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Estimation of burnt coal seam thickness in central Borneo using JERS-1 SAR data

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Abstract. We analysed the interaction of microwaves with a burnt coal seam. This analysis approximated a burnt coal seam as a microwave absorber. The impedance of an incident wave with horizontal polarization (transverse magnetic mode) was derived in order to calculate the relationship between burnt coal seam thickness and backscattering coefficient. The result was confirmed by simulating scattering on a burnt coal seam using the Finite Difference Time Domain (FDTD) method. Both were similar. This relationship was used to estimate burnt coal seam thickness in central Borneo using Japanese Earth Resources Satellite (JERS-1) SAR data. Estimation results and ground data were similar.

1. Introduction

In 1995 the Indonesian government started to open up a peatland area in central Borneo with the aim of converting it to agricultural use. This initiative is known as the 'one million hectares peatland project' (Sarbini 2000). Figure 1 shows the study area (Csar 1997). Vegetation was burnt causing coal seam fires that penetrated underground, and which were difficult to extinguish and to detect by eye. Therefore, it was important to investigate burnt coal seam thickness ξ in order to predict fire position underground and to prevent fires spreading.

In this study, analysis was done to investigate the physical mechanism that linked ground data and remotely sensed data. Hence, analysis of microwave scattering from burnt coal seams was undertaken to estimate the relationship between ξ and the backscattering coefficient σ°. The results were confirmed by simulation of scattering using the Finite Difference Time Domain (FDTD) method (Yee 1966, Tetuko *et al.* 2001a). Subsequently, the potential to use this relationship to estimate ξ from JERS-1 SAR data was evaluated.

2. Analysis and simulation

In this study, a burnt coal seam was approximated to be a microwave absorber. The model used in the analysis and its equivalent circuit are shown in figure 2. Where Z_{TM}, Z_L and Z_C were the effective impedances of incident wave, peatland and burnt coal seam (including fire scars or tree stands), respectively. Air and peatland (supposed to be a perfect conductor) had infinite length. Burnt coal seam

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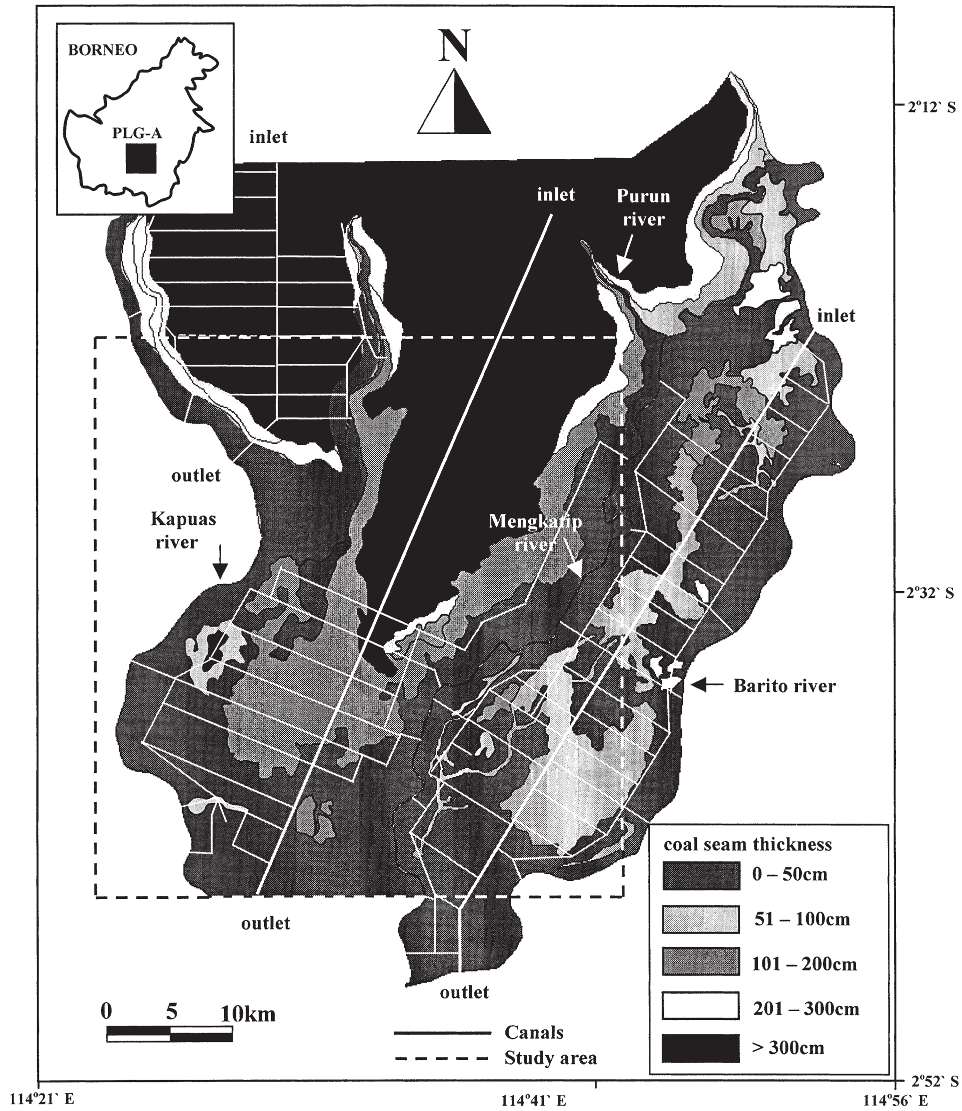

