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A METHOD TO ANALYSE SCATTERED WAVES FROM PINE TRUNK AND ITS APPLICATION TO ESTIMATE TRUNK DIAMETER USING JERS-1 SAR DATA

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ABSTRACT. A numerical method was used to analyse the interaction of L-band microwaves with pine (*Pinus merkusii*) trunk. This method approximated tree trunk as an infinite length of two layers of cylindrical dielectric media. These layers are xylem and heartwood. Horizontal polarisation (transverse magnetic mode) of the scattered wave was derived in order to determine the relationship between tree trunk diameter and backscattering coefficient. The analysis results were confirmed by simulating the scattering problem on trunk using Finite Difference Time Domain (FDTD) method. Both analysis and simulation results were similar. This relationship was used to estimate pine trunk diameters in Saguling forest, west Java, Indonesia from Japanese Earth Resources Satellite (JERS-1) synthetic aperture radar (SAR) data.

1. INTRODUCTION

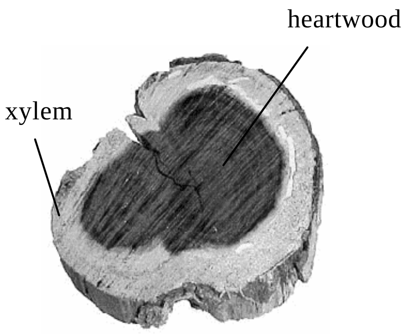
Pine (*Pinus Merkusii*) is the most important tree in Indonesia, especially Java and Sumatra islands, as a source of turpentine or volatile oil (Coppen et al. 1993). Turpentine is distilled from pine resin. Traditionally, it has been employed as a solvent or cleaning agent for paints and varnishes. Most turpentine nowadays is used as a source of chemical isolates that are then converted into a wide range of products. Many of these, including the biggest single turpentine derivative and synthetic pine oil, are employed for fragrance and flavour, besides many important non-aromatic applications such as for polyterpene resins. Pine oil is used in disinfectants, cleaning agents and other products having a pine odour (FAO 1995). Turpentine is obtained via tapping of living pine trees (whether natural stands or plantations).

Indonesia is a large archipelago that consists of more than 17,000 islands with land covering approximately 1.9 million kilometre squares. It is very difficult, time consuming and costly to estimate age or volume of pine using conventional techniques. Recently, remote sensing technology has become an efficient and helpful tool in monitoring forest and plantation in a large area. The main problem in monitoring tropical areas, as Indonesia, is cloudy conditions. The best instrument to monitor these areas is synthetic aperture radar (SAR), as it works effectively in spite of these. However, SAR data are not easily interpreted due to the complex relations of radar backscattering mechanisms between microwaves and pine trunk (Tetuko 2001a).

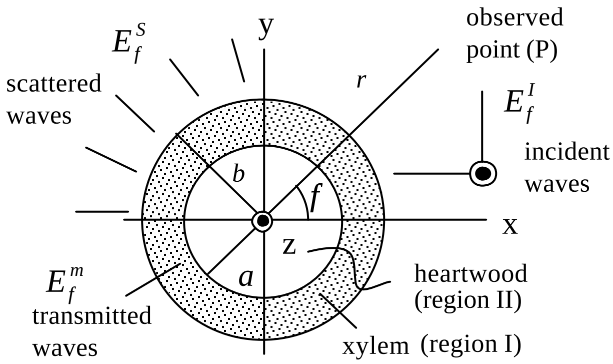
In this study, analysis of scattering problem on pine trunk was done in order to estimate the relationship between its diameter and backscattering coefficient s^{o}_{trunk}. In section 2, modelling and formulation of scattering problems on pine are discussed. In section 3, simulation of transverse magnetic (TM) wave propagation is done using Finite Difference Time Domain (FDTD) method. In section 4, the analytical results are verified by comparing them with simulated ones. The application of this research will be introduced in section 5. Finally, conclusions are given in section 6.

2. ANALYSIS

The scattering problem was analysed using mode expansion method (Tetuko et al. 2001a). Figure 1(a) shows photograph a cross section of pine trunk, composed of two media; xylem and heartwood. A two-dimensional model the trunk is shown in figure 1(b). Two layers of media compose this model with infinite length in z-axis. The radii of heartwood and xylem layer are a and b respectively. Several trunks were measured resulting in approximately a=0.5b. The properties of xylem are determined by complex dielectric constant $\dot{e}_r$ and complex permeability $\dot{m}_r$. $\dot{e}_r$ of several samples were determined experimentally by the authors using dielectric probe kit HP85070B and found to be 3.1-j0.4. The water content of heartwood is high, consequently, it was assumed to be an infinite length of perfect conductor or electromagnetic fields in heartwood is zero. Incident wave was assumed as a plane wave having transverse magnetic mode and incident angle f with respect to direction of observed point P from origin of



(a) Photograph of a cross section of pine (*Pinus merkusii*) trunk.



