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Radar Remote Sensing for Earth and Planetary Science

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Abstract-Among imaging sensors, RADAR, an acronym for **RA**dio **D**etection **A**nd **R**anging, is generally used in different modes. The radar system transmits a microwave signal directing towards the region of interest and detects the signal backscattered by the surface. Due to long wavelength, microwave signal can penetrate through cloud cover, haze, dust and heavy rainfall. This property of microwaves helps in acquiring data in almost all weather and environmental conditions so that data can be collected at any time.

Index Terms-imaging sensors, RADAR, electromagnetic spectrum, microwave signal, backscattering

1 INTRODUCTION

REMOTE sensing in microwave region of electromagnetic wave encompasses both active and passive sensing techniques. Microwave portion of the electromagnetic spectrum covers the range from approximately 1cm to 1m in wavelength (Table-1). Because of their long wavelengths, compared to the visible and infrared, microwaves have special properties that are important for remote sensing. Due to long wavelength, microwave signal can penetrate through cloud cover, haze, dust and heavy rainfall. This property of microwaves helps in acquiring data in almost all weather and environmental conditions so that data can be collected at any time. Active microwave sensors provide their own source of microwave radiation to illuminate the target. Active microwave sensors are divided into two class namely imaging and non-imaging.

Among imaging sensors, RADAR, an acronym for **RA**dio **D**etection **A**nd **R**anging, is generally used in different modes. The radar system transmits a microwave signal directing towards the region of interest and detects the signal backscattered by the surface. The strength of returned backscattered signal is a function of surface parameters like dielectric constant and surface roughness. Due to variability of these parameters, radar returns are different for different targets. The resolution is achieved by time delay and aperture synthesis technique. Radar altimeters, scatterometers and surface penetrating radar are in the class of non-imaging radar. In most cases these are profiling devices which take measurements in one linear dimension, as opposed to the two-dimensional representation of imaging sensors.

Radar altimeters transmit short microwave pulses and measure the round trip time delay to targets to determine their distance from the sensor. Generally altimeters look straight down at nadir below the platform and thus measure height or elevation, sea surface height.

Altimeter is radio wave allows information in subsurface region because of penetration of signal below the surface of a planet. Scatterometers are also generally non-imaging sensors and are used to make precise quantitative measurements of the amount of energy backscattered from targets.

The amount of energy backscattered is dependent on the surface properties (roughness) and the angle at which the microwave energy strikes the target. Scatterometry measurements over ocean surfaces can be used to estimate wind speeds based on the sea surface roughness. Ground-based scatterometers are used extensively to accurately measure the backscatter from various targets in order to characterize different materials and surface types. New emerging techniques like polarimetry and interferometry have recently been added as new dimensions to applications like DEM, land subsidence, planetary and earth science. Passive microwave sensors called radiometers, measures the emissive properties of the earth's surface. A microwave radiometer is a sensitive receiver capable of measuring low levels of emitted microwave radiations from the surfaces under observation.

2 MICROWAVE INTERACTION

When a surface is illuminated with microwave signal, the proportion of energy scattered back to the sensor depends on surface dielectric properties and surface roughness. If the surface is smooth, the incoming radar signal will be reflected off the lake according to Snell's law - at the same angle as the incidence angle. Such reflections return very little signal or no signal strength back to the sensor, resulting in a dark tone in the image.

If the reflection is bounced off by other target thereby redirecting the energy towards the sensor, it would result a strong signal in back direction. These are class of surface reflections. A diffuse surface would behave like a rough surface and medium to bright signal is expected. For volume scattering, signal is penetrated to media. Volume scattering may occur in vegetation, forest or during sub surface imaging. For the case of dielectric constant variability; signal is proportional to dielectric constant of the medium for a

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International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
Issn 2229-5518

given class of roughness. However, for most natural medium, total signal strength a combination of various scattering mechanism present in the resolution cell.

