HOW FAR SAR HAS FULFILLED ITS EXPECTATION FOR SOIL MOISTURE RETRIEVAL

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ABSTRACT

Microwave remote sensing is one of the most promising tools for soil moisture estimation owing to its high sensitivity to dielectric properties of the target. Many ground-based scatterometer experiments were carried out for exploring this potential. After the launch of ERS-1, expectation was generated to operationally retrieve large area soil moisture information. However, along with its strong sensitivity to soil moisture, SAR is also sensitive to other parameters like surface roughness, crop cover and soil texture. Single channel SAR was found to be inadequate to resolve the effects of these parameters. Low and high incidence angle RADARSAT-1 SAR was exploited for resolving these effects and incorporating the effects of surface roughness and crop cover in the soil moisture retrieval models. Since the moisture and roughness should remain unchanged between low and high angle SAR acquisition, the gap period between the two acquisitions should be minimum. However, for RADARSAT-1 the gap is typically of the order of 3 days. To overcome this difficulty, simultaneously acquired ENVISAT-1 ASAR HH/VV and VV/VH data was studied for operational soil moisture estimation. Cross-polarised SAR data has been exploited for its sensitivity to vegetation for crop-covered fields where as co-pol ratio has been used to incorporate surface roughness for the case of bare soil. Although there has not been any multi-frequency SAR system onboard a satellite platform, efforts have also been made to understand soil moisture sensitivity and penetration capability at different frequencies using SIR-C/X-SAR and multi-parametric Airborne SAR data. This paper describes multi-incidence angle, multi-polarised and multi-frequency SAR approaches for soil moisture retrieval over large agricultural area.

Keywords: Soil moisture, surface roughness, crop cover, soil texture, deeper layer moisture, ERS-1 SAR, Radarsat-1 SAR, Envisat-1 ASAR, SIR-C/X-SAR, multi-parametric Airborne SAR

1. INTRODUCTION

Soil moisture is the temporary storage of water within the shallow layer of the earth's upper surface. As compared to the total amount of water available throughout the globe, soil moisture in this layer seems insignificant but it is this thin layer that controls all the agricultural activities. Soil moisture is not only important for vegetation, it also significantly affects the proportion of rainfall that percolates, runs off or evaporates from land. Thus information on soil moisture conditions is a crucial parameter in crop-yield prediction, irrigation scheduling, hydrological, agricultural and meteorological applications. In addition, the measurement of soil moisture aids in predicting the plant stress, desertification and deforestation. Beljaars et al.[1], and Paegle et al.[2] consistently show that operational high-resolution Numerical Weather Prediction and regional atmospheric model forecasts of the 1993 Upper Midwest U.S. flooding event was improved with realistic soil moisture initial conditions. Conventional methods for measuring soil moisture are location specific hence provide point estimates. Since soil moisture is highly dynamic, both spatially and temporally, point estimates cannot be extended over large areas with high accuracy. Hence, for estimating spatial distribution of soil moisture over large agricultural area, remote sensing methods are best suited as they offer a feasible, practical, timely and cost effective means. Furthermore, among the various electromagnetic bands, the microwave bands have the highest potential for remotely sensing the soil moisture. The key factor behind soil moisture estimation using microwaves is the large difference between the dielectric constant of water (~80) and that of dry soil (3 to 4) at microwave frequencies. The Radar Backscattering Coefficient (σ°) is strongly related to soil moisture due to the high dielectric constant of mixture of soil and water [3] This fact has been experimentally verified using many ground based experiments[4]. With

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the verification of these theoretical concepts, lot of expectations were generated of getting soil moisture maps on a routine basis. It should be borne in mind that for an agricultural land, SAR is also sensitive to other target parameters like surface roughness, vegetation cover and soil texture [5]-[8]. At the same time, influence of sensor parameters have also to be understood in order to look at the applicability of these findings over large agricultural areas. Thus, in order to give an answer to the question that "how far has SAR fulfilled its expectations in soil moisture estimation? ", one need to look at the attempts made to explore feasibility of incorporating the effects of surface roughness, vegetation cover and soil texture parameters in the soil moisture retrieval model. There have been studies to understand the effects of surface roughness and crop cover in the soil moisture retrieval model [9]-[11]. Blumberg, et. al. [12], have also suggested to eliminate the effect of surface roughness by means of operating P band scatterometer at 1^o angle of incidence. Oh et al. [13] have developed an empirical model using ratios of co and cross-polarized SAR data. The model attempts to invert the soil moisture and surface roughness in terms of ks with the validity region over ks<3. Dubois et al. [14], have studied angular behaviour of multi frequency, multi polarized SAR for developing an empirical algorithm for retrieval of soil moisture and surface roughness for bare soil using σ^o_{HH} and σ^o_{VV} SAR, which functions over regions with low NDVI. Attempts have also been made by some researchers to incorporate the effect of soil texture in the soil moisture retrieval model [15]. Srivastava et al. [16], have suggested the use of water available to plant as a soil moisture measure in order to incorporate the effect of soil texture in soil moisture retrieval using SAR. Blumberg et al. [12] have observed that higher correlation between soil moisture and SAR backscatter exists for sandy soils amongst sandy and clay soil. While discussing the effect of soil texture on SAR sensitivity to soil moisture, they pointed out that for clay, it is the higher content of clay that makes the water molecules to be tightly bound with soil particles, which in turn restricts them to align with the incident radar signal.

A number of researchers have put serious efforts to incorporate the effect of surface roughness and crop cover using theoretical approach based on physical models [17]. These models simulate the radar backscatter from bare rough surfaces using deviation in surface height (rms height), autocorrelation function, associated correlation length and dielectric constant as the input parameters. Although the modeling approach has shown excellent agreement between the modeled and the observed values of radar backscatter coefficient, it is difficult to extend such techniques for mapping of soil moisture over a large agricultural area owing to their complexity. Moreover, the surface roughness heterogeneity between various fields falling in a large agricultural area makes it impractical to model the surface roughness distribution, which is a prerequisite for using a theoretical model. This calls for a simple and practical means to incorporate the effect of surface roughness information in the soil moisture retrieval model from the satellite platform.

