A semi-empirical modelling approach to calculate two-way attenuation in radar backscatter from soil due to crop cover

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Synthetic aperture radar (SAR) backscatter from crop-covered agricultural fields is a strong function of dielectric properties of the crop, crop canopy structure, crop volume along with moisture and surface roughness of the underlying soil. These unique features of SAR along with its ability to penetrate through vegetation and soil make it a right choice for many agricultural applications like soil moisture estimation and crop monitoring. Backscattering coefficient contains information of the crop as well as the soil underneath and therefore, in order to retrieve soil moisture or the crop parameters from SAR backscatter, it is necessary to separate out the relative contributions of the soil underneath and the vegetation layer. The effect of crop cover on the sensitivity of SAR backscatter towards soil moisture is more severe, as the crop cover not only introduces its own backscatter contribution (σ°_{crop}), but also introduces two-way attenuation in the radar backscatter from the soil surface. An attempt has been made here to adopt a semi-empirical modelling approach to estimate the SAR backscatter contribution from the crop cover (σ°_{crop}) along with the two-way attenuation ($1/L^2$) introduced by the crop cover in SAR backscatter from the soil as well. This has been done using Extended Low-1 beam mode RADARSAT-1 SAR data over parts of Haridwar and Saharanpur districts. We report here the results obtained from the study during March 2005 and March 2006, and discuss the methodology used for the calculation of two-way attenuation in the backscattering coefficient from the soil surface and from that of wheat crop.

Keywords: Backscattering coefficient, crop cover, synthetic aperture radar, soil moisture, two-way attenuation.

A VEGETATION canopy consists of a volume of scattering elements bounded by air on top and by a scattering soil surface at the bottom. Hence, the total backscattering coefficient (σ°_{total}) is governed by the scattering properties of the vegetation elements and the soil surface, as well as by the interaction between the vegetation volume and soil surface in the form of multiple scattering[1,2]. If we consider any crop or biomass cover standing over a soil surface, then the total backscattering coefficient obtained for that area will include contributions from the crop cover (σ°_{crop}) as well as from the underlying soil (σ°_{soil}). Since contributions from the crop volume (σ°_{crop}) act as noise for soil-related studies like soil moisture retrieval and those from the soil surface (σ°_{soil}) act as noise for crop studies, it is necessary to separate out both contributions from the total backscattering coefficient obtained for a crop-covered field. A number of ground-based experiments have been carried out to understand the attenuation of synthetic aperture radar (SAR) signal due to vegetation. Prévot *et al.*[3] have fitted the water cloud model[4,5] on VV polarized ERS-2 and HH polarized Radarsat-1 SAR datasets for monitoring of wheat crop in cold agroclimatic regions of Italy. Microwave attenuation properties of vegetation canopies for winter wheat and soybeans have been reported[6]. Brown *et al.*[7] have also studied the scattering in wheat canopies using X and C band polarimetric measurements obtained from ground-based SAR (GB-SAR). They observed that attenuation in SAR signal from the soil increases with incidence angle. Attempts have also been made by several other researchers to study the attenuation properties of crop cover using experimental and theoretical methods. They have observed that the presence of wheat crop cover causes attenuation of the signal backscattered from the soil. However, they have also observed that HH polarized C-band SAR is less attenuated due to wheat crop cover than VV polarized C-band SAR backscatter. Based upon analysis of ERS-1 SAR data, Picard *et al.*[8] have brought out the limitation of first order coherent scattering models in case of fully grown wheat canopy. Picard *et al.*[9] have reported that multiple-scattering modelling was able to account for the attenuation caused due to wheat crop even in case of VV polarized backscatter. In this communication, a semi-empirical modelling approach has been followed to estimate the backscatter contribution from wheat crop cover and the two-way attenuation in the SAR backscatter from soil surface due to the crop cover by conducting a detailed experiment in the farmer's fields over parts of Saharanpur and Haridwar districts during March (2005 and 2006) using Extended Low-1 beam mode temporal RADARSAT-1 SAR data.

For the present study, two scenes of lower incidence angle (10°–23°) Extended Low-1 (EL-1) beam mode RADARSAT-1 SAR have been acquired over parts of Saharanpur and Haridwar districts on 12 March 2005 and 7 March 2006. The RADARSAT-1 has a C-band SAR sensor with HH polarization[10]. It operates under a variety of viewing modes with varying spatial resolution. Details of RADARSAT-1 EL-1 SAR data acquisition are given in Table 1. In addition to RADARSAT-1 SAR data, GPS-based mobile mapping unit and 1 : 50,000 scale Survey of India (SOI) topographic maps were also used

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for reconnaissance and ground-truth survey, and geo-referencing of temporal SAR data. Reconnaissance survey was conducted two days prior to both the satellite passes.

