showed dominant vertical spatial structures, which cause very strong water-plant dihedral reflection and high backscatter coefficients. However, the top part of the rice plants becomes bent because of the grains near the ripening stage on September 30. The dihedral reflection dominated HH backscatter was greatly attenuated by the horizontally distributed leaves and grains (Lopez-Sanchez, et al., 2009). With the change of spatial distribution structure of the plants from dominant vertical to more horizontal, the rice bunches becomes a more random and complicated volume scattering unit, causing more multi-bounces of the incident radar waves. In other word, the change of the spatial distribution caused more depolarization. Therefore, rice backscatter in HV polarization continuously increased with the increase of the randomness of the rice plants.

Mulberry tree, with its leaves as the food of silkworms, is another widely planted crop for the silk industry in this region. A special management method is applied to the mulberry plantations in order to improve the yield of the leaves. The trees are cut in late autumn, leaving the roots and 10—30 cm high trunks in the field. Tender branches will grow in the following spring and reach the maximum height about three meters in next autumn. This special cultivation causes the continuous vertical development of the mulberry trees every year, thus showing a similar temporal change trend as that of rice. It is not possible to separate them when we map rice fields by the temporal change of the backscatter, whereas the different absolute backscatter coefficient can be added as a second rule during the separation, as shown by Fig. 1 (b).

Extremely increased HH backscatter was observed of some rice fields (machine-rice in Fig.1), whereas the HV backscatter is the same as the ordinary rice fields. This usual phenomenon will be discussed in the following chapter.

5 BRAGG RESONANCE SCATTERING IN RICE FIELDS

The signature of “machineRice” in Fig. 1 is for the white area in the center of Fig. 2, with enhanced HH backscatter and similar HV backscatter as the usual rice fields. Field visit to this area manifested that these were mechanically planted rice fields with constant row direction and spatial intervals between rows. Bragg resonance scattering was the reason for the enhanced HH backscatter at L band SAR. The occurrence of the Bragg resonance scattering requires: (1) well defined row direction and spatial interval between the rows and (2) well defined phase between the neighbouring scatters.

The first condition for the Bragg resonance scattering to occur is defined as in Eq. (2), in terms of the structure parameters of the rice fields

![Fig. 1 Backscatter coefficients as a function of time](image)

(a) HH; (b) HV

![Fig. 2 Color composite of multi-temporal PALSAR images](image)

(a) HH; (b) HV
The radar backscatter from flooded rice fields is considered a result of four major scattering processes. The first scattering process is the reflection by the boundary (water surface) followed by backscattering from the leaves and a further reflection by the boundary. The second process is the reflection by the boundary (water surface) followed by backscattering from the leaves and a further reflection by the boundary. The third process is the double-bounce contribution. The dominant scattering mechanism is due to the multiple scattering from the quasi-randomly distributed elements within bunches of rice, etc., leaves, stems. The phases of the received signals are also randomly distributed and the second condition for Bragg resonance does not hold.

6 RICE MAPPING WITH MULTI-TEMPORAL PALSAR IMAGES

Two field visits were paid in August and October of 2008 to the mechanically planted rice fields, as shown in the center of Fig. 2 (a). We measured the average bunch spacing in range direction and the angle between north and planting directions. The measured Δy is about 20.1 cm. The angle between north and planting direction is 12° off north to east. Considering the orbit inclination 98.16°, γ = 20.16°. These measurements satisfy the first condition for the occurrence of the Bragg scattering.

The radar backscatter from flooded rice fields is considered to arise from four major scattering processes. The first scattering process is the direct scattering from leaves, and the second is the reflection by the boundary (water surface) followed by backscattering from the leaves and a further reflection by the boundary. The third mechanism is the double-bounce which is the reflection by the boundary followed by the second reflection by a bunch (and the reverse of the third process, i.e., reflections by the bunch first and then the boundary), and the fourth is multiple reflection (or volume scattering) by the leaves and/or water surface and stems.