3 SAR POLARIMETRY

An important extension to single-channel SAR remote sensing is the utilization of polarized waves. Polarization is a fundamental characteristic of light. A polarimetric SAR system measures the electric field, backscattered by the scene, including its polarization state. The interaction of the transmitted wave with a scattering object transforms its polarization. Therefore, the polarization of the backscattered wave depends on the polarization of the transmitted wave as well as on the scattering properties of the imaged objects. One special characteristic of SAR polarimetry is that it allows a discrimination of different types of scattering mechanisms. This becomes possible because the observed polarimetric signatures depend strongly on the actual scattering process. In comparison to conventional single-channel SAR, the inclusion of SAR polarimetry consequently can lead to a significant improvement in the quality of classification and segmentation results. Certain polarimetric scattering models even provide a direct physical interpretation of the scattering process, allowing an estimation of physical ground parameters like soil moisture and surface roughness, as well as unsupervised classification methods with automatic identification of different scatterer characteristics and target types.

4 SAR INTERFEROMETRY

SAR interferometry is a new emerging tool that uses information on phase derived by recording the phase difference between two SAR images acquired from slightly different sensor positions. Different sensor positions, called the baseline, can be achieved by a temporal shift (repeat-pass interferometry) or spatial shift (also known as single-pass interferometry). The phases of the backscattered waves from the two positions are measured. The phase information of the two image data files is then superimposed and interference pattern is formed. The phase difference is related with the height of object through imaging geometry. The interferometric coherence or correlation is also a measure of the phase properties of SAR image pairs and indicates displacement and change of the scattering elements

5 APPLICATIONS

5.1 Agriculture

The sensitivity of SAR to canopy geometry and moisture provide complementary information for crop growth models and condition assessment hence SAR has the potential to improve crop discrimination and parameter retrieval. Polarimetric and interferometric studies provide unique information on cropping pattern changes, agricultural land use and plantation conditions.

In agricultural areas, the condition of the soil and the crops changes diurnally, daily and seasonally. Agricultural targets also vary spatially, with differences observed from field to field and within individual fields. Consequently, mapping and monitoring soil and crop characteristics present a challenge. Agricultural crops that have linear features of length comparable to or larger than the incident wavelength tend to cause larger reflections when the polarization alignment agrees with their structural alignment. The polarization of the transmitted microwave (horizontal (H) or vertical (V)) also dictates which components of the vegetation and soil contribute to the total amount of energy scattered back to the SAR sensor. The potential of Synthetic Aperture Radar (SAR) in discriminating among different agricultural crop types has been demonstrated in several studies, especially for rice mapping and monitoring.

In India, the major component of economy is agricultural crops. About 48% of the geographical area is under cultivation, which is highest in the world. This large geographical size and spread of India is associated with a diversity of soil and climate, particularly rainfall and temperature. About 87 %(=125 m ha) of total cultivated area (142 m ha) is under food grains, which includes cereals and pulses. Rice, wheat, sorghum, pearl, millet and maize are some of the important cereals. The other important crops are oil seeds (groundnut, rape seed/mustard), fiber crops (cotton, jute), cash crops (sugarcane, potato, tobacco) and horticultural crops like tea, coffee, mango, apple etc. Indian economy being dominantly dependent on the state of the agricultural production, timely, accurate and unbiased estimation and forecast of acreage and production of major crops is most important. It is an important requirement for planning and management of food security of a country.

Over the years satellite remote sensing has emerged as a cost effective tool for such purpose. The first systematic experiment on crop monitoring using microwave sensor was attempted by space applications centre and a systematic crop growth profile was observed (Fig 3). Subsequently, the profile was used for crop growth stage and crop monitoring. This has given thrust to radar remote sensing programme with emphasis on crop monitoring... The entire methodology of operational rice acreage estimation has been designed based on the Radarsat data. The accuracy of classification depends on the sensitivity of the backscattering coefficients to the differences of the structures of the plants, hence to the different interaction behavior between the electromagnetic wave and the structure of the canopy. It was demonstrated that variation of SAR backscatter to plant parameters of wheat crop could be better characterized when wheat crop is segmented into three different layers. Crop condition indicators can include biomass, height, leaf area, plant water content, chlorophyll and nitrogen content, among others. These indicators must be linked to crop growth stage, and thus it is necessary to monitor these indicators over the entire growing season. One SAR image at given frequency, polarization and incidence angle, is often inadequate to attain the required accuracy of classification. Improvements are expected by multi-temporal and/or multi-polarization and/or multi-angle SAR images. Experiments are conducted with different techniques, frequency, polarization etc.

