Modeling Surface Roughness to Estimate Surface Moisture Using Radarsat-2 Quad Polarimetric SAR Data

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Abstract - Microwave backscattering from the earth's surface depends on several parameters such as surface roughness and dielectric constant of surface materials. The two parameters related to water content and porosity are crucial for estimating soil moisture. The soil moisture is an important parameter for ecological study and also a factor to maintain energy balance of land surface and atmosphere. Direct roughness measurements to a large area require extra time and cost. Heterogeneity roughness scale for some applications such as hydrology, climate, and ecology is a problem which could lead to inaccuracies of modeling. In this study, we modeled surface roughness using Radarsat-2 quad Polarimetric Synthetic Aperture Radar (PolSAR) data. The statistical approaches to field roughness measurements were used to generate an appropriate roughness model. This modeling uses a physical SAR approach to predicts radar backscattering coefficient in the parameter of radar configuration (wavelength, polarization, and incidence angle) and soil parameters (surface roughness and dielectric constant). Surface roughness value is calculated using a modified Campbell and Shepard model in 1996. The modification was applied by incorporating the backscattering coefficient ($\sigma_0$) of quad polarization HH, HV and VV. To obtain empirical surface roughness model from SAR backscattering intensity, we used forty-five sample points from field roughness measurements. We selected paddy field in Indramayu district, West Java, Indonesia as the study area. This area was selected due to intensive decreasing of rice productivity in the Northern Coast region of West Java. Third degree polynomial is the most suitable data fitting with coefficient of determination $R^2$ and RMSE are about 0.82 and 1.18 cm, respectively. Therefore, this model is used as basis to generate the map of surface roughness.

1. Introduction
Soil moisture and roughness, plays an important role in a variety of applications such as hydrology, agronomy or meteorology. Floods, excess runoff and soil erosion is a key factor that is controlled and influenced by condition of the ground surface [8]. On the other hand, the surface roughness effect is involved in the separation of water flow into infiltration and runoff [11]. It has long been recognized that satellite imagery has a unique and important role in monitoring crop and soil conditions for farm management [10].

The important parameters that affect the response of the ground to the radar backscattering can be classified into two categories: (1) the target parameters such as moisture, roughness, and vegetation cover (if present) and (2) the sensor parameters such as frequency, polarization, and angle of incidence.
Radar backscattering from a bare soil surface is determined by the geometry of soil surface, commonly known as surface roughness, and dielectric properties of the soil, which depends on soil characteristics such as moisture, particle-size distribution and mineralogy [9].

Previous researches have been reported that the Synthetic Aperture Radar (SAR) sensors have a high potential to measure surface soil moisture [8]. It is also known that the SAR backscattering signal from bare soil is influenced by characteristics of surface roughness and dielectric constant [1]. Engman et al. (1995) reported that radar backscattering coefficient $\sigma_0$ is related directly to soil moisture as follows:

$$\sigma_0 = f(R, a, M_V)$$  \hspace{1cm} (1)

Where $R$ is surface roughness, $a$ is a soil moisture sensitivity term, and $M_V$ is the volumetric soil moisture.

The dielectric constant of soils is proportional to the amount of water held in the soil [11]. Radar backscattering by a bare soil surface is determined by the geometry of the soil surface, commonly known as surface roughness, and the dielectric properties of the soil, which depend on the soil characteristics such as moisture, particle-size distribution, and mineralogy [9]. In agricultural fields radar backscattering are also affected by vegetation cover, plant water content, and crop residue.

Once the surface roughness parameters could be determined, the interactions of backscattering signal of the microwave to the ground surface is affected solely by the dielectric properties of the soil. Therefore, the microwave sensor offers the potential for estimating near surface volumetric soil moisture.

Surface roughness can be interpreted as the topography of the surface nature on a scale of a few meter to centimeter [4]. Three parameters affect the surface roughness, i.e. RMS height, the correlation length, and the auto-correlation function [5]. Measurement of surface roughness is generally carried out directly in the field using a pin meter or laser profiler [14]. However, direct roughness measurements to a large area require extra time and cost. Therefore, we need an efficient and high accuracy method to model surface roughness measurement at field scale.

Previous researches have reported about the techniques to estimate soil moisture using Synthetic Aperture Radar (SAR) data [17] and [18]. Semi-empirical models are the most popular technique [19], [20], [21] and [18]. The Oh model utilized backscattering coefficients in co-polarized ($p = \sigma_{HH}^0/\sigma_{VV}^0$ and $= \sigma_{HV}^0/\sigma_{VV}^0$ ) and cross-polarized ($\sigma_{HV}^0$) to estimate volumetric soil moisture and surface roughness. The Dubois model links the backscattering coefficients in co-polarized HH and VV to the dielectric constant and surface roughness of the soil.

The correct determination of the surface roughness $h_0$ is difficult by field-based surface roughness measurements because of a scale dependence problem in the statistical parameters of the topography [1]. Campbell and Shepard model [4] was used to quantify the initial model of surface roughness based on empirical relationship $h_0$ to $\sigma_{HH}^0$ and $\theta_i$.