The second condition for the Bragg resonance scattering to occur requires well defined phase difference between neighboring scattering elements. The well defined phase can be found in the case when the incident wave is reflected by the water surface and the regularly spaced bunches of stems, i.e., the double-bounce scattering. For L-band, the backscattering contribution involving leaves is much smaller, while the double-bounce contribution is even more significant than C-band, which has been confirmed by modeling (Le Toan, et al., 1997; Wang, et al., 2005) and by polarimetric SAR decomposition (Ouchi, et al., 2006). It should be noted that a horizontally polarized wave will encounter a phase shift of π upon each reflection with a medium denser than the surrounding air (i.e. refraction coefficient of medium greater than the refraction coefficient of air) such as the plant and the underlying boundary. Specular double bounce (two reflections) will consequently result in a phase shift of 2π of the backscattered wave. Therefore, the stable and constant phase shift between the neighboring rows of rice plants is preserved by the dominant double-bounce scattering mechanism, satisfying the second condition for Bragg resonance scattering to occur. The enhanced backscattering was only found in HH polarization images as indicated by Fig. 1. More than one bounce of the incident wave tends to depolarize the microwave pulse. The HV polarization data is a representation of the results of multi-reflection or volume scattering of the incident wave. The dominant scattering mechanism is due to the multiple scattering from the quasi-randomly distributed elements within bunches of rice, etc., leaves, stems. The phases of the received signals are also randomly distributed and the second condition for Bragg resonance does not hold.

The rice fields mapping capability of HH and HV images was compared, using the method of setting threshold to the temporal ratio image. The ratio image was produced from the data for the well-developed stage of rice (August 15) and the data for the early growing stage (June 30). Fig. 4 shows the ratio images of both HH and HV images. Rice fields have high ratio values will show white color in Fig. 4. The rice fields in the center of Fig. 4 (a) show different color from the other rice fields on the HH ratio image, whereas this difference does not exist on the HV ratio image as shown in Fig. 4 (b). Based on the analysis, a classification method was developed using single polarization images as shown in Fig. 5. In this paper, “image 1” and “image 2” in Fig. 5 represent the HH (or HV) intensity image of June 30 and August 15 correspondingly. The ratio image is calculated as σ_HH/σ_HV. The two thresholds were set for HV images as follows: (1) A = 5 dB to separate rice fields and mulberry plantations from other land covers; (2) B = -22 dB to further separate rice fields from mulberry plantations. Similar method was also applied to HH images with A = 7 dB and B = -12 dB. Fig. 6 shows the rice mapping results. First, we compared the results from HH and HV by visualization referring to the field inventory data. The advantage of HV over HH is obvious in Bragg resonance occurred areas that the right mapping result was achieved from only HV polarization images. Second, we validated and compared the results in the areas without Bragg resonance scattering influence. The overall rice mapping accuracy of HH and HV images are 88.4% and 86%, and with Kappa coefficients 0.77 and 0.72, respectively.
6.2 Rice mapping with HH and HV data combination

The rice mapping results from single polarization data suggest that HV polarization image could be of potential to map rice fields in Bragg resonance areas, whereas HH polarization images provides better accuracy in normal rice fields without Bragg resonance scattering. Therefore, the optimum method for rice mapping using dual polarization mode ALOS PALSAR data is to combine the two polarizations, namely HH and HV. The key to this method is how to identify those rice fields where Bragg resonance scattering occur. From the analysis in this paper, the Bragg resonance areas can be described as follows:

1. In HV polarization images, they show the same backscatter behavior as normal rice fields. The first step for the identification is to use the rice mapping method for general rice fields mapping with HV temporal ratio image.

2. In HH polarization images, they exhibit extremely high backscatter coefficient values. The second step for the identification is to set a threshold, say 2 dB, to the HH image of August 15 in this study.

Combining the above two rules, rice fields with Bragg scattering were identified as shown by the yellow area in Fig. 6 (c), which was used to update the rice map from HH images. Validation showed that, by adopting this rice mapping method of combining HH and HV images, not only the rice fields with Bragg scattering were mapped right, but also the overall mapping accuracy was as good as that of the rice map from HH images in areas without Bragg scattering influence (88.4%) as mentioned in the precious chapter.

7 CONCLUSIONS

In this paper, rice fields backscatter behavior at L band SAR was analyzed, using ALOS PALSAR dual polarization data (HH and HV) of Hai’an county, Jiangsu province. The causes of the backscatter behavior were explained by analyzing the scattering mechanism both at HH and HV polarizations. Based on the analysis, we proposed a rice mapping method by the synergistic use of HH and HV images of ALOS PALSAR. Conclusions were drawn:

1. Rice fields show a similar temporal change in L band SAR HH backscatter to that of C band SAR during the rice growth periods. A significant increase of the backscattering coefficient is observed during the vegetative phase. The backscatter then decreases slightly during the reproductive phase until harvest. HV polarization shows continuous increase of backscattering coefficient with the growth of rice plants.