This paper describes the effort the authors have put into addressing the problem of incorporating the effects of soil texture, surface roughness and crop cover in soil moisture retrieval using multi incidence angle and multi polarised SAR from space platform, without making any assumptions on the distributions of these parameters or without knowing their actual values on ground. Although multi-frequency satellite SAR mission is not planned in near future, an attempt to understand the feasibility of using multi-frequency to enhance the soil moisture estimation prospects has also been discussed. A few examples describing the outcome of case studies carried out over Indian subcontinent to assess the fulfillment of SAR for soil moisture retrieval has been demonstrated using multi incidence, multi-polarised and multi frequency SAR data.

2. FACTORS AFFECTING SAR SENSITIVITY TO SOIL MOISTURE

In order to understand the sensitivity of SAR to soil moisture, firstly we now look at the parameters that affect the SAR return signal from an agricultural land. SAR return signal is affected by the sensor parameters viz. wavelength, polarisation and incidence angle at which the sensor is being operated and target dielectric and geometrical properties in general. SAR backscatter from an agricultural terrain is strongly influenced by the moisture content and surface roughness conditions of the soil, dielectric and geometrical properties of the vegetation prevailing in the agricultural fields at the time of data take. At the same time the soil depth with which the incident microwaves interacts also varies from one wavelength to the other.

2.1 Soil moisture dependence

At microwave frequencies, dielectric constant of dry soil is around 3 and that of water is around 80. Hence dielectric constant for a moist soil, which is a mixture of the two, ranges between 3 and 30. As the dielectric of a material increases, the Fresnel reflectivity also increases resulting in an increased backscatter. Thus SAR backscatter is directly related to moisture content of the target under consideration. i.e. A dry field would yield low backscatter, hence would appear in dark tone and a moist field would appear in bright tone due to high backscatter.

2.2 Penetration depth and its dependence on frequency

The penetration depth of SAR signal is dependent on wavelength. Hence, in order to understand SAR backscatter from soil, it is also important to know the depth of soil profile from which the SAR is sensing the soil moisture. The depth of penetration for a given target is governed by wavelength of incident microwaves signal and the complex dielectric constant of the target as given below.

$$\delta p \cong \frac{\lambda * \sqrt{\varepsilon'}}{2\pi * \varepsilon''} \qquad (1)$$

where, δ_p= Penetration depth; λ= Wavelength; ε' = Real part of complex dielectric constant

ε''= Imaginary part of complex dielectric constant

It can be seen that for a given target, longer wavelengths have higher penetration depth as compared to shorter wavelengths. At the same time, it is the moisture content of different layers of soil profile that determines the SAR backscatter at different wavelengths.

2.3 Surface roughness dependence

Surface roughness is another important parameter that significantly affects the SAR backscatter from soil. A field that is smooth would appear dark due to low backscatter, as smooth surface gives rise to specular reflection whereas a rough field would appear brighter due to higher non coherent scattering component, resulting in an increased backscatter towards SAR antenna. Here it is interesting to mention that magnitude of surface roughness itself is a function of frequency and incidence angle at which the surface is being illuminated. It indicates that the characterization of a soil surface into smooth and/or rough class changes with the SAR sensor parameters. According to Fraunhofer criterion, a surface will appear smooth if the surface rms height (h) satisfies the following condition given by [18],

$$h < \frac{\lambda}{32 \cos(\theta)} \qquad (2)$$

Table-1 gives the cut-off values of rms height for a surface to be considered as a smooth surface illuminated at 45° incidence angle at C, L and P-bands.

Table-1: Cut-off limits for a smooth surface at 45° for C, L and P bands

S. No.	Wavelength (λ)	Incidence angle (θ)	Smoothness criterion (h <)
1.	5.6 cm	45°	0.25
2.	23.5 cm	45°	1.04
3.	85 cm	45°	3.76

Hence as the wavelength increases the same field starts satisfying the smoothness criterion, i.e. for longer wavelength almost all the agricultural fields appear as smooth. Thus a field that is rough for C band could be medium rough for L band and smooth for P band.

2.4 Impact of crop cover

At the same time SAR backscatter for a vegetated terrain depends upon the vegetation volume, dielectric and structure of the vegetation constituents along with the dielectric and surface roughness of underlying soil. For a given vegetation type, the penetration depth of different frequencies depends on the frequency, polarisation as well as incidence angle. For example a shallow incidence angle SAR operating at C-band penetrating only in the upper layer of the canopy where as the crop would become almost transparent to P-band. At the same time, at near nadir incidence angle even C band can reach to the soil underneath the crop cover.

