Soil moisture variation over parts of Saharanpur and Haridwar districts (India) during November-2006 to June-2007 as observed by multi-polarized (VV/HH & VV/VH) ENVISAT-1 temporal ASAR data

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***Abstract*—** *Microwave remote sensing is one of the most promising tools for soil moisture estimation owing to its high sensitivity towards dielectric properties of the target under consideration. 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 target parameters like surface roughness and vegetation (crop) cover. 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 by researchers for 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 acquisitions, 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 mapping. Cross-polarized SAR data has been exploited for its sensitivity towards vegetation for crop-covered fields where as co-polarization ratio has been used to incorporate effect of surface roughness for the case of bare agricultural fields. In order to demonstrate the potential of the developed methodology, an attempt has also been made to study variation of soil moisture status during November-2006 to June-2007 over parts of Saharanpur and Haridwar districts using ENVISAT-1 ASAR data sets acquired at IS1 beam mode. Temporal soil moisture status which reflects the irrigation pattern adopted by the farmers of the study area is matching with the agricultural activities like sowing and harvesting. Study indicates the potential of soil moisture information for agricultural applications like irrigation scheduling.*

Keywords*— *ENVISAT-1 ASAR, Polarization, Cross-pol. ratio, Co-pol. Ratio, Incidence angle, Soil Moisture, Surface roughness, crop cover, agricultural fields..

I. 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, and many other hydrological, agricultural and meteorological applications. In addition, the measurement of soil moisture aids in predicting the plant stress, desertification and deforestation. It has been observed that operational high-resolution Numerical Weather Prediction and regional atmospheric model forecast of the 1993 Upper Midwest U.S. flooding event was improved considerably with realistic soil moisture initial conditions[1-2]. Conventional methods used for measuring soil moisture are location specific and 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 remote sensing of soil moisture. The key factor behind soil moisture estimation using microwave is 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 the verification of these theoretical concepts, vast expectations were generated for getting soil moisture maps on a routine basis. However, 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 [5-23]. However, effect of surface roughness and vegetation cover is more severe than soil texture.

There have been studies to understand the effects of surface roughness and crop cover in the soil moisture retrieval model [24-33]. 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 [34]. 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 good 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 [8, 11, 17-18, 22, 26-27].

This paper describes the authors' efforts in addressing the problem of incorporating the effects of surface roughness and crop cover in soil moisture retrieval using multi-polarized SAR from space platform, without making any assumptions on the distributions of these parameters or without knowing their actual values on ground. In order to demonstrate the potential of the developed methodology, an attempt has also been made to study variation of soil moisture status during November-2006 to June-2007 over parts of Saharanpur and Haridwar districts using IS1 beam mode of ENVISAT-1 ASAR data.

II. FACTORS AFFECTING SAR SENSITIVITY TO SOIL MOISTURE

In order to understand the sensitivity of SAR to soil moisture, firstly we 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, polarization 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 satellite pass. Moreover, the soil depth with which the incident microwaves interacts also varies from one wavelength to the other.

A. *Soil moisture dependence*

At microwave frequencies, dielectric constant of dry soil is around 3 and that of water is around 80. Hence dielectric constant of 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 and appears in dark tone where as a moist field would appear in bright tone due to high backscatter.

B. *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 where the SAR is sensing the soil moisture. The depth of penetration for a given target is governed by wavelength of incident microwave signal and the complex dielectric constant of the target as given below.

$$\delta p \cong \frac{\lambda * \sqrt{\varepsilon'}}{2\pi * \varepsilon''}$$

where,

δp = 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 [18].

C. *Surface roughness dependence*

Surface roughness is another important parameter that significantly affects 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 mono-static 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. Moreover, 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 [35].

D. *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 depends on the frequency, polarization as well as incidence angle. For example a shallow incidence angle SAR operating at C-band can penetrate 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 [36].

III. DATA SET & STUDY AREA

Due to lower penetration capability of C-band as compared to L-band or P-band, it is always preferred to choose low incidence angle SAR data for soil moisture estimation with C-band. Moreover as the objective of this study was to study the temporal variation of soil moisture by incorporating the effects of surface roughness and soil moisture, seven scenes of simultaneously acquired co-polarized (HH/VV) IS1 beam mode ENVISAT-1 ASAR data sets were acquired to incorporate the effect of surface roughness in the soil moisture retrieval model by generating co-pol. ratio image. Whereas seven more scenes of simultaneously acquired Like- and Cross-polarized (VV/VH) IS1 beam mode ENVISAT-1 ASAR data sets were ordered to incorporate the effect of crop cover in the soil moisture retrieval model. Study area was selected over parts of Saharanpur and Haridwar districts in U.P. and Uttarakhand. The study area is mostly flat level terrain and is dominated by agricultural land. Study area include irrigated as well as un-irrigated agricultural land and therefore provide full range of soil moisture. The study area over parts of Sahranpur and Haridwar districts covers fine loamy, coarse loamy, fine silt and sandy soils. Along with SAR scenes, topographic maps and optical data from Landsat has also been used in the analysis. Detailed ground truth data collection campaigns in synchronous to all the SAR passes have been carried out as per the procedure described by Patel & Srivastava, (2013) [37].