(b) Geometry of scattered waves from a pine trunk.

Figure 1. Pine trunk

coordinate system. Wave propagation is in –x direction. Based on this figure, the ϕ component of the electromagnetic fields in free space and xylem were determined as

$$\text{Incident wave } E_\phi^I = E_o^I \sum_{m=0}^{\infty} U_m J_m(k_o r) j^m \cos m\phi \qquad (r > b) \qquad (1)$$

$$\text{Scattered wave } E_\phi^S = E_o^I \sum_{m=0}^{\infty} b_m H_m^{(2)}(k_o r) \cos m\phi \qquad (r > b) \qquad (2)$$

$$\text{Transverse wave } E_\phi^m = E_o^I \sum_{m=0}^{\infty} \{a_m J_m(kr) + a'_m N_m(kr)\} \cos m\phi \qquad (a \le r \le b) \qquad (3)$$

where the wave number of xylem is $k = k_o\sqrt{\mu_r \varepsilon_r}$ and k_o is wave number in free space. $a_m \sim b_m$ are amplitude coefficients. E_o^I is amplitude coefficient of incident electric field. J_m, N_m, and $H_m^{(2)}$ are *m*-nd order of Bessel function, Neumann function, and 2nd kind of Hankel function. Where

$$U_m = \begin{cases} 1 & (m = 0) \\ 2 & (m = 1,2,3,\cdots) \end{cases} \qquad (4)$$

By substituting (1) – (3) in Maxwell's equations below

$$\nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t} \qquad (5) \qquad\qquad \nabla \times \boldsymbol{H} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} \qquad (6)$$

the magnetic field of each medium was derived as

$$H_z^I = j\frac{1}{\omega\mu_o r} E_o^I \sum_{m=0}^{\infty} U_m \{J_m(k_o r) + k_o r J'_m(k_o r)\} j^m \cos m\phi \qquad (r > b) \qquad (7)$$

$$H_z^S = j\frac{1}{\omega\mu_o r} E_o^I \left\{ \sum_{m=0}^{\infty} b_m H_m^{(2)}(k_o r) \cos m\phi + k_o r \sum_{m=0}^{\infty} b_m H_m'^{(2)}(k_o r) \cos m\phi \right\} \qquad (r > b) \qquad (8)$$

$$H_z^m = j\frac{1}{\omega\mu_o r} \left[E_o^I \sum_{m=0}^{\infty} \{a_m J_m(kr) + a'_m N_m(kr)\} \cos m\phi + kr E_o^I \sum_{m=0}^{\infty} \{a_m J'_m(kr) + a'_m N'_m(kr)\} \cos m\phi \right]$$

$$(a \le r \le b) \qquad (9)$$

Further, by substituting (1) – (3) and (7) – (9) in the boundary condition of each interface between media given below:

$$r=b \qquad E_\phi^m = E_\phi^I + E_\phi^S \qquad (10) \qquad\qquad H_z^m = H_z^I + H_z^S \qquad (11)$$

$$r=a \qquad H_z^m = 0 \qquad (12)$$

the amplitude coefficient b_m of scattered wave from tree trunk E_ϕ^S was obtained as;

$$b_m = -\frac{U_m j^m \{a_m J_m(k_o b) + k_o b b_m J'_m(k_o b)\}}{\{a_m H_m^{(2)}(k_o b) + k_o b b_m H_m'^{(2)}(k_o b)\}} \tag{13}$$

where

$$a_m = \dot{m}_r \left\{ \frac{a_1}{a_2} J_m(kb) + N_m(kb) \right\} + (b'_m - a'_m \frac{a_1}{a_2}),\ b_m = \dot{m}_r \left\{ \frac{a_1}{a_2} J_m(kb) + N_m(kb) \right\},$$

$$a_1 = N_m(ka) - kaN'_m(ka),\ a_2 = J_m(ka) - kaJ'_m(ka),\ a'_m = J_m(k_o b) + k_o b J'_m(k_o b),$$

$$b'_m = N_m(kb) + kbN'_m(kb)$$

The amplitude coefficient b_m of the scattered wave from heartwood only was calculated similarly using the boundary condition

$$E_f^S + E_f^I = 0 \qquad (r = a) \tag{14}$$

Then the amplitude coefficient will be

$$b_m = -\frac{U_m J_m(k_o a) j^m}{H_m^{(2)}(k_o a)} \tag{15}$$

Finally, by substituting the amplitude coefficient b_m of (13) and (15) in (2), and calculating the power logarithm of division of these scattered electric fields, the backscattering coefficient s^{o}_{trunk} with respect to diameter of tree trunk was obtained. To confirm the analysis result, simulation of scattered wave from a pine trunk using FDTD method is discussed in the next section.