2. Bragg resonance scattering occurs when the rice fields’ structure (row orientation and space interval) satisfies certain conditions in some machine-planted fields. The Bragg scattering causes greatly enhanced backscattering in some rice fields, making it difficult for rice mapping with L band HH images. The result from the analysis in this paper is consistent with that of Ouchi, et al. (2006), indicating of the inefficiency of L band HH data for rice mapping.

3. The HV polarization backscattering is from the quasi-randomly distributed elements within bunches of rice, e.g. leaves, stems. The phases of the received signals are also randomly distributed and the second condition for Bragg resonance does not hold. There is no difference in backscattering coefficient between machine-planted rice fields and manually planted rice fields. Therefore, HV polarization of ALOS PALSAR provides a solution to the Bragg resonance scattering effect.

4. A rice mapping method by the synergistic use of HH and HV images of ALOS PALSAR was proposed, and good results were achieved. The backscattering of HH polarization is from the water plant double bounce scattering, which is unique for the water flooded
rice fields. The backscattering of HV comes from the volume scattering of the rice plants, which is not unique to rice and can be observed in other land covers. Generally, HH provides more accurate rice maps than HV. However, HV polarization is not affected by Bragg resonance scattering because of the volume scattering. The Bragg resonance affected rice fields can only be identified using HV images. We conclude that the best method of rice mapping with ALOS PALSAR is to combine the HH and HV images. With the proposed method, rice mapping accuracy of about 88.4% was achieved.

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REFERENCES


ALOS PALSAR双极化数据水稻制图

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摘 要: 以江苏省海安县为研究区, 使用2008年获取的日本ALOS卫星PALSAR双极化模式数据, 分析水稻在L波段SAR图像上的后向散射特征, 并提出相应的水稻制图方法。水稻在L波段表现出与C波段相同的时相变化特征。HH极化后向散射依赖于水稻植株的空间分布结构, 某些机械插秧区域的布拉格共振现象引起水稻后向散射严重增强, 给利用PALSAR数据水稻制图带来了困难。而HV极化不存在布拉格共振现象。在考虑布拉格共振影响的条件下, 提出了联合PALSAR双极化模式HH和HV极化数据、基于时相变化特征进行水稻制图的方法, 获得了88.4%的制图精度。

关键词: ALOS, PALSAR, L波段, 水稻制图, 布拉格共振

1 引 言

水稻作为一项主食和生计系统, 在亚洲的可持续农业和农村发展框架中地位显著 (FAO, 2008)。中国是世界水稻产量大国, 水稻生产处于重要的位置。面对人口庞大且仍在增长的现状, 如何制定作物生产政策, 解决粮食问题, 已受到国家决策和生产部门的极大重视。急需了解中国水稻的分布面积及动态变化情况。从全球环境变化来看, 了解水稻生长区域对大气中甲烷(CH4)的排放非常重要。甲烷是仅次于二氧化碳(CO2)的第二大温室气体。

为了监测水稻产区面积和耕作强度的变化, 传统的水稻监测方法基于对地面收集资料的统计分析, 既耗时耗材, 又不准确。卫星遥感作为一种独特的工具, 持续不断地为此提供及时的、空间和时间上连续的数据。然而由于水稻多分布在热带、亚热带地区, 那里常被云雾覆盖, 给光学遥感技术的应用带来了困难。而合成孔径雷达(SAR)遥感具有全天时、全天候和穿云透雾的观测能力, 其作用在水稻监测中十分明显, 是最可靠的遥感数据源。利用C波段SAR监测水稻的研究很多, Kurosu等人(1995)的研究表明多时相ERS-1数据与水稻生长关系密切; Le Toan等人(1997)和Wang等人(2005)开展了基于蒙特卡罗模拟的水稻冠层相干散射模型的理论研究, 水稻作物生长期内后向散射系数不断增加, 从生殖期到成熟期略有下降。基于ERS-1/2, ENVISAT ASAR和RADARSAT-1数据, 从而多时相模拟表明, 在水稻作物生长期至成熟期后向散射系数不断增加, 从生殖期到成熟期略有下降。基于ERS-1/2, ENVISAT ASAR和RADARSAT-1数据, 从而多时相模拟表明, 在水稻作物生长期至成熟期后向散射系数不断增加, 从生殖期到成熟期略有下降。
从生长初期到生长末期，后向散射系数可增长10 dB，这一时相变化特征是过去利用C波段SAR进行水稻制图的主要方法。