Total of 28 ENVISAT-1 ASAR data sets have been used in the analysis. Figure-1 shows all these ENVISAT-1 ASAR multi-polarized images. It should be noted that there is one day difference in acquisition of VH polarized data as compared to like (HH/VV) polarized ENVISAT-1 SAR data sets. However, since VH polarized data is used only to represent vegetation cover it will not affect the overall accuracy of soil moisture maps generated during the course of this study. Radiometric calibration of all the 28 ENVISAT-1 ASAR data sets have been carried out using the standard procedure adopted for SAR calibration [38-43].

IV. SOIL MOISTURE ESTIMATION USING SAR

A. *Ground truth data collection: 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. Lot of work have been carried out using the theoretical modeling approach to incorporate the effect of surface roughness in the soil moisture retrieval model.

Although the modeling approach has shown good agreement between the modeled and the observed values of radar backscatter, it is difficult to extend such techniques for mapping of soil moisture over a large

ISSN: 2349-6495

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 angles are comparable 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 (σ°_{LOW} - σ°_{HIGH}) is high for smooth fields and low for rough fields. Multi-parametric SAR data covering multi-incidence angle, multi-polarized, multi-frequency data from various platforms and various advanced techniques like SAR Interferometry (InSAR), SAR Polarimetry (PolSAR) and Interferometric Polarimetric (PolInSAR) techniques have been explored by many researchers to understand the interaction of SAR signals with target under consideration and to incorporate the effects of various target and sensor parameters on SAR backscatter and Polarimetric parameters[44-52].

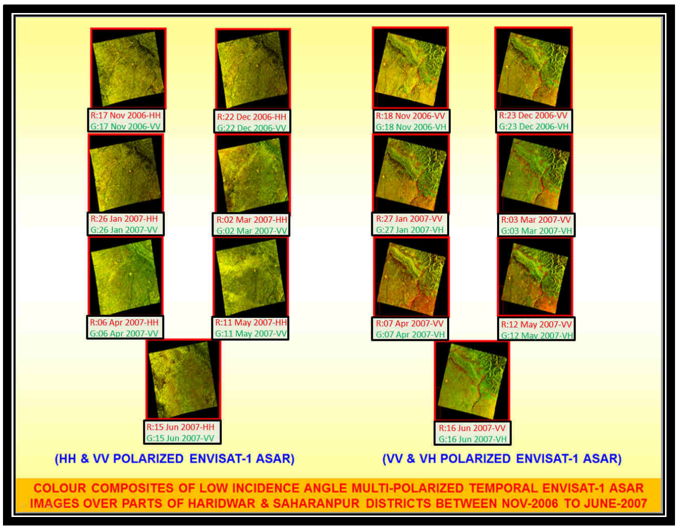

Fig-1: Color-composite of low incidence angle multi-polarized (HH/VV & VV/VH) ENVISAT-1 ASAR images over parts of Haridwar and Saharanpur districts between November-2006 to June-2007

Angular behavior of multi-incidence angle SAR data has been exploited by many researchers to incorporate the effect of surface roughness in the soil moisture retrieval model. Hence, the effect of surface roughness in the soil moisture retrieval was incorporated by using (σ°_{low} - σ°_{high}) as a surface roughness indicator).

Although above concept 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 soil moisture status between the acquisitions 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. It has been observed that log of the like polarization ratio is sensitive to surface roughness conditions prevailing in the agricultural fields at the time of SAR pass [18, 35]. Hence in order to incorporate the effect of surface roughness in the soil moisture retrieval model an additional term as $\ln(\sigma^\circ_{HH} - \sigma^\circ_{VV})$ is included in the conventional soil moisture retrieval model. The improved model can be represented as eq.-1.

$$SM = A + B^*(\sigma^\circ_{VV}) + C^*\ln(\sigma^\circ_{HH} - \sigma^\circ_{VV}) \quad (1)$$

A regression analysis was carried out on 36 soil samples taken from bare fields to develop soil moisture retrieval model using SM (Soil Moisture) values obtained through ground truth and laboratory analysis as dependent variable and their ENVISAT-1 SAR backscatter values [σ°_{VV} and (σ°_{HH} - σ°_{VV})] were extracted from the multi-polarized ENVISAT-1 SAR image pair as independent variable. The coefficient of determination was found to be 0.88 for the model represented by Equation-1. The rms error between observed and estimated Soil Moisture using 11 data points over bare soil which were not used for model development was found to be 2.35. The details of the developed model are given in Table-1.

