On the Bragg Scattering Observed in L-Band Synthetic Aperture Radar Images of Flooded Rice Fields

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SUMMARY This article presents the analysis of the Bragg scattering phenomenon which has been observed in the images of machine-planted rice paddies acquired by the JERS-1 L-band synthetic aperture radar (SAR). The simultaneous measurements of rice plants were made at the SAR data acquisition times. Large differences of 20–25 dB in image intensity between the transplanting and ripening stages are found to be dependent on the planting direction and bunch separation. This selective image enhancement is a result of the Bragg resonance backscatter due to the double-bounce of incident L-band microwave between the flooded water surface and periodically planted bunches of rice plants. Support for the idea of double-bounce scattering is provided by the decomposition analysis of L-band and X-band polarimetric Pi-SAR data; and a simple numerical simulation based on the physical optics model shows fairly good agreement with the JERS-1 SAR data. The results presented in this paper is mainly of academic interest, but a suggestion can be made on the selection of suitable microwave band for monitoring rice fields.

key words: synthetic aperture radar (SAR), Bragg scattering, rice plants, JERS-1 SAR, Pi-SAR

1. Introduction

The Bragg scattering phenomenon was first reported in the X-ray diffraction from crystals [1], and the results were reformulated by Bragg in 1913 [2], [3] (the paper was first read in November 1912 after the presentation of [1] in June 1912), followed by the analysis of the X-ray diffraction pattern from the structure of diamond [4]. In 1955, this scattering mechanism revived in a rather different research field of remote sensing in the radio wave band as the enhanced radar backscatter from ocean waves [5]. Over land, the Bragg scattering from rice plants was reported [6], [7] showing that the JERS-1 L-band SAR images of mechanically planted rice fields showed strong radar backscatter if the planting orientation, incidence angle and the distance between the bunches of rice plants are matched to the Bragg resonance condition. During the process of developing a monitoring system of rice plants by multi-frequency polarimetric SARs [7]–[11], the enhanced backscatter was observed in the JERS-1 and airborne Pi-SAR (Polarimetric interferometric-SAR) [12] L-band images of flooded rice fields in the Kojima district, Okayama, Japan.

In this paper, we develop the previous experimental result [6], [7] to a step further to interpret, in a more quantitative manner, the Bragg scattering mechanism in the JERS-1 SAR data of the Kojima rice fields. Simultaneous field measurements were made with the SAR flights, and LANDSAT-TM data were also collected for comparison with the SAR data. Double-bounce of incident microwave between the flooded water surface and the bunches of rice plants is found to be responsible for the observed Bragg scattering, and a support to this double-bounce is given by the three-component decomposition analysis [13] of the L-band and X-band polarimetric Pi-SAR images. A simple numerical simulation based on the physical optics scattering model is carried out to verify the Bragg scattering phenomenon observed in the JERS-1 SAR images.

2. Experimental Results

2.1 Field Data

The field data in the test site were collected from 1998 to 2001, although some measurements were restricted to several parameters of limited sample areas. The test site consists predominantly of rice paddies with farming houses, roads, irrigation canals, some lotus ponds and non-rice vegetation fields. The most of rice paddies are divided into the size 50 × 50 m or 100 × 50 m, but some fields are further divided into smaller sizes. The farming practice is such that wheat seeds are sown in Dec., and after harvesting in May in the following year, the fields are ploughed and flooded in early June. Transplantation of young rice plants from nurseries is made by machines in the middle of June and harvesting starts in late Oct. Because of the machine transplantation, the bunches of plants have regular intervals ranging from 17 to 26 cm.

Table 1 shows the measured parameters of rice plants from 80 divisions of the fields. At the JERS-1 SAR data acquisition on the 24th of June 1998, the transplantation from nurseries was just finished. The plants grew to about 1.1 m in height on the 20th of Sept. Harvesting started in Oct., but...
Table 1  Parameters of rice plants in 1998. The units are all in centimeters (cm) except the number of leaves.