3. DATA SET & STUDY AREA

Results from various case studies are included in this paper covering data from ISRO's ground based scattorometer, single channel ERS-1/2 SAR data, multi-incidence angle Radarsat-1 SAR, multi-polarised Envisat-1 ASAR, multi-frequency data from SIR-C/X-SAR and airborne SAR mission. ERS-1/2 SAR operated at C band, in VV polarisation with central incidence angle 23^o. Two incidence angle data from Extended low-1 beam mode, 16^o central incidence angle and S4 beam mode at 36^o central incidence angle data of Radarsat-1 SAR operating at C band with HH polarisation are used. Envisat-1 operates at multi-inciende angle in dual polarisation mode. Airborne SAR operated in multi-frequency (C, L, P), multi-polarisation (VV, HH, VH, HV) mode. Radarsat-1 and Envisat-1 data were acquired over parts of Agra, Mathura and Bharatpur districts, India and also over the parts of Saharanpur and Haridwar districts, India. Both the study areas are mostly flat level terrain and are dominated by agricultural land. These areas include irrigated as well as un-irrigated agricultural land and therefore provide full range of soil moisture. The study area over parts of Agra, Mathura and Bharatpur, consists of fine loamy, coarse loamy, fine silty, sandy and fine textured soils. The study area over parts of Sahranpur and Haridwar district covers fine loamy, coarse loamy, fine silty and sandy soils. Along with SAR scenes, optical data from IRS (Indian Remote Sensing Satellite) L-III (Linear Imaging Self Scanning-III) have also been used to delineate crop-covered fields from bare fields. Spectral bands for IRS LISS-III are Green (0.52-0.59μm), Red (0.62-0.68μm), Infra red (0.77-0.86μm) and Short wave Infrared (1.55-1.70μm) with the spatial resolution of 23.5 meters.

4. SOIL MOISTURE ESTIMATION USING SAR

Soil texture is also one of the target parameter that significantly affects the SAR backscatter as it determines the dielectric property of soil water mixture. In order to incorporate the effect of soil texture, a soil moisture measure has been developed based upon the characteristic interaction of SAR with the water inside soil medium [16]. The following subsection describes scientific rationale of the conceptualised soil moisture measure.

4.1 Incorporating the effect of soil texture

Wet soil is a heterogeneous mixture of soil, water and air pockets. In general, the water in wet soil can be further divided into bound water and free water. The percentage of free water and bound water present in a soil medium largely determines the dielectric constant of a soil medium [19]. Moreover, the percentage of bound water and free water depends upon the surface area of soil particles present in the soil medium. As the surface area of soil particles in a soil medium depends upon the particle size and the relative proportions of various-sized particles in a given soil hence, the dielectric constant of wet soil varies with soil texture. The amount of soil moisture at wilting point (15 bar pressure) is very tightly held with soil particles. Thus, there is a strong synergy between bound water and water at 15 bar pressure as both represents the amount of water which is very tightly held with soil particles. Since the amount of water free to interact with the incident microwaves, and give significant contribution to the SAR backscatter, is close to the amount of water available to plants per unit volume of soil, a soil moisture measure is defined in terms of water that is above the wilting point as given by Equation (3) [16].

SM_WAP=(Observed soil moisture from sampling location – Soil Moisture at 15 bar pressure for the same location) (3)

The SM_WAP defined by Equation (3) was then related to SAR backscatter (σ°) by the following equation,

$$SM\_WAP = A + B * (\sigma^\circ) \quad (4)$$

In order to demonstrate the effectiveness of SM_WAP, an experiment over smooth bare fields alone was conducted to ensure that it is only the soil texture other than soil moisture that affects the SAR backscatter. Figure-1 shows the variation of Radarsat-1 SAR backscatter to various soil moisture measures i.e. gravimetric soil moisture (SM_G), volumetric soil moisture (SM_V), soil moisture in terms of percentage of field capacity (SM_FC) and soil moisture in terms of water available to plants per unit volume of soil (SM_WAP). A total of 57 soil samples were collected during the ground truth survey, carried out in synchrony with the satellite pass. Out of the 57 soil samples 50 samples were used to develop the empirical model and remaining 7 were used to validate the empirical relationship. The study of Figure-1 reveals that by representing soil moisture in terms of SM_WAP, R^2 increased considerably from 0.88 to 0.96 as compared to the case where soil moisture is represented as gravimetric soil moisture (SM_G). At the same time, it was observed that the rms error for SM_WAP was the lowest at 0.62, as compared to that of 2.23 obtained for model developed using gravimetric soil moisture over an independent dataset. Thus, SM_WAP effectively incorporates the effect of soil texture in soil moisture estimation using Synthetic Aperture Radar by representing the soil moisture in terms of the water available to plants in that soil medium.