ALOS PALSAR是世界上首个L波段(波长为23.6 cm)极化星载SAR传感器。其最大特点是具有全极化SAR数据获取能力，但仅限于在局部地区获取有限的研究数据。它常规运行在双极化(HH/HV)条带式扫描模式，幅宽和轨道重访周期均可满足水稻监测的常规运行。Ouchi等人(2006)分析了JERS-1 SAR数据(仅有HH极化)的水稻后向散射特征，得出了结论：由于布拉格共振现象的影响，L波段SAR不适合水稻监测。

相对于JERS-1 SAR，ALOS PALSAR增加的HV极化方式为解决布拉格共振的影响提供了可能，对PALSAR双极化模式数据进行水稻监测方法研究很有意义。

使用C波段(约5.6 cm)SAR时相差异进行水稻制图，水稻生长初期数据的获取至关重要。但L波段(约23 cm)波段相对较长，在C波段上表现为粗糙的地物在L波段上可表现为光滑表面。因此，对于L波段，水稻生长初期数据获取的时限更加宽松(Ishitsuka等，2007)。应用潜力更为广泛。本文采用2008年江苏省海安县的PALSAR双极化模式数据，开展水稻后向散射特征分析和制图方法研究。首先，对研究区的基本情况和数据获取进行介绍；其次，分析水稻在L波段SAR图像上的时相和极化特征，并着重对某些机械插秧田表现出的布拉格共振现象的特征和成因进行分析；最后，提出利用ALOS PALSAR双极化模式(HH/HV)数据进行水稻识别的方法。

2 研究区和数据

江苏省海安县被选为研究区，县域地理坐标位于32°32′N—32°43′N，120°12′E—120°53′E。年平均气温14.5℃，1月最冷，平均1.7℃，7、8月最热，平均27℃。年均降水量1025 mm，79%的年份在800 mm以上。气候温和，雨水充沛，是江苏省重要的水稻生产基地。一年双季作物，一季是冬小麦或油菜，第二季作物中，90%种植水稻，每年6月初开始插秧，10月中旬收割完毕，生育期在135 d左右。在该研究区水稻生长期内，桑园是该地区另外一种主要的农作物覆盖类型。获取了位于海安县内同一轨道、同一图幅号共6个时相的PALSAR双极化模式数据(表1)。水稻在生长周期内，有5个主要生长时期：插秧期、秧苗生长期、分蘖期、抽穗期和成熟期。其中6月30日、8月15日和9月30日获取的数据分别处于生长期、抽穗期和成熟期，同时获取了3景水稻生长期内的TerraSAR-X数据(3 m分辨率，HH/VV极化)和1景10 m分辨率的ALOS AVNIR-2多光谱数据(10 m分辨率)。在水稻生长期内共开展了3次地面调查(2008年7月、8月和10月)，获取了代表水稻、桑园、主要蔬菜和其他地类的81个GPS面数据，以及大量GPS点数据。高分辨率数据和GPS测量数据一起用作分类结果验证。
3 数据预处理

数据预处理是分析和分类的基础，本文的数据预处理流程为：(1)辐射定标；(2)图像对图像配准；(3)多视处理；(4)多通道滤波(Quegan和Yu，2001)；(5)地理编码。最终数据采样间隔为10 m。

采用日本宇宙航空研究开发机构(JAXA)提供的方法(式(1))进行定标，得到sigma0数据(Shimada等，2009)。

\[ \sigma^0 = 10 \log(\sqrt{I^2 + Q^2}) + CF - 32.0 \]  
式中，I和Q代表复型数据的实部和虚部；CF是定标常数，对于HH极化和HV极化分别为-83.2和-80.2。

4 水稻后向散射时相特征

和C波段SAR一样，水稻在L波段HH极化上的后向散射表现出很强的时相性：

(1)生长初期植株矮小，雷达波在光滑的水面发生镜面发射，回波极少，因此后向散射很弱(对应图1中2008-06-30的水稻1)；

(2)随着水稻竖直生长，水面和植株茎秆构成的二面角结构是主要的散射单元，加上植物生长引起含水量增加，雷达后向散射随之增加，在水稻生长期末达到顶峰(对应图1中8月15日的水稻1)；