<table>
<thead>
<tr>
<th>parameters</th>
<th>24 June</th>
<th>20 July</th>
<th>7 Aug.</th>
<th>20 Sept.</th>
</tr>
</thead>
<tbody>
<tr>
<td>height</td>
<td>16</td>
<td>49</td>
<td>72</td>
<td>109</td>
</tr>
<tr>
<td>numberof leaves</td>
<td>69</td>
<td>82</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>leaf width</td>
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<td>1.0</td>
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<td>1.3</td>
</tr>
<tr>
<td>leaf thickness</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>bunch diameter</td>
<td>N/A</td>
<td>5.0</td>
<td>6.0</td>
<td>7.6</td>
</tr>
</tbody>
</table>

on the 12th of Oct. the JERS-1 satellite was terminated and no JERS-1 SAR data were available since that month. The bunch spacing was measured after harvesting. The biomass was not measured in 1998, but the extensive field measurements from several 1 m × 1 m sample areas in 2001 showed that the average total biomass increased up to approximately 2.5 kg/m². Note that the field data on the 20th of July in Table 1 are taken only as a reference and the date do not correspond exactly to the JERS-1 data acquisition.

2.2 JERS-1 and LANDSAT Data

The JERS-1 SAR operated at L-band of wavelength $\lambda = 23.5$ cm (frequency 1.275 GHz) with HH-polarization the nominal incidence angle $\theta = 39^\circ$, and the single-look azimuth and range resolution of $\rho_x = 6$ m and $\rho_y = 18$ m respectively. It was launched in Feb. 1992 with the repeat cycle of 44 days and terminated in Oct. 1998, just before harvesting in the Kojima test site. From 1999 the RADARSAT-1 C-band SAR data, and airborne Pi-SAR [12] and AIRSAR data [8], [14] were used for the project. In the present paper, however, analysis is carried out only for the JERS-1 L-band, and Pi-SAR L-band and X-band data. Six sets of JERS-1 SAR raw data were collected over the test site before irrigation to harvest during each year in 1997 and 1998. For the purpose of comparison, two sets of LANDSAT-TM data were also collected in on the 31st of May and on the 18th of July, 1998. We could not find any other LANDSAT data free from cloud cover during the project from 1998 to 2001.

Figure 1 shows the NDVI (normalized difference vegetation index) computed from the two sets of LANDSAT-TM data over the Kojima rice fields in 1998. The NDVI, which is a measure of the amount of vegetation, is defined as

$$\text{NDVI} = \frac{\text{NIR} - \text{VIR}}{\text{NIR} + \text{VIR}} \quad (1)$$

where NIR and VIR correspond respectively the reflectivities of the Near Infra-Red band and the Visible Red band. The NDVI on the 31st of May is represented by magenta color and that on the 18th of July by green. In May, the fields were flooded with water without any rice plants, and the NDVI takes very small values. While in July the rice plants were grown to approximately 50 cm yielding large NDVI values. The areas in green in Fig. 1 indicate that the fields are predominantly rice fields, and the field survey also confirmed this. Thus, under favorable weather conditions, the optical data can be a powerful source of information to monitor rice fields.

Figure 2 is the multitemporal JERS-1 SAR data over the test site. The images acquired on the 24th of June and on the 7th of Aug. 1998 are colored in magenta and green respectively. On the 24th June, the young rice plants of mean height 16 cm were just transplanted from nurseries, and there was little backscatter RCS of about $-23$ dB from the flooded water surface. As is well known, small vegetation such as young rice plants is too small to backscatter the L-band microwave. On the 7th of Aug., the plants grew to the mean height of 72 cm (see Table 1), so that a small amount of L-band radar backscatter can be expected. However, unlike the LANDSAT-TM NDVI data of Fig. 1, the multitemporal JERS-1 SAR image in Fig. 2 does not show
the rice growth over the entire fields, but only selected fields give rise to strong radar backscatter as indicated by green color.

It is useful at this point to define the coordinate system of the rice fields. In Fig. 3, $\gamma$ is the angle of plantation measured from the range direction, $x$ and $y$ are the azimuth and range spatial variables respectively, $\Delta x$ and $\Delta y$ are the bunch spacings in the corresponding directions, and $(r_m,n,\beta_m,n)$ is the polar coordinate position of a bunch $(m,n)$ at the rectangular coordinate position $(x_m,n,y_m,n)$.