The study area is dominated by agriculture land covered by alluvial, well-drained loamy soils – both coarse and fine-grained. Two major canals pass through this region: the Ganga canal flowing from the northeast to the southeast direction, and the Yamuna canal flowing from the northwest to the west direction. During data acquisition in March 2005 and March 2006, the wheat crop was at the grain-filling stage. Seventy-eight sampling locations were identified for ground-truth data collection and moisture estimation. Out of 78 sampling locations, 30 fields (stations) were without crop, and the remaining 48 fields had wheat crop at the grain-filling stage. Other land-cover categories like water bodies, human settlements and forest plantations were also present in the study area.

Sampling locations were selected carefully after reconnaissance field survey. Enough care was taken regarding homogeneity of sampling locations in terms of soil moisture, surface roughness and crop cover with a minimum size of 100 m × 100 m (refs 11 and 12). A ground-truth data collection campaign was also carried out in synchrony with the RADARSAT-1 passes. The information gathered during ground-truth data collection consists of collection of soil samples along with information about the crop type, crop height and associated field conditions. The soil samples were taken with the help of auger and core sampler for the measurement of gravimetric soil moisture and bulk density of soil samples. Fresh weights of soil samples were noted and they were oven-dried for 24 h at 105°C. The dried samples were weighed once again for dry weight. With the help of fresh weight and dry weight for each of the 78 (30 from bare soil and 48 from wheat crop-covered soil) sampling fields, the gravimetric soil moisture was calculated. Field results of gravimetric soil moisture for bare and wheat-covered soil are given in Table 2. Gravimetric soil moisture was then converted to volumetric soil moisture by multiplying the gravimetric soil moisture of the sample with its bulk density. The bulk densities were calculated for all the 78 sampling sites using 100 cc of undisturbed soil sample taken with the help of a core sampler.

Table 1. Details of RADARSAT-1 SAR data used in the analysis

Date of pass	12 March 2005	7 March 2006
Beam mode	Extended low	Extended low
Beam position	EL1	EL1
Incidence angle	10°–23°	10°–23°
Nominal resolution (m)	35	35
Look direction	Ascending	Ascending
Orbit number	48820	53965
Incidence angle (central)	16°	16°
Pixel spacing (m)	12.5	12.5
Nominal area (km)	170 × 170	170 × 170
Number of looks	1 × 4	1 × 4
Product type	Path image	Path image
Data format	CEOS	CEOS
Number of image lines	13,921	14,268
Number of image pixels	13,842	13,880
Number of bits per pixel	16 bits unsigned	16 bits unsigned
Image size	385 Mb	396 Mb

For the RADARSAT-1 data supplied from the Canadian Centre of Remote Sensing (CCRS), output scaling in terms of gain and offset was applied to the data to ensure optimum utilization of the available dynamic range. The scaling used can vary from scene to scene, making it difficult to directly relate information between various scenes. Hence for any quantitative analysis, it is necessary to convert the image data to the calibrated radar backscatter ($\sigma°$) image. For this purpose, the SAR image was radiometrically calibrated using the following procedure.

$$\sigma° \text{ (in dB)} = 10.0 \times \log_{10} [(\text{DN}^2 + \text{offset})/\text{gain}] + 10.0 \times \log_{10} \sin\alpha, \quad (1)$$

where DN is the digital number of the SAR image and α the local incidence angle at that pixel position in the range direction. The header information was used for the calculation of α, the local incidence angle at each pixel[10]. These conversions yielded a 32 bit real image of $\sigma°$ in dB.

After conversion of the DN values to $\sigma°$ values, speckle suppression was carried out using Enhanced Lee-filtering algorithm[13]. RADARSAT-1 SAR backscatter image of 12 March 2005 was geo-referenced using the Ground Control Points (GCPs) from 1 : 50,000 scale SOI topographic maps and GPS measurements. The Extended Low-1 SAR image of 7 March 2006 was then co-registered with geo-referenced 12 March 2005 SAR image using nearest neighbourhood method of resampling[14]. After geo-referencing the SAR data, the rail/road/canal networks and ground-truth locations were digitized and transferred onto the images. The backscattering coefficient values were extracted from the SAR images for all the 78 sampling locations. Details of variation in SAR backscatter coefficient ($\sigma°$) for bare and wheat-covered fields are given in Table 2. Once the backscattering coefficient values for all the sampling locations were obtained, a semi-empirical modelling approach was attempted to estimate the values of backscattering coefficient of crop ($\sigma°_{\text{crop}}$) and two-way attenuation ($1/L^2$).