B. *Incorporating the effect due to crop cover*

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, depolarization takes place due to multiple reflections within vegetation volume. As the amount of depolarization is much higher for larger vegetation volume and larger amount of dielectric discontinuities with in the vegetation volume, it is obvious that amount of depolarization can be used as an indicator of the overall vegetation cover [13, 28]. 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 (σ°_{VH}) in the soil moisture retrieval model. This model can be written in the form of equation-2 (Srivastava, et. al., 2006) [18]

$$SM\_WAP = A + B^*(\sigma^\circ_{VV}) + C^*(\sigma^\circ_{VH}) \quad (2)$$

A regression analysis was carried out on 43 soil samples taken from crop covered fields to develop soil moisture retrieval model for crop covered soil using Soil Moisture 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- polarized ENVISAT-1 ASAR image pair as

Table-1: Details of model developed for bare and crop covered fields along with validation exercise

Soil cover	Model Development			Model Validation	
	Model	# Data Points	R2	# Data Points	rmse
Bare	SM_WAP = A + B*($\sigma0_{vv}$)+C*log($\sigma0_{HH}$ - $\sigma0_{vv}$)	36	0.88	11	2.35
Crop	SM_WAP = A + B*($\sigma0_{VV}$)+C*($\sigma0_{VH}$)	43	0.93	13	1.45

independent variable, using Equation-2. The coefficient of determination was found to be 0.93 for the model represented by Equation-2. The rms error between observed and estimated Soil Moisture using 13 data points, which were not used for model development was found to be 1.45. The details of the developed model are given in Table-1

V. SOIL MOISTURE MAP GENERATION

All the 28 ENVISAT-1 ASAR data sets (HH-Pol: 07; VV-Pol: 14 & VH-Pol: 07) have been geo-referenced and co-registered with each other. Seven scenes of optical data from LANDSAT have also been geo-referenced and co-registered with SAR data sets. Since methodology required all the three polarization combinations of HH, VV & VH, common area having all the three polarizations have been extracted for further analysis.

Since two separate models have been developed during the course of study to incorporate the effects of surface roughness (model represented by equation-1) & crop cover (model represented by equation-2), the study area has been classified into broad classes of bare and crop covered land. Finally for all the seven dates i.e. 17-Nov-2006; 22-Dec-2006; 26-Jan-2007; 02-Mar-2007; 06-Apr-2007; 11-May-2007 & 15-Jun-2007, both the models have been separately applied on corresponding images of HH; VV & VH polarized SAR data sets for that particular month. Finally seven soil moisture maps have been generated as shown in Figure-2. Soil moisture maps are segmented in six levels of soil moisture i.e. less than 10%, between 10% to 15%, between 15% to 20%, between 20% to 25%, between 25% to 30% and greater than 30%.

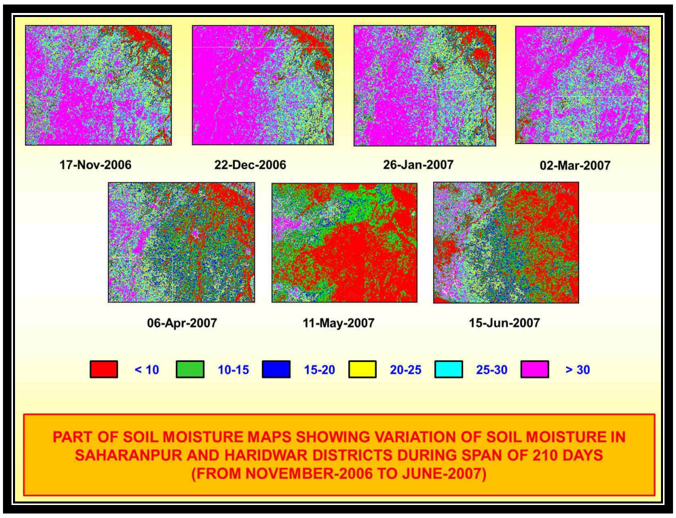

Fig-2: Sub-image of soil moisture maps showing variation of soil moisture in parts of Saharanpur and Haridwar districts during a span of 210 days (i.e. from November-2006 to June-2007)

Once soil moisture maps have been prepared they have been thoroughly studied for temporal soil moisture variation in the study area over a period of 210 days and actual area in square kilometer under different soil moisture ranges have been calculated for all the seven months. The temporal variation of soil moisture in terms of area is given in Table-2 whereas percentage area under different soil moisture ranges has been given in Table-3.