Figure 4 shows the image intensity as a function of months in the rice fields with the off-range angles of $\gamma = 1^\circ$ and $8^\circ$ in the top and bottom graphs respectively. In May the 11th, the fields were ploughed and covered with bare soil, so that the average intensity ($\sim -21$ dB) is larger than that ($\sim -23$ dB) of the data on the 24th of June when the fields were flooded with small rice plants just transplanted from nurseries. The image intensity increases substantially on the 7th of Aug., and decreases slightly on the 20th of Sept. Similar intensity increase has been observed in the fields with off-range angles of $15^\circ$, $38^\circ$, and $87^\circ$ (not shown in this paper). These areas of increased intensity correspond to those indicated by green color in Fig. 2. As will be shown later, this selective image enhancement is due to the regularly spaced bunches of machine-planted rice plants, which satisfy the Bragg resonance condition.

The upper and lower diagrams in Fig. 5 are the temporal intensity variations of the rice fields located at the off-range angles of $\gamma = 28^\circ$ and $51^\circ$ respectively. These areas correspond to the (non-green) dark areas without temporal changes in Fig. 2. None of the fields in these off-range angles and bunch spacings satisfy the Bragg condition; and, unlike Fig. 4, there is no marked increase in image intensity with time. Other fields which do not show the intensity increase are those of the off-range angles of $56^\circ$, $65^\circ$, and $76^\circ$. For the fields that do not satisfy the Bragg condition, the RCS increases from the specular water surface to grown rice plants only by a few dB. Thus, the rice plants in these test sites are almost transparent to the L-band microwave of
the JERS-1 SAR.

2.3 Bragg Resonance Condition

Enhanced radar backscatter occurs from the fields where the scatterers (bunches of rice plants) satisfy the Bragg resonance condition defined as

$$\Delta y = \frac{\lambda}{2 \sin \theta \cos \gamma}$$

(2)

Figure 6 shows the image intensity of the Aug. data as a function of the average bunch spacing $\Delta y$ in range direction for the fields with the off-range angles $\gamma = 1^\circ$, $42^\circ$. The solid and broken vertical lines indicate the bunch spacings that satisfy the Bragg condition for $\gamma = 1^\circ$ and $42^\circ$ respectively. From Eq. (2), these spacings are respectively 18.7 cm and 25.1 cm. As in Fig. 6, the observed intensity peaks are in good agreement with the theoretical bunch spacings that satisfy the Bragg condition.

For the Bragg resonance scattering to occur, the received signals must have well defined phase difference between neighbouring scattering elements. From the previous studies [15]–[17] the radar backscatter from flooded rice fields is considered to arise from four major scattering processes as illustrated in Fig. 7. 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 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 forward and reverse double-bounce terms can be treated principally as a same process. If the dominant scattering mechanism is due to the direct scattering from quasi-randomly distributed leaves, the phases of the received signals are also randomly distributed, and the resonance condition does not hold. The same applies to the last multiple reflection. For the reflection from the boundary to leaves and retro-reflection by the boundary, the phases of the return signals are also spatially random. It is likely, therefore, that the phases of the backscattered field are spatially random if the scattering process involves randomly distributed leaves. The well defined phases that satisfy the Bragg resonance condition 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.

The model calculation of the C-band RCS from rice plants of similar parameters of Table 1 has also shown that the direct volume scattering is comparatively negligible (less than $-20$ dB), and that the backscatter results primarily from the double-bounce term [16]. For L-band, the backscattering contribution involving leaves is much smaller, and the double-bounce contribution is even more significant than C-band [18]. It is then a good approximation to consider that the L-band backscatter arises almost entirely from the discrete contributions of double-bounce between the water surface and the bunches of rice plants.

2.4 Evidence for Double-Bounce Scattering

A further support to the double-bounce scattering between the water surface and bunches of rice plants can be given by the three-component decomposition analysis [13] of polarimetric Pi-SAR data. In this analysis, the backscattered power is decomposed into the surface, double-bounce and volume scattering (the 4th component of helix scattering is included in the recent work [19]). Briefly, the analysis is carried out in the following manner.