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
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Fig 3(a) shows a typical curve for radar backscatter at C-band. Fig 3 (b) shows typical paddy fields at different growth stages.

5.2 Soil Moisture

The knowledge of soil moisture is important for meteorology, hydrology, agronomy and numerous other earth systems sciences. The advantage of remote sensing retrieval techniques would be that they would allow to repeatedly collecting spatial soil moisture estimates at reasonable costs.

SAR systems show a relatively high sensitivity to soil moisture due to the large contrast in the dielectric constants of dry and wet soils at microwave frequencies especially below 10 GHz. Much hope has been put in the capability of SAR to retrieve soil moisture. A shift in volumetric moisture content between approximately 2.5 to 50 per cent can cause a variation of 3 to 30 in relative dielectric constant and 8 to 9 dB rise in backscattering coefficient (depending upon frequency and soil texture) for vv polarization.

The basic conclusion is that currently orbiting SAR sensors can provide surface soil moisture information with known accuracy at small-scale mapping. Future research should be dedicated to refining the approaches that meet the requirements at field level. However, there are many obstacles yet to be overcome for a truly operational application for watershed management. Fig 4 shows soil moisture mapping of India's first large area mapping of soil moisture.

5.3 Snow And Glaciers

The traditional methods for snow pack studies consist of establishing a number of sample points within a given basin for which physical measurements are performed. Optical remote sensing data is useful to provide information on aerial extent of snow, etc. Beside all weather utility of the microwave data, it is also sensitive to wetness and has penetration capability in the snow pack. Various studies have indicated that backscattering coefficient data are useful for quantitative estimation of snow characteristics.

Snow is in general, a mixture of ice crystals, liquid water, and air. The ice crystals are deposited on the earth's surface as result of atmospheric precipitation or wind or mechanical deposition. If the snowpack is below 0º C, it is unlikely to contain any liquid water. This state is termed as dry snow. However at temperatures above 0º C, significant quantities of liquid water may also be present. This is called wet snow. Snow when metamorphosed to ice and slides down on the mountain slopes or in a valley becomes a glacier. Fig 5 shows an image of snow covered area.

5.4 Flood

SAR has the potential to provide near real time wide area coverage required for flood event assessment and monitoring and delineation of flood hazard zone. Water surface reflects very little radiation back in the direction of the radar antenna, thus flooded areas and other water features can be easily distinguished from the surrounding land.

SAR has the potential to provide near real time wide area coverage required for flood event assessment and monitoring and delineation of flood hazard zone. Water surface reflects very little radiation back in the direction of the radar antenna, thus flooded areas and other water features can be easily distinguished from the surrounding land. Several experiments on mapping of floods have been performed

5.5 Forestry

The analysis of radar data acquired at different frequencies show that sensitivity and correlation of radar backscatter with biomass and volume increases with increasing wavelength. The radar backscatter at higher wavelength i.e. P- and L-bands, have been found to be significantly correlated with tree density, biomass and volume, as they penetrate below the crown. The radar backscatter at lower frequencies i.e. C- and X bands usually have greater textural details than P and L bands, as they do not penetrate below the crown layer of the trees.