As discussed earlier, the total backscattering coefficient ($\sigma°_{\text{total}}$) obtained from a crop covered field includes the contributions from the crop and underlying soil. Contribution from the underlying soil also encountered with the two-way attenuation introduced by crop cover. Thus two main constituents of the backscattering coefficient from vegetation-covered soil are backscattering from the crop volume ($\sigma°_{\text{crop}}$) and from the bare soil ($\sigma°_{\text{soil}}$).

Table 2. Field results for gravimetric soil moisture during the March 2005 and March 2006 campaign along with variability of Extended Low-1 RADARSAT-1 SAR backscatter

Wheat crop-covered soil			Bare soil		
Minimum	Maximum	Standard deviation	Minimum	Maximum	Standard deviation
Gravimetric soil moisture (% g/g)					
2.68	29.12	6.93	3.36	26.96	6.98
Extended Low-1 RADARSAT-1 SAR backscatter ($\sigma°$) in dB					
–12.44	–4.49	2.34	–12.15	–5.01	1.84

Table 3. Results of regression analysis performed for eqs (3) and (9)

Model used	*A*	*B*	R^2	No. of data points
Equation (3): $\sigma^\circ_{\text{soil}}$ (in dB) = $A + B *$ soil moisture	–11.93346	0.233614	0.79	30
Equation (9): $\sigma^\circ_{\text{total}} = A + B *$ exp (0.053792 * soil moisture)	0.045279	0.088860	0.77	48

A and *B* are coefficients of eqs (3) and (9). R^2 is the coefficient of determination.

In order to resolve the SAR backscatter of vegetation-covered soil into its constituents, we assume that the SAR backscatter contributions from soil add incoherently with the backscattering contributions from vegetation. In that case, the canopy backscattering coefficient or total backscattering coefficient from a crop covered field ($\sigma^\circ_{\text{total}}$), may be expressed in terms of $\sigma^\circ_{\text{crop}}$, $\sigma^\circ_{\text{soil}}$ and the two-way attenuation ($1/L^2$) with the help of a relation suggested by Ulaby *et al.*[15]

$$\sigma^\circ_{\text{total}} = \sigma^\circ_{\text{crop}} + \sigma^\circ_{\text{soil}}/L^2. \tag{2}$$

In order to calculate the values of $\sigma^\circ_{\text{crop}}$ and $1/L^2$, it has been assumed that the vegetation cover can be treated as a single class in view of the fact that the effects of the vegetation cover on $\sigma^\circ_{\text{total}}$ are of the second order in comparison with the effects of soil moisture[16]. For this purpose separate models can be developed between $\sigma^\circ_{\text{soil}}$ and soil moisture for bare soil condition[17–23]. Coefficients obtained from this model can be substituted in eq. (2) to calculate the values of $\sigma^\circ_{\text{crop}}$ and $1/L^2$.

In order to use eq. (2) for calculation of $\sigma^\circ_{\text{crop}}$ and $1/L^2$, it is necessary to express the value of $\sigma^\circ_{\text{soil}}$ in m^2/m^2. For this purpose, a regression analysis was performed between soil moisture taken from 30 bare fields during ground-truth data collection and the backscattering coefficient values extracted for all these 30 locations from Extended Low-1 beam mode RADARSAT-1 image. This relationship can be written as

$$\sigma^\circ_{\text{soil}} \text{ (in dB)} = A + B \times \text{soil moisture}. \tag{3}$$

Results of the regression analysis are given in Table 3. R^2, standard error, F-statistics and significance of F of the regression analysis were found to be 0.79, 0.865, 103.029 and 6.916E-11 respectively. High values of R^2, F statistics and low values of standard error and significance of F clearly indicate the goodness-to-fit of the model given by eq. (4). The derived coefficients of regression analysis given by eq. (3) are

$$\sigma^\circ_{\text{soil}} \text{ (in dB)} = -11.93346 + 0.233614 \times \text{soil moisture}. \tag{4}$$