In this paper, we used curve fitting method to model surface roughness between initial surface roughness derived from SAR backscattering intensity and field measurement using pin meter at forty-five points. The RADARSAT-2 quad polarimetric data were used to model the surface roughness.

The SAR capabilities in data acquisition for tropical condition is the most significant advantages for ground surface mapping [2]. The mapping capability could be expanded to the other purposes especially in agricultural monitoring. A temporal data of linearly quad-polarized SAR is superior for mapping soil moisture content as well as discussion in [10]. The RADARSAT-2 could observe the ground surface and provide the data quickly in single or temporal acquisition. The provided information at C-band are not only in HH polarization mode, but also in VV, HV, and VH polarization modes. A fully-polarized mode is superior to obtain more information than single-polarized mode such as HH or HV.

The objectives of this paper are to obtain surface roughness model based on RADARSAT-2 quad polarimetric SAR and field measurement and also to estimate the moisture based on the appropriate surface roughness model.
2. Methodology

2.1. Study Area

We selected paddy field in Indramayu region, West Java, Indonesia as study area (Figure 1). Indramayu district is geographically located at position 107° 52' - 108° 36' BT and 6°15' - 6°40' latitude with the coverage area of 204.011 ha. Based on data from the Indramayu district regional planning, land use patterns consist of paddy field Irrigation 116.675 ha, dry land 87.336 ha and non-irrigation paddy field 92.795 ha. Altitude region generally ranges between 0-18 m above sea level and the low lying areas ranges between 0-6 m above sea level that consist of swamps, ponds, paddy fields, yards. Most of surface terrain with slope of between 0% - 2% covering an area of 201.285 ha (96.03%) of the total area. This situation is susceptible to drainage, when rainfall is high low areas will occur puddles and when the dry season would cause severely drought.

Figure 1. Study area in Indramayu Region, West Java is showed by red rectangular of RADARSAT-2 acquisition paths, blue triangle are points of field survey and measurements.

Figure 2. Ground surface condition of study area in colour composite of RADARSAT-2 image using Freeman decomposition R, G, B=$P_{\text{volume}}$, $P_{\text{double-bounce}}$, $P_{\text{surface}}$ [22]. Yellow triangles with numbers 49 to 53 are measurement points. The photographs show different paddy stage observed on 18 June 2014.
Two RADARSAT-2 backscattering intensity images were selected with lag acquisition time is about four month with field survey measurement. In order to obtain high quality data, the geometric and radiometric corrections were applied before analyses were taken into account. The RADARSAT-2 is utilized by a quad polarimetric SAR at C-band frequency (=5.3 GHz). Fine quad polarization mode was used in this study with incidence angle from 31.50° to 42.95° and a nominal spatial resolution about 8 m and an area of approximately 25 x 25 square kilometers. RADARSAT-2 images were acquired from June to October 2014 (Table 1).

Table 1. RADARSAT-2 SAR image data sets acquired over Indramayu, West Java, Indonesia

| Study site | Acquisition date | Beam Mode | Orbit | Polar | Inc Ang | Product type |
|------------|------------------|-----------|-------|-------|---------|--------------|
| Indramayu 1 | 2014-06-04 | FQ24 | Ascending | HH+VH+V+HV | 42.95 | SLC |
| Indramayu 2 | 2014-06-18 | FQ12 | Ascending | HH+VH+V+HV | 31.50 | SLC |
| Indramayu 2 | 2014-08-05 | FQ12 | Ascending | HH+VH+V+HV | 31.50 | SLC |
| Indramayu 1 | 2014-08-15 | FQ24 | Ascending | HH+VH+V+HV | 42.95 | SLC |
| Indramayu 1 | 2014-09-08 | FQ24 | Ascending | HH+VH+V+HV | 42.95 | SLC |
| Indramayu 2 | 2014-09-22 | FQ12 | Ascending | HH+VH+V+HV | 31.50 | SLC |
| Indramayu 1 | 2014-10-02 | FQ24 | Ascending | HH+VH+V+HV | 42.95 | SLC |
| Indramayu 2 | 2014-10-16 | FQ12 | Ascending | HH+VH+V+HV | 31.50 | SLC |

Information on the range and azimuth spacing, nadir angle, and satellite altitude for SLC format SAR data were obtained from the RADARSAT-2 production file. Using this information, all the SAR parameters derived above were converted from slant to ground range, followed by an ortho-rectification and geo-referencing. Information from satellite radar system was analyzed using The Next ESA SAR Toolbox (NEST). The NEST is an open source toolbox for reading, post-processing, analyzing and visualizing the large archive of data from European Space Agency (ESA) SAR missions [16]. The speckle noise in the data was reduced by 5 x 5 pixel Lee filter. The filtering was applied to the multilook image with looks factor 5 and 4 for azimuth and range direction, respectively. All data was geographically corrected using SRTM-3 Version 4. The multitemporal RADARSAT-2 data processing for this study can be divided into four parts: terrain correction, conversion digital number, calculate surface roughness and combining calculate roughness. The methodology employed during this study was as follows.