Figure 1. Location of the study area and ground data.

had ξ thickness. The incident wave was approximated as a plane wave with horizontal polarisation and incident angle θ_i.

Based on transmission line theory (Tanaka 1972), impedances of each medium became

$$Z_C = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \tag{1}$$

$$Z_L = 0 \qquad \text{(a perfect conductor)} \tag{2}$$

$$Z_{TM} = \frac{Z_0}{\varepsilon_r}\sqrt{\varepsilon_r\mu_r - \sin^2\theta_i}\,\tanh\left(j\frac{2\pi\xi}{\lambda}\sqrt{\varepsilon_r\mu_r - \sin^2\theta_i}\right) \tag{3}$$

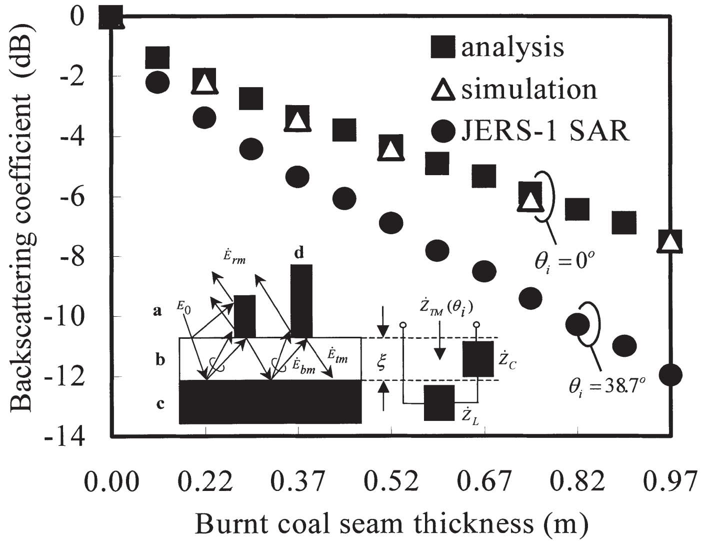

Figure 2. Model used in the analysis and its equivalent circuit, where E_{rm}, E_{tm}, and E_{bm} are the electric field of reflected waves, transmitted waves and waves that are reflected by peatland, respectively ($m = 1, 2, 3, ...$), θ_i and E_o were the incident angle and the intensity of incident wave, respectively. a, b, c and d are air, burnt coal seam, peatland media and fire scars or tree stands, respectively. The total reflected wave was approximated by $E_y^{scat} = E_{r1} + E_{r2} + E_{r3} + \ldots$. The plot shows the relationship between burnt coal seam thickness and backscattering coefficient: analysis, simulation and JERS-1 SAR.