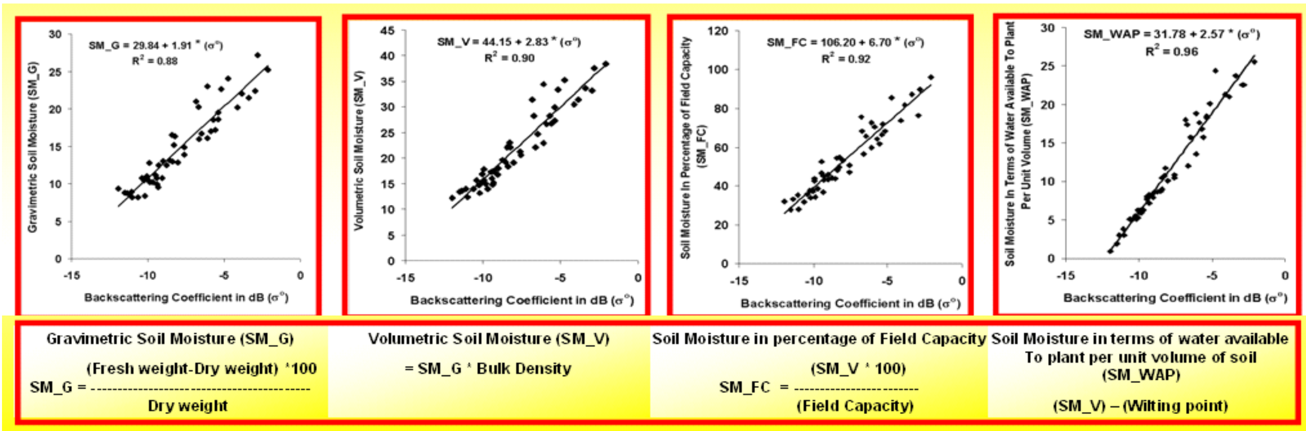

Fig-1 Variation of Radarsat-1 SAR backscatter to various soil moisture measures

4.2 Soil moisture estimation: Single frequency case (C-Band SAR)

Microwave remote sensing is one of the most promising tools for soil moisture estimation owing to its high sensitivity to dielectric properties of the target. Many ground-based scatterometer experiments were carried out for exploring this potential. Experiments carried out using ISRO's ground based scatterometer over parts of Jodhpur and Nawagam, India resulted in a sensitivity of 0.32db/(%g/g) at C band 20^o incidence angle. After the launch of ERS-1, expectation was generated to operationally retrieve soil moisture information over large area. However, single channel SAR data from ERS-1 was found to be inadequate to resolve the effects of surface roughness and crop cover. Figure-2 shows the effect of surface roughness on SAR backscatter for similar moisture content. It was observed that SAR backscatter obtained from single channel ERS-1 SAR could not resolve effect of surface roughness from that of soil moisture. Besides based upon the experience from ISRO's ground based scatterometer experiments, for a radiometric resolution of 2.5 db of ERS-1 SAR, one could at best expect 8% levels of soil moisture resulting in two to five levels of soil moisture for a given scene depending upon the soil moisture variability existing within a scene.

In a quest to reach to operational soil moisture estimation, efforts were put to make use of multi-parametric SAR data and the soil moisture measure described in previous section, a methodology which incorporates the effect of surface roughness and crop cover in soil moisture retrieval has been developed over a period of time [20]-[22]. The crux of the methodology is in the fact that one need not make any assumptions about the distribution of these parameters and one can incorporate the effects of these parameters from space platform alone. Efforts have been made to ensure that the different approaches adopted for incorporating the effect of soil texture, surface roughness and crop cover in soil moisture retrieval are combined and a methodology for soil moisture retrieval is arrived at for operational monitoring of soil moisture status over large agricultural area [23]. The following subsections describes the scientific rationale which leads to the possible approaches for incorporating the effect of surface roughness and vegetation cover for arriving at soil moisture estimation using multi-incidence angle, multi-polarised as well as multi-frequency SAR. While retrieving soil moisture using multi-incidence angle SAR, there is a requirement of having to have the soil moisture and surface roughness condition remaining unchanged between acquisition of low and high incidence angle SAR passes. However, the gap between low and high incidence angle SAR acquisition is typically that of 3 days in case of Radarsat-1 SAR. With the availability of multi-polarised SAR system on board Envisat-1 it has become feasible to

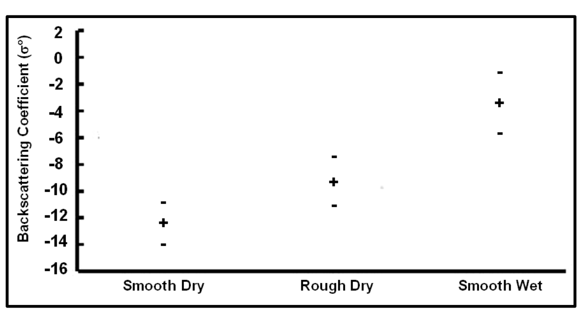

Fig. 2: Effect of surface roughness on SAR

simultaneously acquire SAR data in dual polarised mode. Using these simultaneously acquired like/like (HH/VV) and like/cross (VV/VH) polarised SAR data from Envisat-1 ASAR, efforts have been put to look for feasibility of operationally arriving at spatial distribution of soil moisture. For this purpose cross polarised SAR data has been exploited for its sensitivity to vegetation whereas co-pol ratio (HH/VV) has been exploited for its sensitivity to surface roughness in case of bare soil condition.

4.2.1 Incorporating the effect of surface roughness

Surface roughness significantly affects SAR backscatter response of a target. Hence, for fallow fields, mapping of soil moisture with higher accuracy calls for incorporating the effect of surface roughness in the soil moisture retrieval model. A lot of work has been carried out using the theoretical modelling approach to incorporate the effect of surface roughness in the soil moisture retrieval model. Although the modelling approach has shown excellent agreement between the modelled and the observed values of radar backscatter, it is difficult to extend such techniques for mapping of soil moisture over a large agricultural area owing to their complexity and the scarcity of required input parameter. This calls for a simple and practical means to incorporate the effect of surface roughness information in the soil moisture retrieval model from the satellite platform. For a rough surface, the SAR backscatter signal strength at low and high incidence angle are compatible with each other whereas for a smooth surface, the SAR backscatter signal strength at a higher incidence angle is much less than that at low angle of incidence, hence, the ($\sigma°_{LOW}$ - $\sigma°_{HIGH}$) is high for smooth fields and low for rough fields. Angular behaviour of multi-incidence angle SAR data has been exploited to incorporate the effect of surface roughness in the soil moisture retrieval model [20], [21]. Hence, the effect of surface roughness in the soil moisture estimation was incorporated by using ($\sigma°_{low}$-$\sigma°_{high}$) as a surface roughness indicator as given by equation-5 [23].

$$SM\_WAP = A + B*(\sigma°_{LOW}) + C*(\sigma°_{LOW} - \sigma°_{HIGH}) \quad (5)$$

A regression analysis was carried out using soil moisture from 17 bare fields represented in SM_WAP values and their Radarsat-1 SAR backscatter values [$\sigma°_{LOW}$ and ($\sigma°_{LOW}$-$\sigma°_{HIGH}$)] extracted from the multi-incidence angle SAR image pair as independent variable, using Equation-5. The coefficient of determination was found to be 0.93 for the model represented by Equation-5 with 2.65 as the value of rms error between observed SM_WAP and estimated SM_WAP for the validation data set consisting of 10 samples. The details of the developed model are given in Table-2.