The scattering matrix is defined by

$$S = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix}$$

(3)

where $S$ is the complex scattering matrix consisting of $S_{ij}$ ($i = H, V; j = H, V$) complex components, and each component is defined, using the amplitude $|S_{ij}|$ and phase $\phi_{ij}$, by $S_{ij} = |S_{ij}| \exp(i \phi_{ij})$. For the monostatic radars, $S_{HV} = S_{VH}$. The phases of $S_{ij}$ are not absolute, so that their values are

![Fig. 6](image1.png) Intensity variation of the image acquired on the 7th of Aug. 1998 as a function of the bunch spacing $\Delta y$ in range direction for the off-range angles $\gamma = 1^\circ$, $42^\circ$. The vertical solid and broken lines indicate the bunch spacings for which the Bragg resonance condition is satisfied for $\gamma = 1^\circ$, $42^\circ$.

![Fig. 7](image2.png) Mechanisms of L-band microwave backscatter by rice plants.
determined with reference to the phase of the complex amplitude of a particular $S_{ij}$. In general, the reference phase is taken as that of $S_{HH}$. The three-component decomposition analysis states that under the condition $S_{HH}S_{HV}^{\ast} \approx S_{VV}S_{HV}^{\ast} \approx 0$, the following 3 equations with 4 unknown parameters $a$, $b$, $f_s$, $f_d$ can be deduced.

\begin{align}
\langle S_{HH}^2 \rangle &= f_s|b|^2 + f_d|a|^2 + f_v \\
\langle S_{VV}^2 \rangle &= f_s + f_d + f_v \\
\langle S_{HH}S_{VV} \rangle &= f_s b + f_d a + f_v/3
\end{align}

where the angular brackets indicate taking an ensemble average. In Eq. (4), $f_s$ and $f_d$ are the surface and double-bounce contributions, and $f_v$ is the volume scattering contribution given by $f_v = 3\langle S_{HV}^2 \rangle$. Equation (4) cannot be solved unless one of the unknown parameters is known. It is possible to assume that the surface scatter is dominant and put $a = -1$, if the real term of $\langle S_{HH}S_{VV} \rangle$ is negative, then the double-bounce is dominant with $b = 1$. Once the values of $a$, $b$, $f_s$, $f_d$ are known from Eq. (4), the power of surface, double-bounce and volume scattering can be estimated from

\begin{align}
P_s &= f_s(1 + |b|^2) \\
P_d &= f_d(1 + |a|^2) \\
P_v &= 8f_v/3
\end{align}

where $P_s$ and $P_d$ are the powers of the surface and double-bounce scattering respectively, and the power of the volume scattering $P_v$ can be estimated directly from the cross-polarization contribution $f_v = 3\langle S_{HV}^2 \rangle$.

The result of the decomposition analysis of the L-band polarimetric data acquired on the 13th of July 1999 is shown in Fig. 8. The double-bounce, volume and surface scatterings are represented by red green and blue respectively. The azimuth and range directions are from top to bottom and from right to left respectively, and the incidence angle at the scene center is 38.4°. At the time of data acquisition in July, the rice plants were grown to their height approximately 50 cm with irrigation water underneath.

The vertical red lines in the district marked “A” correspond to irrigation canals and narrow roads with canals alongside. These lines are at right angles to the radar illumination direction, so that the strong double-reflection occurs between the water surface and canal banks, similar to the double-reflection by corner reflectors. There are several blue linear features along irrigation canals indicating the surface scattering from the canal banks with their sides facing toward the radar. The surface scattering can also be seen along the canals in the district “B.” These canals are closely, but not exactly, at right angles to the radar illumination direction. The canals and roads in the districts “C” and “D” are not at right angles to the radar illumination direction, and hence the double-bounce is not a dominant scattering mechanism in these districts. Small red images along the roads are the result of double-bounce between house flanks and ground, and between the water surface and the bridge connecting the district “A” and “C” at lower left.
From Eqs. (6)–(9) the image intensity stalks, and between leaves and tributary randomly. The backscatter from the lotus ponds is a result of the double-bounce between the water surface and stalks, and between leaves and/or stalks.