(3)当水稻进入繁殖期，随著稻穗变得饱满，水稻植株结构发生变化，由竖直生长逐渐转向顶部下垂，稻穗和叶片趋向横向分布。横向分布的叶片和稻穗对后向散射雷达波的衰减增强，此时后向散射系数有所降低(对应图1中9月30日的水稻1)。在HV极化上趋势略有不同，即随着水稻生长后向散射系数持续上升(图1(b))，在图2(b)上水稻表现为蓝色。这种同极化与交叉极化水稻后向散射时相特征的差异源于水稻植株空间取向的变化。在本文数据获取的6月15日和8月30日，水稻主要呈现垂直空间取向。在这期间，随著水稻垂直生长，下垫面(水或泥)和植株构成的二面角散射不断增强。而在9月30日，水稻植株成熟，稻穗颗粒饱满，植株顶部下垂。一方面，横向分布的叶片和稻穗对二面角散射回波信号的衰减增强，引起HH极化后向散射降低(Lopez-Sanchez等，2009)；另一方面，叶片和稻穗的横向结构使得水稻植株成为一个越发随机、复杂的体散射结构，多路散射发生的几率增加。雷达波的多次散射增强去极化，而HV极化通道正是记录的这部分去极化信息。因此，HV极化后向散射随着水稻植株空间取向随机度增加而不断增强。

在水稻作物种植期内，桑树是另一种主要的农作物。桑园的生产管理有一个显著的特点：为了提高桑叶的产量，在秋末桑树被砍，仅留下略高于(10—30 cm)地面的主干，来年春天重新长出细长的嫩枝条，在八九月间长到3 m左右。这种特殊的耕作方式使桑园表现出持续地竖直生长，其雷达后向散射随时间的变化趋势与水稻相似。这使得利用极值法识别水稻时易引起二者混淆。但图1也显示了桑园的后向散射系数始终高于水稻，这可被用于二者区分。

我们发现某些机械插秧的稻田(图1中标注的水稻2)后向散射在HH极化上远高于其他地物，但在HV极化上与普通水稻田相当。接下来将对此加以分析。
针对图2(a)产生布拉格共振现象的机械插秧区域，我们进行了地面测量：(1)插秧走向大致为南北向，北偏东约12度；(2)行间距Δy约为20.1 cm。成像时卫星升轨飞行，轨道倾角为98.16度。因此，γ约为20.16度。这些参数符合式(2)。

水稻田雷达后向散射主要由4种基本的散射组成(Le Toan等，1997；Wang等，2005)：(1)水稻植株的直接散射，主要散射体为叶片；(2)水面(或土壤)和叶片构成的直接反射。雷达波穿透叶片到达水面形成一次镜面反射，到达叶片再次被弹回至水面，与水面形成二次镜面反射被卫星天线接收；(3)水面和成束的植株茎秆构成的二面角散射；(4)植株体内部的多次散射，或称为体散射。

水稻对C波段和L波段雷达波的散射特性已通过蒙特卡罗模拟模型(Le Toan等，1997；Wang等，2005)和对机载全极化数据进行极化目标分解获取散射机制信息(Ouchi等，2006)得以证实。相比C波段，L波段雷达波波长更长，水稻叶子对散射的贡献更小，二面角散射的主导作用更为明显。对于水平极化的电磁波，当在比周围空气密度更大的介质上反射一次，将引起相位弧度的改变。镜向的二面角反射(两次反射)将引起弧度的后向散射回波相位的变化。因此，在HH极化上，二面角散射的主导性机制使得相邻两行间距恒定的水稻具有稳定有规律的相位差，满足布拉格共振产生的第二个条件。

6 多时相PALSAR水稻制图

通过对L波段PALSAR水稻后向散射分析得知，水稻后向散射无论在HH还是HV极化上都有很强的时相性，但是同化化数据的布拉格共振现象使得这种时相性在不同地点表现不一致。交叉极化(HV)数据不受布拉格共振的影响。
6.1 单极化水稻制图