Step 1: Terrain Correction: RADARSAT-2 in Multilook Image (MLI) products were initially georeferenced. Due to variations in the topography and the tilt of the sensor position, distances of real word position can be distorted on the image. Terrain correction was applied to compensate for these distortions so that the geometric representation of the image will be same to the real world [16].

Step 2: Conversion Digital numbers (DN): The image digital numbers (DN) are in units of amplitude and were converted to backscatter coefficient ($\sigma^0$) as follows:

$$\sigma^0 = 10 \times \log(C)$$  \hspace{1cm} (2)

$$C = \frac{(DN^2 + B)}{A}$$  \hspace{1cm} (3)

B is the offset; and A is the range-dependent gain, both supplied in the Look up Table (LUT) file [15].

Step 3: Calculate surface roughness: Surface roughness value is calculated using a modified Campbell and Shepard model (1996). The modification was used by incorporating the backscattering coefficient ($\sigma^0$) of quad polarization HV, HH and VV modes as follows:

$$H_{0-hv}(\lambda) = -\frac{1}{60} \ln \left( 1 - \frac{\sigma^0_{HV}}{0.04 \cos \theta} \right)^{0.5}$$  \hspace{1cm} (4)

$$H_{0-hh}(\lambda) = -\frac{1}{60} \ln \left( 1 - \frac{\sigma^0_{HH}}{0.04 \cos \theta} \right)^{0.5}$$  \hspace{1cm} (5)
Where $\lambda$ is wavelength and $\theta$ is incident angle.

Then, the surface roughness was calculated by combining eq. 4 - 6 (equation 7). One of the results can be shown in figure 5.

$$H_0 = \sqrt{H_{0-hv} \times H_{0-HH} \times H_{0-vv} \times \cos \theta}$$  \hspace{1cm} (7)$$

2.2. Surface Roughness Measurement

Field surveys were carried out to obtain the soil moisture and surface roughness at time of RADARSAT-2 overpasses in June, August, September and October 2014. Total sample location for surface roughness measurements is 45 observation points. Following Saepuloh et al. (2012), a Pin meter made of steel plate with dimension 30 x 30 cm was used to measure surface roughness.

![Pinmeter](image-url)

**Figure 3:** The Pinmeter to measure Surface roughness at field.

3. Result And Discussion

Image of the Freeman decomposition of RADARSAT-2 Quad Pol were used as pre-analysis of the changing conditions of a paddy field (see Figure 2 in the middle). Blue and black colour indicate paddy field containing water. Points 49 to 54 show the different phase of planting rice (Table 2). Surface roughness value can be an indicator of soil moisture level. In Figure 4 show surface roughness value increases linearly with the value of soil moisture. Normally, the water supply in vegetative phase lower than flooding phase.

**Table 2. Surface roughness model and soil moisture measurement**

| No. | Surface Roughness Model | Soil Moisture Measurement | Phase |
|-----|------------------------|---------------------------|-------|
| 49  | 2.92                   | 25.88                     | Vegetative |
| 50  | 2.72                   | 29.88                     | Vegetative |
| 51  | 2.82                   | 44.73                     | Vegetative |
| 52  | 3.04                   | 39.4                      | Flooding |
| 53  | 2.77                   | 37.96                     | Flooding |
| 54  | 3.13                   | 36.19                     | Flooding |
Mapping of surface roughness using SAR imagery is very effective for a large area when compared with direct measurements to the field due to problems of time and cost. We also incorporated quad polarized HH, HV, and VV data to the roughness model and obtained a fit model for the soil roughness measurements. Third degree polynomial is the most suitable data fitting with coefficient of determination $R^2$ and RMSE are about 0.84 and 1.2 cm, respectively (Figure 5). Therefore, this model was used as basis to generate the map of surface roughness and served as one parameter to model soil moisture. Modelling of soil moisture is still on going works, so that in this paper we focus to obtain the appropriate roughness model.

**Figure 4.** Scatter plot of surface roughness model and soil moisture measurement

**Figure 5:** Correlation between surface roughness at field and model.
4. Conclusion
Measuring surface roughness at field is reliable for small field scale, but not feasible for large field scale applications. In this study, the roughness model was developed successfully to map the characteristics of surface roughness parameters using RADARSAT-2 (Figure 6). The model is advantage to minimize field data collection. The surface roughness model was validated by field measurements with coefficient of determination about 0.84. The results showed that the surface roughness derived from RADARSAT-2 imagery agreed to the surface roughness at the field. Generally, the surface roughness model was lower or larger than field roughness measurement as presented by polynomial 3rd degree curve. The paddy field in flooding and vegetative phases could be identified by low and high RMS surface roughness, respectively. The moisture saturated condition was interpreted significance to the low RMS surface roughness.

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