The role of multi-frequency and multi-polarization SAR data in forestry applications has gained momentum in recent years with substantial amount of studies ranging from forest vegetation characterization to forest biophysical parameter retrieval. Most of these studies have demonstrated potential of P-, L- and C-band SAR in forestry applications. Microwave interactions are sensitive to the roughness and physical geometry of forests This, when combined with the ability of microwave radiation to penetrate forest canopies results in a sensitivity of SAR backscatter to key biophysical variables such as tree density and above ground biomass). A number of results have shown that at all frequencies, backscatter from the cross-polarized channel consistently has a higher correlation with forest biomass, as compared to the other linear polarizations. In a comparative evaluation of multi-frequency, multi-polarized SAR response to plant density, highest sensitivity to plant density was observed for L band cross-polarized backscatter

In India, various attempts have been made to establish the relationship between radar backscatter in C-, L- and P-bands and forest stand variables. (Tree height estimation in Tundi forest region, Jharkhand, India has also been attempted using SAR interferometric data. The study has demonstrated the potential of multi-date coherence SAR data for the estimation of canopy height in forest area.

5.6 Geology / Geomorphology & Landuse

Microwaves have shown potential for mapping geological structures more precisely. Furthermore, penetration in the dry soil is useful for detecting subsurface features.

Over the past few decades, radar remote sensing has proven to be an effective tool for the extraction of geological information, unhindered by external illumination and weather conditions. Outlines of topographic features and

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
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textures of rock surfaces commonly appear more prominent in radar images than in images obtained at shorter (optical and infrared) wavelengths. Radar images provide distinct image textures that may denote erosion characteristics of the surface and the generalized bulk lithologies of the underlying rocks, thus providing information for geological mapping.

The intensity of radar backscatter is also affected by the dielectric properties of surface materials. This allows discrimination of rocks and sediments that have strongly contrasted moisture content or mineralogical composition. This finds useful applications for Quaternary mapping. In some arid regions, subsurface penetration of radar energy has revealed the outlines of ancient buried drainage systems. Rock types such as limestone covered by thin Aeolian sand cover could also be identified.

Radar is an active system, which illuminates the surface with a beam of microwave radiation. Radar is most sensitive to surface roughness and soil moisture differences (variation in the complex dielectric constant which is a measure of the electrical properties of surface materials). Radar can penetrate the surface micro-layer in the soil-covered areas. Lineaments are extremely well manifested on SAR images, and on several occasions structural features; for example, fractures, folds, faults etc. have been detected, as well as extended in SAR imageries. Also, look angle and direction have a major impact on the response and manifestation of surfacial features in SAR imageries. Earlier results have shown that RADARSAT-1 C-band horizontally polarized images have been very useful for geomorphology, geological structures and rock units mapping The SAR image is more effective than optical imagery for studying features such as surface roughness and topography. This is due to variation in radar backscatter as a function of wavelength (C-band, 5.6 cm), incident angle and polarization. Useful information on terrain morphology and surface relief (related to geological structure) is provided by SAR imagery, due to effect of radar backscatter sensitivity to slope angle and to shadow effects caused by topographic relief.

Radar interferometry offers a unique means of mapping ground movements. The technique uses the phase of radar images as a measure of distances from ground to the satellite-bearing instrument. Accuracies of the order of radar wavelength (~ cm) are obtained with these measurements. The important parameters include contributions from (i) trajectories, (ii) topography, (iii) ground movements, (iv) atmosphere and (v) others, including instrument. Development of new techniques in this direction needs evaluation of Synthetic Aperture Radar (SAR) interferometry technique for Digital Elevation Model (DEM) generation and geological hazards assessment. Most of the geophysical processes such as earthquakes, landslides and glacier flows are associated with crustal movements at the surface of the earth.

For various regional studies, radar scatterometer has shown some potential in monitoring the resources and its variability. Fig 10 shows regional microwave data derived from scatterometer at C-band.

5.7 Planetary Science

Radar systems for planetary remote sensing had been used since early 1972 with the first altimeter in venera-8 for the measurements. Various planetary science experiments were conducted using radar instrument Venus was the first planet where radar sensors was used extensively because of thick atmosphere. The thick clouds of Venus are composed mostly of toxic carbon dioxide. The atmosphere of Venus is made up mainly of carbon dioxide, and thick clouds of sulfuric acid completely cover the planet. Pioneer provided first global height of lunar surface using altimeter data. Height of Venus surface was found to be -2 to 12 km. SAR images of whole Venus surface were acquired at resolution of 100 m. This helped in knowing many details of Venus surfaces. It was discovered that 85 percent of Venus surface is covered by Volcanic flow. Further, there is no water thus lacking in degradation. On Mars surface, there were two radars mainly for detecting sub surface buried ice. The two instruments namely Sharad (SHallow RADar) from NASA and MARSIS (Mars radar surface and ionosphere sounder). Both the instruments have detected a large area ice buries in north polar region of Mars. Cassini radar, capable of altimeteric and SAR mode of operation, provided detailed map of Titan (Moon of Saturn) and data of many other moons of Jupiter and planetary bodies.