The L-band decomposition result of Fig. 8 can be compared with the X-band decomposition result shown in Fig. 9. At X-band, the backscattering from rice fields is dominated by the surface scattering from the leaves of rice plants on the crown part. The volume scattering is caused mainly from tall vegetation including shrubs, reeds and lotus plants. The double-bounce scattering is only due to the house flanks and ground, and also the bridge at lower left. The effect of double-bounce from the canals is reduced considerably, because plants on the canal banks are “rough” for X-band microwave, yielding diffuse scattering (but they are “smooth” at L-band).

The result of the decomposition analyses of L-band and X-band data is a further support to the Bragg resonance scattering which arises from the double-bounce scattering between the water surface and the regularly spaced bunches of rice plants.

2.5 Simulation Study

Under the assumption that the L-band radar backscatter from flooded rice fields comes from the discrete contributions of double-bounce scattering between the water surface and the bunches of rice plants, a simple simulation study based on the physical optics scattering model is carried out to compute the RCS from quasi-regularly spaced bunches of rice plants. In the simulation model, the backscattered complex amplitude is given by

\[ E = E_0 \sum_{m,n=-\infty}^{\infty} W_{m,n} \sqrt{\sigma_{m,n}} \exp(i\phi_{m,n}) \] (6)

where \(E_0\) is the normalizing constant, \(W_{m,n}\) is a point spread (impulse response) function defined by

\[ W_{m,n} = \sin(\pi x_{m,n}/\rho_x) \sin(\pi y_{m,n}/\rho_y) \] (7)

\(\sqrt{\sigma_{m,n}}\) is the scattering amplitude from a bunch at \((x_{m,n}, y_{m,n})\) as in Fig. 3, and \(\rho_x\) and \(\rho_y\) are the resolution cells in the corresponding directions. The phase is given by

\[ \phi_{m,n} = 2k \sin(\theta) r_{m,n} \cos(\gamma + \beta_{m,n}) \] (8)

and the polar coordinate parameters are

\[ r_{m,n} = \left( (m \Delta x)^2 + (n \Delta y)^2 \right)^{1/2} \]
\[ \beta_{m,n} = \arctan((m \Delta x)/(n \Delta y)) \] (9)

where From Eqs. (6)–(9) the image intensity \(I = EE^*\) is computed where the asterisk denotes taking complex conjugate.

The parameters entering into Eqs. (6)–(9) are known or measured from the field measurements, except for the backscatter amplitude \(\sqrt{\sigma_{m,n}}\) from individual bunches. Because of this unknown parameter, the simulated intensity is normalized by the mean background intensity of the image areas with non-Bragg scattering. In the Kojima rice paddies, the most of transplanting machines are designed to transplant 6 bunches together. The spacing of these 6 columns are fairly accurate, but the next column and row are often displaced from the first when the planting machine takes a corner-turn. The amount of displacement depend on the farmer’s driving skill. The field measurements show that the errors in \(\Delta x\) and \(\Delta y\) are approximately 15 cm and 12 cm respectively for both the cases of (1) \(\Delta x = 30\) cm and \(\Delta y = 19\) cm, and (2) \(\Delta x = 30\) cm, \(\Delta y = 25\) cm. These random fluctuations are included in the simulation and also the scattering amplitude \(\sqrt{\sigma_{m,n}}\) is assumed to be Gaussianly distributed about its mean, and the mean amplitude is estimated from the SAR data.

The image intensity averaged over 10 realizations is shown in Fig. 10 for the two cases, where the solid lines are the simulation results and circles are the JERS-1 SAR data. Increasing the number of realizations reduces noise to some extent, but does not change the simulation results significantly. A fairly good agreement can be seen between the simulation result and JERS-1 SAR data as shown in Fig. 10.

3. Conclusions

Results and discussions are presented on the enhanced radar backscatter observed in the JERS-1 L-band SAR images of
machine-planted rice fields. The ground-truth, decomposition analysis of airborne Pi-SAR data and a simulation study based on the physical optics scattering model have shown that the selective enhanced backscatter is a result of the Bragg resonance scattering from the double-reflection between regularly spaced bunches of rice plants and irrigated water surface. The present paper is mainly of academic interest, but it is reconfirmed that L-band SAR is not suitable for monitoring rice plants, in particular, machine-planted rice plants, because of the strong Bragg scattering effect.

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References


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