VI. CONCLUSION

In this study simultaneously acquired ENVISAT-1 ASAR HH/VV and VV/VH data sets were studied for operational soil moisture mapping. Cross-polarized SAR data has been exploited for its sensitivity towards vegetation for crop-covered fields where as co-pol. ratio has been used to incorporate effect of surface roughness for the case of bare soil. In order to demonstrate the potential of the developed methodology, an attempt has also been made to study variation of soil moisture status during November-2006 to June-2007 over parts of Saharanpur and Haridwar districts using IS1 beam mode of multi-polarized temporal ENVISAT-1 ASAR data sets. Temporal soil moisture status derived with the help of seven (07) soil moisture maps generated between November-2006 to June-2007 reflect the irrigation pattern adopted by the farmers of the study area and therefore matched with the agricultural activities like sowing and harvesting. Study indicates the potential of soil moisture information for agricultural applications like irrigation scheduling.

Table-2: Temporal variation of area under different soil moisture ranges

TEMPORAL VARIATION OF SOIL MOISTURE OVER PARTS OF SAHARANPUR AND HARIDWAR DISTRICTS DURING NOVEMBER-2006 TO JUNE-2007							
S. No.	Date	AREA UNDER DIFFERENT SOIL MOISTURE CONDITIONS (IN PERCENTAGE OF TOTAL STUDY AREA)					
		> 10%	10% - 15%	15% - 20%	20% - 25%	25% - 30%	< 30%
01	17-Nov-06	05.69 %	04.46 %	08.56 %	15.10 %	19.26 %	47.03 %
02	22-Dec-06	05.45 %	03.76 %	06.72 %	11.41 %	14.27 %	58.50 %
03	26-Jan-07	07.41 %	04.91 %	08.84 %	13.96 %	17.12 %	47.82 %
04	02-Mar-07	01.90 %	01.86 %	04.26 %	11.28 %	20.56 %	60.26 %
05	06-Apr-07	15.58 %	17.03 %	19.13 %	15.72 %	11.70 %	20.91 %
06	11-May-07	57.61 %	25.64 %	07.33 %	04.52 %	02.55 %	02.41 %
07	15-Jun-07	45.73 %	18.56 %	15.29 %	11.13 %	07.17 %	06.34 %

The significant outcome of the research work reported in this study is its ability to generate soil moisture maps on operational basis by incorporating the effects of surface roughness and crop cover in soil moisture retrieval model using multi-polarized SAR from space platform, without making any assumptions on the distributions of these parameters or without knowing their actual values on ground.

Table-3: Temporal variation of area under different soil moisture ranges in terms of percentage

TEMPORAL VARIATION OF SOIL MOISTURE OVER PARTS OF SAHARANPUR AND HARIDWAR DISTRICTS DURING NOVEMBER-2006 TO JUNE-2007							
S. No.	Date	AREA UNDER DIFFERENT SOIL MOISTURE CONDITIONS (In Square Kilometers)					
		< 10%	10% - 15%	15% - 20%	20% - 25%	25% - 30%	> 30%
01	17-Nov-06	37.22	29.15	55.98	98.68	125.96	307.56
02	22-Dec-06	35.67	24.61	43.92	74.61	93.30	382.60
03	26-Jan-07	48.49	32.10	57.81	91.32	111.10	312.76
04	02-Mar-07	12.43	12.17	27.86	73.80	134.44	394.13
05	06-Apr-07	101.89	111.36	125.11	102.80	76.50	136.78
06	11-May-07	376.78	167.73	47.96	29.53	16.68	15.73
07	15-Jun-07	299.10	121.39	99.97	72.79	46.89	41.46

VII. ACKNOWLEDGEMENTS

Authors are extremely thankful to Dr. Y.V.N. Krishnamurthy, Director, Indian Institute of Remote Sensing, Dehradun and Shri A.S. Kiran Kumar, Director, Space Applications Centre, Ahmedabad for encouragement and support. Authors express their sincere gratitude to Dr. S.K. Saha, GD ERSS & Dean (A) IIRS, Dr P.K. Pal, DD, EPSA, Dr. J.S. Parihar, former DD, EPSA, Dr B.S. Gohil, Group Director, ADVG for their guidance and support.

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ISSN: 2349-6495

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