3. SIMULATION

In this study, we considered the scattered waves from pine trunk to explore the relationship between backscattering coefficient s^{o}_{trunk} and the diameter using Finite Difference Time Domain (FDTD) method (Kane 1966). Detail derivation of the scattered fields in simulation area is discussed in (Tetuko et al. 2001b), where the absorbing boundary condition was used Gerrit Mur method (Gerrit 1981). The second kind of Mur method was applied in this analysis, because it involves small calculation-memory size and its accuracy is assured (Uno 1998).

Figure 3 depicts the simulation model. It was done in two-dimension (2D), where each medium has infinite length in z-axis. This solution space is divided into *INX* x *INY* grids (units of cell size). Incident wave is a plane wave of intensity as that shown by Gaussian pulse.

Finally, the backscattering coefficient s^{o}_{trunk} was defined as

$$s^{o}_{trunk} = 20\log\left(n\left|E_y^{scat}\right| / \left|E_y^{inc}\right|\right)_{f=1.275GHz} \tag{16}$$

where E_y^{inc} is observed electric field intensity in frequency $f = 1.275$ GHz of scattered wave that is scattered by only heartwood (perfect conductor). *n* is trunk numbers in a pixel size of SAR data.

4. RESULTS AND DISCUSSION

In solution space, see figure 3, infinite length of trunk is considered. This trunk is composed of two media; xylem and heartwood. The radius varies from 0 to 40 grids (or 0 to 0.5 m). The solution space edges were surrounded by artificial absorbing boundary condition (Mur method). Incident wave was a plane wave of intensity as that shown by Gaussian pulse, which propagates from left to right of the solution space at speed of light. Parameters of simulation were solution space grids $INX = INY =$ 300, space-increments $\Delta x = \Delta y = 1.25 \times 10^{-2}$ m, time-increment $\Delta t = 2.5 \times 10^{-11}$ s, maximum intensity of initial electric field 100 V/m, and running time $t = 600\Delta t$ s. Figure 4 shows scattered wave from pine trunk with $n = 50 \sim 300$, where running time was calculated using $t = n\Delta t$ s. The observed point P was at 1.5 m from centre of trunk. This point was used to observe the intensities of scattered electromagnetic fields. In this study, we observed only the horizontal polarisation component (transverse magnetic wave) or electric field E_y^{scat} in backscattering direction ($f = 0^o$). The backscattered electric field was computed and Fast Fourier transform was employed to obtain electric field intensity of preferred frequency, in this case, frequency of Japanese Earth Resources Satellite (JERS-1) SAR,

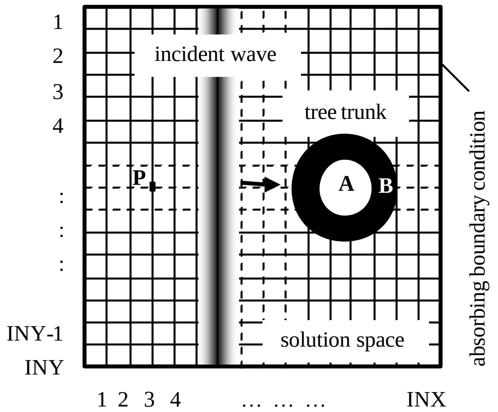


Figure 3. Simulation model.

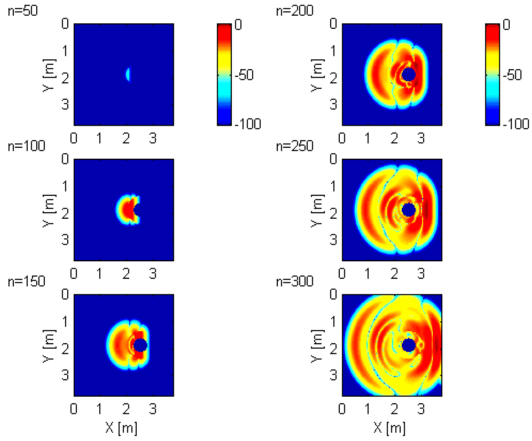


Figure 4. Scattered waves in solution space from $t = 50\Delta t$ s to $300\Delta t$ s.