Where Z_0, ε_r, μ_r and λ were the intrinsic impedance ($= 120\pi\,\Omega$), complex dielectric constant, complex specific permeability ($\mu_r = 1 + j0$), and wavelength, respectively. In addition, j was equal to $\sqrt{-1}$. The dielectric constant ε_r of several burnt coal seam samples was measured using dielectric probe kit HP85070B and it was obtained as $\varepsilon_r = 2.5 - j0.1$. Then the reflection coefficient was denoted as

$$\Gamma = \frac{Z_{TM} - Z_0 \cos\theta_i}{Z_{TM} - Z_0 \cos\theta_i} \tag{4}$$

Finally, the backscattering coefficient was defined by equation (5).

$$\sigma^\circ = 20\log_{10}|\Gamma| \tag{5}$$

By substituting each parameter and ξ (0 m to 1 m) in equation (1)–(5), a relationship between ξ and was obtained and this is shown in figure 2 (σ°). In this study, the FDTD method was employed to simulate scattered waves from burnt coal seams to confirm the result of the analysis above. Constants of the simulation were similar to constants in Tetuko *et al.* (2001a). Peatland thickness (a perfect conductor), computation time t and an observed point Q were $50\,\Delta x$ m, $1200\,\Delta t$ s and $120\,\Delta x$ m (from peatland surface), respectively. Where Δx and Δt are the space and time increments. The incident wave was a Gaussian pulse with pulse width $\tau = 2 \times 10^{-9}$ s and initial location at $150\,\Delta x$ m from the peatland surface. A scattered electric field was observed at point Q. Subsequently, a fast fourier transform was employed to obtain the electric field intensity of preferred frequency ($f = 1.275$ GHz). Finally, the backscattering coefficient was calculated by

$$\sigma^\circ = 20\log_{10}(|E_y^{scat}|/|E_y^{inc}|)_{f=1.275\ \mathrm{GHz}} \tag{6}$$

where E_y^{scat} and E_y^{inc} are observed electric field intensities in frequency $f = 1.275$ GHz of the scattered wave that are scattered by the burnt coal seam and peatland only, respectively. The derivation of equations (1)–(5) and simulation were discussed fully in Tetuko *et al.* (2001b).

The analysis and simulation (Δ) results are shown in figure 2 ($\theta_i = 0°$). Both are similar. By considering the influence of JERS-1 SAR incident angle $\theta_i = 38.7°$ (David *et al.* 1997), a relationship between ξ and $\sigma°$ for JERS-1 SAR was obtained (●). In the next section, the result was used to estimate ξ in the study area using JERS-1 SAR data.

3. Data processing and classification

The JERS-1 SAR data (path 95, row 305, 29 July 1997) used to estimate ξ was processed at level 2.1 by the Earth Observation Research Centre of the National Space Development Agency of Japan. Firstly, a 3×3 median filter was employed and, secondly, a 5×5 average filter was used to reduce inherent speckle noise (Tetuko *et al.* 2001a). At the same time, the image was also referenced to the universal transverse mercator co-ordinate system, through a polynomial rectification using 30 ground control points collected from aerial (Bakosurtanal 1990) and topographic maps with scale 1:50 000 (Bakosurtanal 1991). This procedure yielded a geometric accuracy of 0.1 pixels. Then the spatial resolution of the image was resampled to 12.5 m.

A supervised classification was performed to classify the image into six classes. The aerial and topographic maps, ground data and SPOT-HRV data (29 July 1997) were used to select training sites, i.e. paddy field, bush swamp, forest, bush land, burnt coal seam and settlement. Finally, burnt coal seam was reclassified into four classes as shown in figure 3. By supervised classification, the average pixel intensity I of each class was obtained. These values were substituted in the equation $\sigma° = 20\log I - 68.2$ dB (Shimada 1998) to obtain backscattering coefficients. By plotting the results on figure 2 (●), the average ξ of each class was obtained (see table 1). It shows that ξ in the study area was between 0.33 m and 0.52 m. A sampling of 30 burnt coal seam locations yielded similar results to ground data (figure 1). By combining the results with SPOT-HRV data (figure 3), fire position and thickness of burnt coal seam could be estimated at the same time.