Although the model given by equation-5 is able to incorporate the effect of surface roughness in the soil moisture retrieval model, the time difference between the acquisition of lower and higher incidence angle SAR data restricts the use of this model if there is large difference in between the acquisition of lower and higher incidence angle SAR passes. Availability of simultaneously acquired dual polarized Envisat-1 ASAR data has provided the opportunity to exploit the sensitivity of like polarization ratio (HH/VV) towards surface roughness conditions. Authors have observed that log of the like polarization ratio is sensitive to surface roughness (Figure-3). Hence in order to incorporate the effect of surface roughness in the soil moisture retrieval model an additional term as ln($\sigma°_{HH}$ -$\sigma°_{VV}$) is included, given by equation- 6

$$SM\_WAP = A + B*(\sigma°_{VV}) + C*\ln(\sigma°_{HH} - \sigma°_{VV}) \quad (6)$$

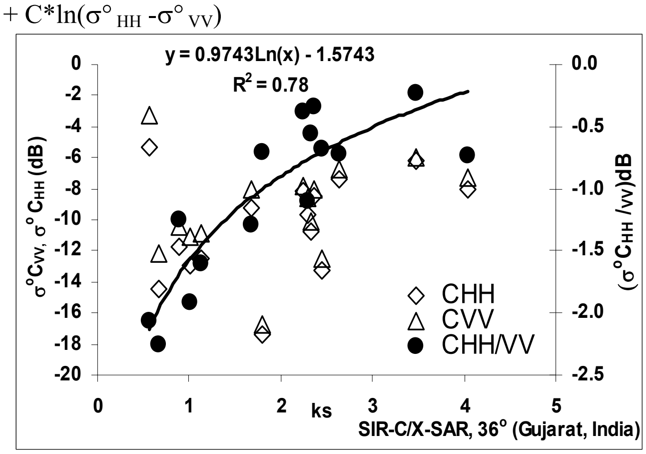

Fig. 3: variation of like polarisation ratio with surface roughness

A regression analysis was carried out on 12 soil samples taken from bare fields to develop soil moisture retrieval model using SM_WAP values obtained through ground truth and laboratory analysis as dependent variable and their Envisat-1 SAR backscatter values [$\sigma°_{VV}$ and ($\sigma°_{HH}$ -$\sigma°_{VV}$)] were extracted from the multi-polarised Envisat-1 SAR image pair as independent variable. The coefficient of determination was found to be 0.89 for the model represented by Equation-6. The rms error between observed and estimated SM_WAP using 7 data points over bare soil which were not used for model development was found to be 2.15. The details of the developed model are given in Table-2.

4.2.2 Incorporating the effect due to crop cover

When SAR views a crop-covered field at higher incidence angle it undergoes an increased path length through the vegetation volume, resulting in higher interaction with crop canopy. It has been observed that for crop covered fields, the return signal at higher incidence angle, $\sigma°_{high}$, is an effective crop canopy descriptor as it represents the overall effect of crop cover, i.e. the combined effect of crop type, crop structure, crop volume, canopy moisture etc. in the soil moisture retrieval model [20], [22]. An empirical model for soil moisture retrieval for crop covered soil has been developed by including an additional term of $\sigma°_{high}$ in the soil moisture retrieval model as a crop canopy descriptor. Thus for the crop covered soil, the soil moisture retrieval model is as given by equation-7 [23].

$$SM\_WAP = A + B*(\sigma°_{LOW}) + C*(\sigma°_{HIGH}) \quad (7)$$

A regression analysis was carried out on 26 soil samples taken from wheat crop covered fields to develop soil moisture retrieval model for crop covered soil using SM_WAP values obtained through ground truth and laboratory analysis as dependent variable and their Radarsat-1 SAR backscatter values [$\sigma°_{LOW}$ and $\sigma°_{HIGH}$], extracted from the multi-incidence angle SAR image pair as independent variable. The coefficient of determination was found to be 0.95 for the model represented by Equation-7. The rms error between observed and estimated SM_WAP using 22 data points over crop covered soil which were not used for model development was found to be 1.81 The details of the developed model are given in Table-2.

With the availability of simultaneously acquired like (VV) and cross (VH) polarized Envisat-1 ASAR data, one can overcome the limitation of non availability of simultaneous acquisition of multi-incidence angle SAR data. Authors have used cross-polarized SAR backscatter to incorporate the effect of crop cover in the soil moisture retrieval model. From crop covered fields, depolarisation takes place due to multiple reflections within vegetation volume. As the amount of depolarisation is much higher for larger vegetation volume and larger amount of dielectric discontinuities with in the vegetation volume, it is obvious that amount of depolarisation can be used as an indicator of the overall vegetation cover. Hence, the effect of crop cover can be incorporated in the soil moisture retrieval model by including an extra term of cross-polarized SAR backscatter ($\sigma°_{VH}$) in the soil moisture retrieval model. This model can be written in the form of equation-8 [24].

$$SM\_WAP = A + B*(\sigma°_{VV}) + C*(\sigma°_{VH}) \quad (8)$$

A regression analysis was carried out on 14 soil samples taken from Bajra/Jowar crop covered fields to develop soil moisture retrieval model for crop covered soil using SM_WAP values obtained through ground truth and laboratory analysis as dependent variable and their Envisat-1 SAR backscatter values [$\sigma°_{VV}$ and $\sigma°_{VH}$] extracted from the multi-

Table-2: Results of single frequency case (C-band, multi-incidence angle/ multi-polarisation)

Soil cover	Model Development			Model Validation	
	Model	# of Data Points	R^2	# of Data Points	rms error
Bare	SM_WAP= $A + B*(\sigma°\ low) + C*(\sigma°\ low - \sigma°\ high)$	17	0.93	10	2.65
	SM_WAP= $A + B*(\sigma°_{VV}) + C*\ln(\sigma°_{HH} - \sigma°_{VV})$	12	0.89	7	2.15
Crop	SM_WAP= $A + B*(\sigma°\ low) + C*(\sigma°high)$	26	0.95	22	1.81
	SM_WAP= $A + B*(\sigma°_{VV}) + C*(\sigma°_{VH})$	14	0.92	10	1.49

polarised Envisat-1 SAR image pair as independent variable, using Equation-8. The coefficient of determination was found to be 0.92 for the model represented by Equation-8 with 1.95 as the value of SEE. The rms error between observed and estimated SM_WAP using 10 data points, which were not used for model development was found to be 1.49. The details of the developed model are given in Table-2.