Here it is required to emphasize that the relationship given by eq. (4) holds good only when $\sigma^\circ_{\text{soil}}$ is expressed in dB. If $\sigma^\circ_{\text{soil}}$ is expressed in m^2/m^2, as is the case with eq. (2), then the relation between $\sigma^\circ_{\text{soil}}$ and soil moisture takes the form

$$\sigma^\circ_{\text{soil}} \text{ (in m}^2\text{/m}^2) = A' \times \exp(B' \times \text{soil moisture}). \tag{5}$$

Equation (5) was simplified to express it in the form of eq. (4) by taking log of both the sides and then multiplying both the sides by 10. After these changes, eq. (5) resembles eq. (4), as given below

$$10 \times \log \sigma^\circ_{\text{soil}} \text{ (in m}^2\text{/m}^2) = 10 \times \log A' + (10 \times B' \times \log e) \times \text{soil moisture}. \tag{6}$$

Comparison of eq. (6) with eq. (4) yields $A' = 0.064072$ and $B' = 0.053792$.

Substitution of the values of A' and B' in eq. (5) yields

$$\sigma^\circ_{\text{soil}} \text{ (in m}^2\text{/m}^2) = 0.064072 \times \exp (0.053792 \times \text{soil moisture}). \tag{7}$$

The value of $\sigma^\circ_{\text{soil}}$ (in m^2/m^2) expressed by eq. (7) was substituted in eq. (2). This changed eq. (2) to

$$\sigma^\circ_{\text{total}} = \sigma^\circ_{\text{crop}} + (0.064072/L^2) \times \exp (0.053792 \times \text{soil moisture}). \tag{8}$$

Equation (8) represents a linear line of the form $Y = C + mX$. Hence coefficients of eq. (8) were obtained by performing a linear regression analysis between $\sigma^\circ_{\text{total}}$ and exp($0.053792 \times$ soil moisture), keeping $\sigma^\circ_{\text{total}}$ as the dependent variable and exp($0.053792 \times$ soil moisture) as the independent variable, as given by eq. (9)

$$\sigma^\circ_{\text{total}} = A + B \times \exp (0.053792 \times \text{soil moisture}), \tag{9}$$

where $A = \sigma^\circ_{\text{crop}}$ and $B = 0.064072/L^2$.

Regression analysis was performed using the soil moisture values extracted from the wheat fields and their corresponding SAR backscatter values extracted from the RADARSAT-1 Extended Low-1 images. Results of the regression analysis are given in Table 3. R^2, standard error, F statistics and significance of F of the regression analysis were found to be 0.77, 0.039, 153.809 and 2.829E-16 respectively. High values of R^2, F statistics and low values of standard error and significance of F clearly indicate the goodness-to-fit of the model given by eq. (10). The derived coefficients of regression analysis given by eq. (9) are

$$\sigma^{\circ}_{\text{total}} = 0.045279 + 0.088860 \times \exp(0.053792 \times \text{soil moisture}). \quad (10)$$

Comparison of eqs (10) and (8) yields the values of $\sigma^{\circ}_{\text{crop}}$ and $1/L^2$ as: Backscattering coefficient from the crop canopy = 0.045. Two-way attenuation by the crop canopy = 1.387.

Calculation of two-way attention introduced by crop cover at every pixel is difficult. There are a number of theoretical models that can cater to modelling the attenuation due to vegetation. However, the stringent requirement of a number of input parameters makes it impractical to use these models over large agricultural areas to arrive at vegetation attenuation properties. Thus accurate measurements of the microwave attenuation properties of vegetation canopies over a large agricultural area do not exist as two-way attenuation and $\sigma^{\circ}_{\text{crop}}$ are functions of the vegetation parameters (plant height, density, water content, volume and shape/structure of the canopy) and the radar parameters (frequency, incidence angle and polarization configuration). In this communication, an attempt has been made to calculate the values of $\sigma^{\circ}_{\text{crop}}$ and two-way attenuation for a large agricultural area. These values can be used to retrieve the soil moisture underneath the crop-covered fields. However, as $\sigma^{\circ}_{\text{crop}}$ and two-way attenuation are dynamic quantities, their values reported here are specific to wheat crop at a specific growth stage. Hence, detailed experiments should be carried out to calculate the values of $\sigma^{\circ}_{\text{crop}}$ and two-way attenuation for a particular crop at a critical growth stage, where soil moisture underneath is required to be estimated.

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