本文采用对两个时相比值图像设定阈值的方法进行水稻识别，并比较HH和HV极化的识别能力。首先利用水稻生长期旺盛期(8月15日)和生长期初期(6月30日)数据计算了强度比值图像(图4)，水稻区域呈偏白色调。从图4(a)HH极化比值图像可见，由于电磁区域布拉格共振现象的影响，位于图像中心部分的水稻并不明显。而在图4(b)HV极化图上，该区域和其他水稻田同样明显。基于数据分析结果，构建了利用单极化数据识别水稻的分类方法(图5)。图6(a)中图5的“图像1”和“图像2”分别为6月30日和8月15日的HH或HV极化后向散射强度图像，计算得到比值图像(σ₂/σ₁)。

对于HV极化，设定了两个阈值：(1) A = 5 dB，把水稻田和桑园从其他地类中区分开；(2) B = -22 dB，区分水稻田和桑园。类似的方法也应用于HH极化图像上，将输入换成对应的HH极化图像，阈值分别为 A = 7 dB和B = -12 dB。

图7是水稻制图结果。首先基于实地调查数据通过目视对由HH和HV的制图结果进行了比较，在布拉格共振发生区域二者的识别能力显著容易见(如图6中间部分)：HH极化数据无法正确识别水稻，HV则可以。其次，对没有布拉格共振现象影响的区域的制图精度进行验证，HH极化和HV极化数据分类总体精度分别为88.4%和86%，Kappa系数分别为0.77和0.72。

6.2 HH和HV极化联合水稻制图

由单极化水稻识别结果可知，在布拉格散射区域唯有HV极化能准确识别水稻，但在没有布拉格散射发生的区域，HH极化的识别精度稍高。将两种极化数据相结合是利用ALOS PALSAR双极化数据进行水稻制图的合理方法。关键在于如何识别布拉格散射区域的水稻田。根据前述分析，可从如下两方面描述这些区域的后向散射特征：

(1) 在HV极化上普通水稻田特征相同。即如6.1节所述利用图5所示方法识别包含布拉格散射区的水稻田；

(2) 在HH极化上后向散射系数值异常高。如图1所示在8月15日HH图像上超过2 dB。
依据这两个条件可以准确识别布拉格散射发生的水稻田(图6(c)黄色区域),并利用其更正由图5所示方法得到的HH极化水稻分布图。图6(c)显示了利用这种方法得到的HH和HV极化图像联合得到的水稻分布图。验证表明,不仅布拉格散射区域的水稻田得到了准确识别,而且,总体识别精度与HH极化数据在无布拉格散射发生区域的制图精度相当。

7 结 论

用江苏省海安县多时相ALOS PALSAR双极化(HH/HV)数据分析了L波段SAR水稻的后向散射特征,包括时相变化特征和布拉格共振现象,并从两种极化雷达波的散射机理出发做出了解释。基于分析结果,提出了联合同极化和交叉极化数据进行水稻制图的方法。研究结论可归纳如下:

(1)随着水稻的生长,其在L波段HH极化SAR的后向散射特征变化与C波段SAR规律相似,从生长初期后向散射很低,到生长旺盛期后向散射达到顶峰,最后在成熟期略有降低;HV极化变化趋势与之略有不同,随着水稻生长,后向散射不断增强。

(2)某些机械插秧的水稻田在L波段HH极化SAR上的布拉格共振现象是水稻制图应考虑的重要因素,这一特殊的后向散射机制引起了行向和行间距符合一定规则的水稻田的后向散射系数严重增强,改变了常规的时相变化特征。本文的分析结果与以往研究相符(Ouchi等,2006),单独采用L波段同极化数据水稻制图的结果不佳。

(3)交叉极化(HV极化)回波信号主要来自水稻植株散射体内部随机分布的叶片、枝干等散射单元,由此产生的回波信号的相位也是随机的,不满足布拉格共振条件。在机械插秧和传统插秧区域水稻后向散射特征一致。因此,HV极化可以有效解决布拉格共振现象对L波段SAR水稻制图的限制。

(4)提出了联合ALOS PALSAR HH和HV极化数据的水稻制图方法,并取得了很好的效果。HH极化后向散射信号主要来自水稻植株的二面角反射,这些信号的相位也是随机的,不满足布拉格共振条件。在机械插秧和传统插秧区域水稻后向散射特征一致。因此,HV极化可以有效解决布拉格共振现象对L波段SAR水稻制图的限制。HH极化数据联合使用L波段SAR进行水稻制图的最佳选择。应用这种方法,文中水稻制图精度达到了约88.4%。

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