4.3 Potential of multi-frequency SAR data in the field of soil moisture estimation at different soil depth

There have not been any SAR system in past on-board satellite platform which gives SAR data in multi frequency mode, at the same time there are no plans for any such systems in near future. However there exists a possibility of combining data from different satellite for arriving at a multi-frequency data over the study area. e.g. L-band from PALSAR-ALOS and C-band from RISAT/Radarsat. Hence some of the potential applications of multi-frequency SAR data in the field of soil moisture estimation are also explored. The case studies are carried out using SIR-C/X-SAR data over Bhavnagar, Gujarat which was operated in the L, C and X bands and also using multi-parametric Airborne SAR data over parts of Rajashthan, India acquired during September 2004. Multi-frequency SAR data has immense potential in the field of soil moisture estimation. In the following sections, sensitivity of multi-frequency SAR to soil moisture at varying depth is discussed for bare soil as well as for crop covered soil.

4.3.1 Impact of surface roughness and soil moisture on multi-frequency SAR signature: bare soil

Wavelength is one of the most important sensor parameter that affects soil moisture estimation, as it is the wavelength that determines the depth from where the signal is coming back. As longer wavelengths have higher penetration depth within the soil medium, longer wavelengths sense soil moisture from deeper layers as compared with shorter wavelengths that mostly interacts with soil surface or very small soil column (0-10 cm) near soil surface. However, due to non-availability of longer wavelengths in most of the operational satellites (e.g. ERS-2, Radarsat-1, Envisat-1, proposed Radarsat-2, proposed RISAT etc.) the potential of SAR is limited only up to surface soil moisture estimation. Based upon the limited multi-parametric SAR data from Airborne SAR and from missions like SIR-C/X-SAR, the authors have explored the potentials of longer wavelengths in the field of soil moisture estimation. For example during SIR-C/X-SAR mission, potential of longer wavelengths to estimate deeper layer soil moisture was clearly brought out as seen in the figure-4. In figure-4, it is clearly seen that L-band is able to sense deeper layer soil moisture. Figure-4 also indicates that C-band and X-band are not able to sense deeper layer soil moisture due to their low penetrability within soil medium. However during the data take of SIR-C/X-SAR during the month of April 1994 there were no crops and there hardly was any moisture in the agricultural fallow fields. Hence, for understanding impact of surface roughness and soil moisture in different soil profile, at various frequencies and polarisations, multi-parametric Airborne SAR data over

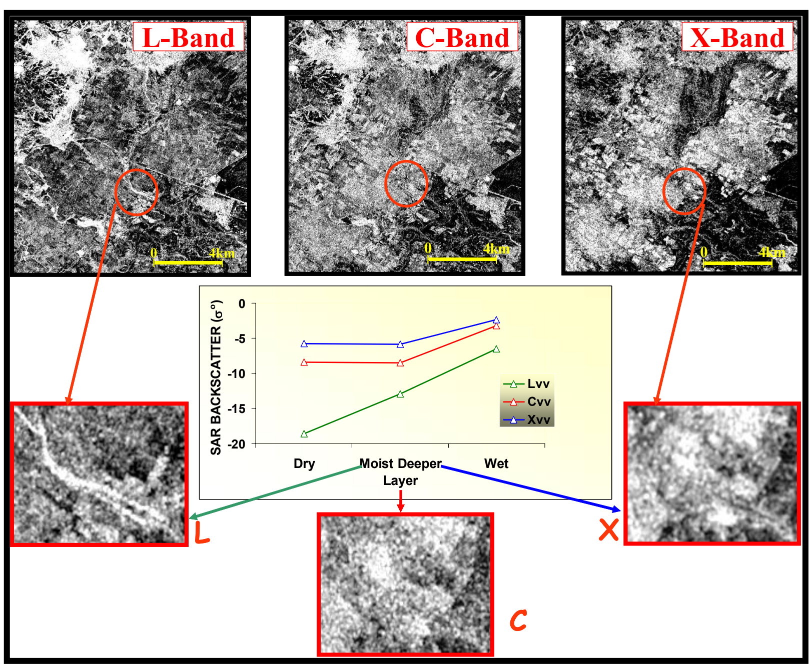

Fig. 4: Multi-frequency SIR-C response to deeper layer soil moisture

an agricultural area having varying surface roughness and varying soil moisture content at different soil profiles has been studied. A multi-frequency colour composite image generated over the area by assigning Red colour to P-band, Green colour to L-band and Blue colour to C-band at VV polarisation showed various tones for fallow fields in the multi-frequency colour composite image. In particular agricultural fields in various tones of red were showing deeper layer moisture content, as they were prominent in P-band, which is able to penetrate soil up to the deeper layers. These tones were a net resultant of SAR response to the moisture at different depths and surface roughness conditions.

Figure-5 shows SAR backscatter at C, L and P bands at linear polarisation for five fields demonstrating the impact of surface roughness and soil moisture on SAR backscatter. The five fields used in the scatter-plot are labelled as A, B, C, D and E. The surface roughness and soil moisture information of these fields is given in Table-3. The surface roughness is characterized as (S→Smooth, MR→Medium rough, VR→Very rough) and the soil moisture at three soil profiles i.e. top layer, middle layer and deeper layer has been characterized as (d→ dry, mm→ medium moist, m→ moist).