$f = 1.275$ GHz, was used. Finally, backscattering coefficient was calculated using (16) and results are shown in figure 5 (simulation).

In the analysis, direction of scattered wave was the same as of observed point P or $f = 0^o$. Consequently, E_f^S was equivalent to E_y^{scat} calculated in the simulation assuming a single trunk in each pixel. By substituting the parameters of JERS-1 SAR in the analysis equations, the results shown in figure 5 (■) were obtained. The results compare well with simulation ones for scattering waves from a single trunk (☐). However, a small error was found. It is considered that the error was generated by the FDTD calculation error caused by calculation using discretized grids. By using (16), the relationship between backscattering coefficient and trunk diameter for *n* trunks in a pixel was calculated. In the study area, pines are planted 4m apart or in a pixel (12.5m x 12.5m) were found 9 trunks. Consequently, the relationship between backscattering coefficient and diameters for 1 to 9 trunks was calculated. Figure 5 shows the analysis results. The results were applied to estimate pine trunk diameter as explained in the next section.

5. APPLICATION: STUDY AREA AND DATA PROCESSING

The study area was pine forest around Saguling lake, west Java, Indonesia (figure 6). The region has altitude ranging from 10m to 45m. Biome of this area are pine forest, mixed vegetation area, settlement and paddy fields (dry land) called *ladang*. The soil type around the study area is wetland. Ground data were collected in 1999 and the diameters of pine trunk obtained were between 0.2 and 0.4m.

The JERS-1 SAR data was examined in order to estimate the diameters of pine tree trunk in the study area. The data (path 106, row 312) was acquired on 13 May 1997 during the dry season. The data was processed at level 2.1 or standard geocoded data and was resampled to Universal Transverse Mercator (UTM) projection by the Earth Observation Research Centre (EORC) of the National Space Development Agency (NASDA) of Japan.

Firstly, a 3x3 median filter was employed and secondly, a 5x5 average filter was used to reduce inherent speckle noise (Sunar et al. 1998). The data was also referenced to the UTM co-ordinate system, through a polynomial rectification using 30 ground control points collected from topographic maps of scale 1:25.000 (BAKOSURTANAL 1990). This procedure yielded a geometric accuracy of 0.1 pixels. Then the spatial resolution of SAR data was resampled to 12.5m.

Supervised classification was performed to classify the image into six classes. Topographic maps and ground data were used to select training sites, i.e. river and paddy field, bush, forest 1, forest 2, forest 3, mixed forest, and settlement (figure 6). Average pixel intensity *I* of each class was obtained. These values were substituted in the equation $s^o = 20\log I - 68.2$ dB (Shimada 1998) to obtain backscattering coefficients. By plotting the results (figure 5), the average diameter of each class was obtained (see table 1). By considering the roughness and soil type of the study area, we obtained backscattering coefficient s^o_{soil} as -21dB (Ulaby 1990). Consequently, by using the equation

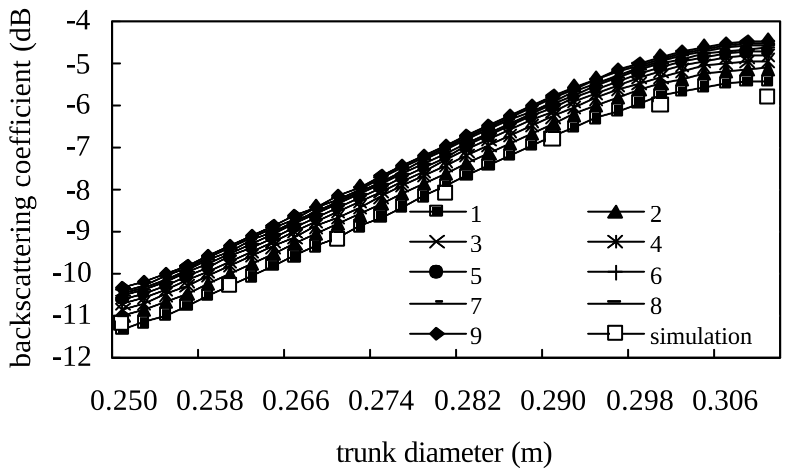


Figure 5. Relationship between tree trunk diameter and backscattering coefficient