4. Conclusion

The analysis and simulation were conducted to analyse the relationship between backscattering coefficient and burnt coal seam thickness. Both were similar. By comparing with ground data, it was demonstrated that it is possible to estimate burnt coal seam thickness in central Borneo, Indonesia using JERS-1 SAR data. A variation of this analysis and simulation could be used to estimate oil slick thickness and archaeological site detection.

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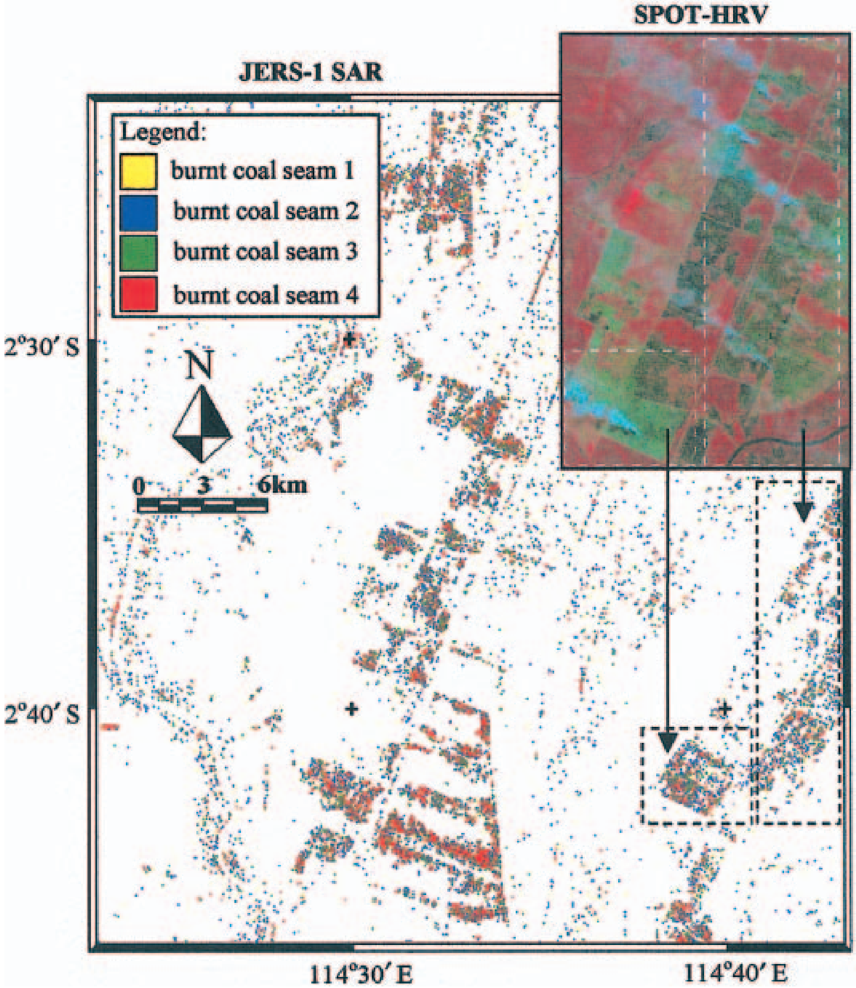

Figure 3. SPOT-HRV data and supervised classification results of JERS-1 SAR data (29 July 1997).

Table 1. Burnt coal seam thickness in the study area.

Classes	Backscattering coefficient (dB)	Burnt coal seam thickness ξ (m)
Burnt coal seam 1	-7.0	0.52
Burnt coal seam 2	-6.5	0.48
Burnt coal seam 3	-5.8	0.37
Burnt coal seam 4	-5.0	0.33

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