Table-3: Surface roughness, and moisture status at upper, middle and deeper layers of soil profile

S. No.	Field-ID	Surface Roughness			Soil Moisture		
		C-band	L-band	P-band	Top layer	Middle layer	Deeper Layer
1.	A	S	S	S	MM	MM	MM
2.	B	S	S	S	M	M	M
3.	C	R	MR	S	MM	MM	MM
4.	D	R	MR	S	D	MM	MM
5.	E	VR	R	MR	MM	MM	MM

S: Smooth; MR: Medium Rough; VR: Very Rough; MM: Medium moist; M: moist; D: Dry

It can be observed that for smooth surface fields A and B the dynamic range due to soil wetness conditions for HH as well as VV is of the order of 7 db at C band, 10 db at L band and 1.2 db at P band. A comparison of C band response for dry field D and medium moist field C both being rough surfaces for C band shows the influence of surface roughness on dynamic rage due to variation in soil wetness conditions. The dynamic range for HH polarisation is that of 5 dB whereas for VV poalrisation it is as low as 2 dB. Multi-frequency response for field-C and field-D at VV polarisation also leads to another interesting observation, which depicts the penetration depth of different frequencies. The C-band (VV) SAR backscatter has reduced by 1.9 dB for these two fields, which were having uniform surface roughness. Field-C is having medium moisture in the top layer, whereas for field-D, the soil moisture of top layer was dry. The moisture of middle and deeper layer of the soil profile is medium moist for both the fields C and D. This fact confirms that C-band could sense only the soil moisture of the upper layer of the soil. For L-band as well as P-band there is negligible change in the SAR backscatter for these two fields since the soil moisture profile as well as the surface roughness has not changed significantly. For L-band (VV) the variation is in accordance to the moisture content for the fields A, B C and D. However for the field E, the surface roughness, which is very high has resulted in an increase of 6.1 db as compared to the field D which is having similar moisture content. For P band all the fields are appearing as smooth with the exception of field E which is slightly rough even for P band giving an increase of 3 dB in backscatter (VV) as compared to field D having similar moisture conditions.

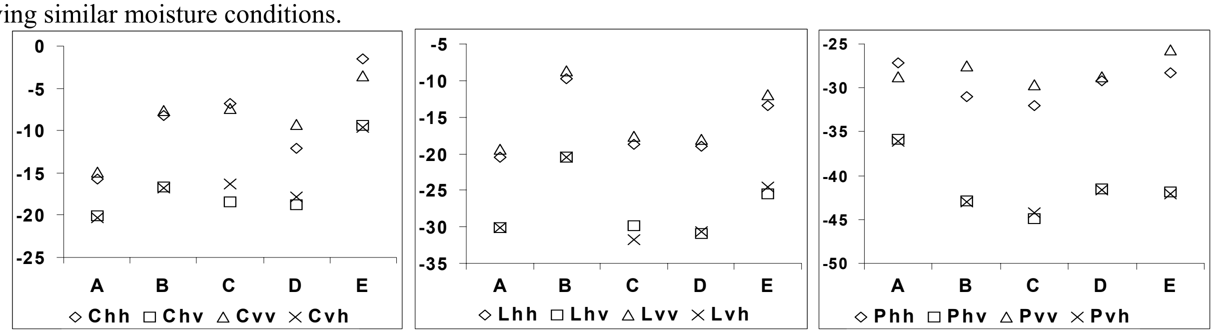

Fig. 5: SAR backscatter at different frequency and polarization for bare agricultural fields having varying surface roughness and soil moisture conditions.

For P band, since the deeper layer of all the fields are having almost uniform moisture except for field-B, which is moist deeper layer, the backscatter values of fields A, C and D are uniform where as the SAR backscatter at field-B is slightly high as compared to other fields. This demonstrates the sensitivity of P-band to soil moisture and surface roughness. There is a small difference in HH and VV depending upon the combined effect of surface roughness and moisture of the soil for C and L band. However for the field B, VV polarisation of P band is higher as compared to HH polarisation by 3.5 dB indicating that amongst polarisation, VV is able to penetrate deeper as compared to HH in case of bare soil conditions. The HV and VH polarised backscatter were mostly same and did not differ amongst themselves for a given target. The variation in cross polarization is affected by both surface roughness as well as soil moisture. At C-band the influence of surface roughness seems to be having greater impact on SAR backscatter whereas at L-band cross polarized SAR backscatter appears to be more governed by the moisture content.

4.3.2 Impact of crop structure and soil moisture on multi-frequency SAR signature: crop covered soil

Longer wavelengths are known for higher penetration within the vegetation volume and depending upon the wavelength and plant parameters (e.g. plant moisture, plant height, plant volume etc.), SAR signal can reach up to the underlying soil surface. For example in case of cultural crops, L-band can provide the information about soil moisture with reasonable good accuracies. Similarly due to very long wavelength (30cm –100cm), P-band can penetrate even tree cover to reach up to underlying soil. Hence by proper selection of longer wavelengths, it is possible to estimate soil moisture with reasonably good accuracies even under crop or vegetation cover conditions. Two types of crops were present during the Airborne SAR data take, namely vegetable crop (Pumpkin) and Bajra (Pearl millet). Pumpkin is a creeper crop having broad leaf structure spread over soil, where as Bajra is having a vertical structure with a height of around 2 meters. In order to understand the impact of crop structure and penetration depth on soil moisture sensitivity of SAR backscatter at different frequency and different polarisation, SAR signature of four fields, namely Bajra (B1) with dry soil profile moisture and Bajra (B2) with moist soil profile, Pumpkin with top and middle layer moist with a dry deeper layer (P1) and another Pumpkin (P2) field with moist soil profile has been studied. Moisture status of these four crop covered fields is given in Table-4.