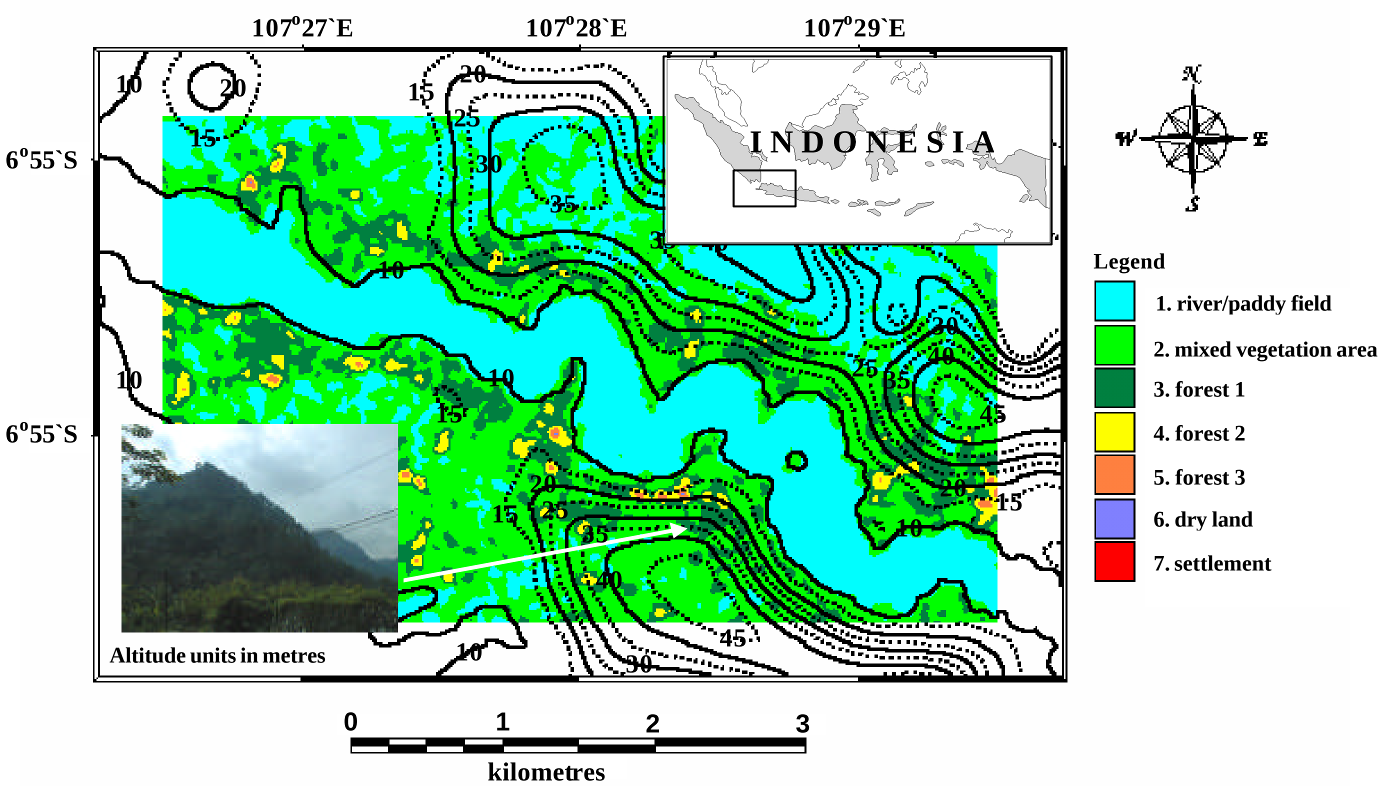


Figure 6. Supervised classification results of JERS-1 SAR data (path 106, row 312, 13 May 1997).

Table 1. Classification and estimation results

class names	average of backscattering coefficient σ^{o} (dB) ($\sigma^{o} = \sigma^{o}_{trunk} + \sigma^{o}_{soil}$)	diameter of tree trunk (m)
forest 1	-31	0.255
forest 2	-29	0.273
forest 3	-26	0.299

$$s^{o} = s^{o}_{trunk} + s^{o}_{soil} \qquad (17)$$

the total backscattering coefficient s^{o} was obtained. Where s^{o}_{trunk} and s^{o}_{soil} are backscattering coefficient of trunk and soil, respectively. The results showed the diameter of pine in the study to be between 0.255m and 0.299m. A sampling of 10 locations yielded similar results to ground data collected in 1999.

6. CONCLUSIONS

Numerical analysis was conducted to analyse the relationship between the backscattering coefficients s^{o} and diameter of pine trunk ($f = 0^{o}$). The analysis results were confirmed by simulation using FDTD method. Subsequently, the relationship was successfully used in estimating trunk diameter of pine from JERS-1 SAR data. While this study focused on single site in Indonesia, it is reasonable to expect that this method or variations should be successful in estimating tree trunk diameters, in similar forest regions of the world using SAR data, for forest volume and biomass determination.

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