For lunar surface studies, SELENE was the first sensor carried surface penetration radar for studying the subsurface structures below the surface of moon. The SELENE mission was launched by JAXA on 14th Sept 2007 for the study of sub surface structure. The Lunar Radar Sounder (LRS) on-board the KAGUYA (Selene) lunar orbiter had provided data of subsurface stratification and tectonic features in the shallow part (several km deep) of the lunar crust, by using an FM/CW radar technique in HF (~5MHz) frequency range. Knowledge of the subsurface structure is crucial to better understanding, not only of the geologic history of the moon, but also of the moon's regional and global thermal history of the moon and of the origin of the Earth-Moon system. A typical radargram is shown in Fig 11 , where bright line corresponds to surface reflection and a sub surface structure is also seen here. A number of structures were found in the lunar region and mapped.

SAR imaging of lunar surface was done first time by Channdrayaan-1 Mini SAR. The main purpose of instrument was to detect water ice signature in lunar polar region. Chandrayaan-1 was the first lunar orbital satellite carrying a SAR payload. The Mini-SAR was flown on Chandrayaan-1 mission on 22nd October 2008 with an objective to gather data on the scattering properties of terrain in the polar regions of the Moon. Additionally, the SAR was designed to collect information about the scattering properties of the permanently dark areas near the lunar poles at optimum viewing geometry, which are invisible to normal imaging sensors and thereby detect the presence of water ice in the

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
Issn 2229-5518

permanently shadowed regions on the lunar poles up to a depth of a few meters. The Mini SAR sensor operated at S-band (2.38 GHz frequency) with transmission in left circular polarization (LCP) and reception in linear horizontal (H) and vertical (V) polarizations. The instrument illuminated the surface of moon at 35-degree incidence angle with a ground range resolution of 150 meter and 18 km range swath. Typical image strip consisted of approximately 300 km by 18 km size. Lunar surface properties at both polar and equatorial regions were investigated using data from the miniaturized synthetic aperture radar (Mini-SAR) onboard ISRO's Chandrayaan-1. The investigation showed that circular polarization ratio (CPR), which is an important parameter that represent scattering associated with planetary ice as well as dihedral reflection was anomalously high inside some of the craters in the polar regions. Other stokes parameters such as degree of polarization (m) and LH-LV relative phase (δ) also showed distinctly different types of scattering mechanisms inside and outside the craters on lunar surface. Fig 12 shows craters in south pole region indicating presence of water ice. Lunar reconnaissance Orbiter (LRO) in 2009 also carried Mini-RF instrument is dual-polarized synthetic aperture radar, which transmits in circular polarization (left-hand polarization for both instruments) and receives two coherent orthogonal linear polarizations (H and V). LRO mission reconfirmed the availability of water ice in polar region of lunar surface. In order to further independently confirm such signatures, dual frequency SAR in Chandrayaan-2 is planned.

6 CONCLUSION

In general, radar sensor has shown its potential for many of earth and planetary science applications. In most of cases, SAR has shown its utility for applications required to be done under cloudy conditions. For example, disaster monitoring, kharif crop monitoring and monitoring areas consistently covered under clouds. Unique applications like soil moisture and snow wetness monitoring have been attempted using region specific models. Research for forestry, Geology and land use has proven the unique role of radar sensors. For planetary surface studies, radar has shown its potential for the study related lunar water ice detection, buried ice in Jupiter, sub surface reflector mapping etc. In view of unique advantages, new mission definitions are being taken up for earth and planetary surface with added knowledge on interferometry and polarimetry.