Table-4: Soil moisture status at top, middle and deeper layers of Bajra and Pumpkin fields

S. No.	Crop Type	Field-ID	Soil Moisture		
			Top Layer	Middle Layer	Deeper Layer
1.	Bajra	B1	Dry	Dry	Dry
2.	Bajra	B2	Moist	Moist	Moist
3.	Pumpkin	P1	Moist	Moist	Dry
4.	Pumpkin	P2	Moist	Moist	Moist

The effects of different crop structure and soil moisture underneath them at different soil layers on SAR response at different frequency and polarization can be understand with the help of figure-6. It can be observed from the figure-6 that for all the bands including C-band, cross-polarized (VH/HV) SAR backscatter is able to pickup the difference in the Bajra and pumpkin areas. The cross-polarized SAR responded to crop structure for all the frequency, the cross-polarized backscatter were less affected by the moisture content at C and P band as compared to L-band. The broad leave structured pumpkin always has resulted in higher backscatter at cross polarisation at all the frequency as compared to

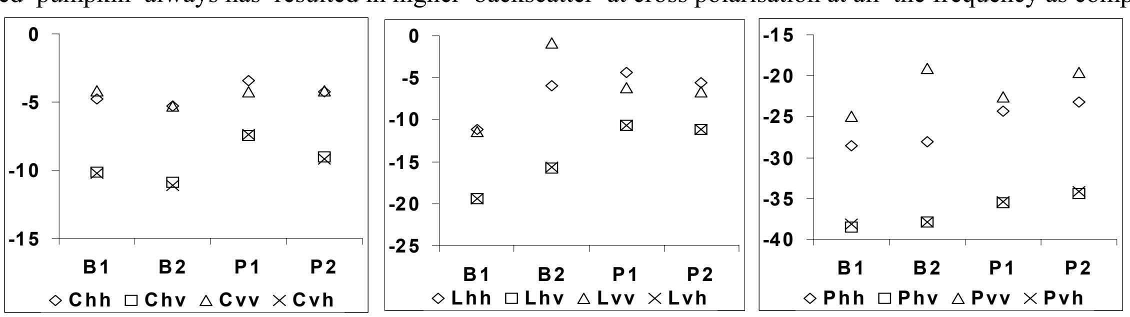

Fig. 6: SAR backscatter at different frequency and polarization for Bajra and Pumpkin crops with varying soil moisture conditions.

vertical thin leave structured bajra crop. The comparison of L-band VV polarised SAR backscatter over Bajra (B2) and pumpkin (P2) crops, with nearly similar moisture status in the total soil profile, reveal that due to vertical structure of Bajra crop, L-band VV polarized SAR backscatter has resulted in an increase of 4.7 dB in comparison to L-band HH polarized SAR backscatter. The dramatic effect of transmit / receive polarization of SAR backscatter with the crop structure is further confirmed by comparing the SAR backscatter values of L-band at HH and VV polarization over pumpkin (creeper) crop. It was observed that in case of pumpkin, HH polarized SAR backscatter is giving higher return as compared to VV polarized SAR backscatter due to broad leaf structure and horizontal growth pattern of creeper crops. However backscatter from HH and VV polarisation of C-band, is more or less same for both the crops. P-band HH polarisation did show response to crop structure with P-band HH polarized SAR backscatter over pumpkin (P2) area with moist soil profile being 5 db higher as compared to the Bajra (B2) crop with similar soil moisture profile status. The effect of penetration capability is dramatically brought out for the case of pumpkin fields. There is no difference in C and L band response between the two Pumpkin fields (P1 & P2), whereas the penetration of P-band through the crops and deep down the soil can be confirmed with the P-band VV backscatter for the P1 field with dry deeper layer resulted in a decrease of 3 db in comparision to the Field P2 with moist deeper layer. Thus P-band VV polarised signal could penetrate up to 75-90 cm depth even in presence of thick crop cover. For the same two fields, the change in P-band HH polarisation is that of 1.2 dB. Thus the effect of deeper layer moisture was more pronounced for VV polarisation as compared to HH polarisation for P-band. Further nearly similar backscatter of Bajra (B2) and Pumpkin (P2) at P-band at VV polarisation reconfirms the fact that the crop is almost transparent and it is mainly the moisture of underlying soil that is affecting P-band SAR backscatter.

5. CONCLUSION

Authors have tried to assess the SAR sensitivity for large area soil moisture in order to find out as to how far SAR has fulfilled its expectation for soil moisture retrieval. The impact of interfering target parameters viz. surface roughness, crop cover and soil texture is discussed and ways to handle them is presented using case studies carried out by authors over Indian subcontinent. It has been shown that it is feasible to retrieve soil moisture using operationally available satellite SAR data with certain conditions. Use of Steep and shallow incidence angle Radarsat-1 SAR data has been successfully demonstrated to incorporate the effect of surface roughness and crop cover in large area soil moisture retrieval. Although, at present simultaneous acquisition in multiincidence angle is not available, still with the constellation SAR becoming reality in future, this approach appears to be a good candidate for operational monitoring of soil moisture over large agricultural area. Envisat-1 ASAR data has also been demonstrated as useful in developing approaches to incorporate the effect of surface roughness and crop cover in soil moisture retrieval models. Penetration capability of SAR backscatter from longer wavelengths have been demonstrated in the case of crop covered as well as bare soil conditions under varying crop structure and surface roughness conditions. A soil moisture measure in terms of water available to plant has been demonstrated to be able to incorporate the effect of soil texture. Results of various case studies reported in this paper suggest that it is feasible to retrieve soil moisture using SAR provided one adopts appropriate measures to handle the impact of surface roughness and crop cover from space.

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