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
Issn 2229-5518

Radar Band	Frequency (GHz)	Wavelength (cm)
Millimeter	40 to 100	0.75 to 0.30
Ka	26.5 to 40	1.1 to 0.75
K	18 to 26.5	1.7 to 1.1
Ku	12.5 to 18	2.4 to 1.7
X	8 to 12.5	3.75 to 2.4
C	4 to 8	7.5 to 3.75
S	2 to 4	15 to 7.5
L	1 to 2	30 to 15
UHF	0.3 to 1	100 to 30

Table-1: Radar bands

SAR sensor	Year of launch	Band	Polarization	Incidence angle(Deg)	Swath (Km)	Resolution (m)	Repeat Cycle
Seasat	1978	L	HH	23	100	25	30
SIR-A	1981	L	HH	50	50	40	NA
SIR-B	1984	L	HH	15-60	30	17-58	NA
ERS-1	1991	C	VV	23	100	30	35
JERS-1	1992	L	HH	35	75	18	44
SIR-C/X-SAR	1994	C, L	Quad-pol	17 to 63	10-200	15-45	NA
		X	HH				
ERS-2	1995	C	VV	23	100	30	35
RadarSAT-1	1995	C	HH	10 to 50	40-500	8-100	24
SRTM	2000	X, L	VV	Variable	30-350	20-30	
EnviSAT-1	2002	C	HH/HV, VV/VH	14 to 45	100-400	30-1000	35
PALSAR	2004	L	VV,HH, H/HV, VV/VH	18 to 55	70	10-100	44
TerraSAR-X	2006	X	Quad-pol	15 to 60	10 to 100	2-16	11
RadarSAT-2	2008	C	Quad-pol	10 to 50	10-500	8-100	24
Cosmo Skymed	2007-2009	X	Quad-pol	20 to 60	20-400	1-100	16
RISAT	2012	C	Quad-pol	20-49	10-240	3 - 50	13
PALSAR	2013	L	VV,HH, H/HV, VV/VH	18 to 55	70	2-100	44
Sentinel-1	2014	C	Dual (HH/HV, VV/HV)	Variable	80	5-80	14

TABLE-2 PAST and present SAR satellites

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
Issn 2229-5518

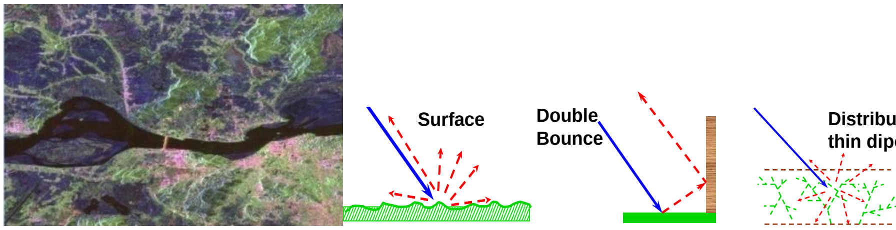

Fig.1: L-band polarimetric SAR decomposition over parts of Assam including various elements of scattering mechanism (B: surface, R: Double bounce, G: Volume).

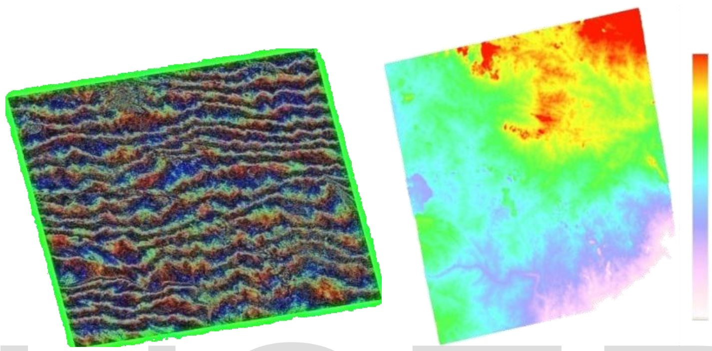

Fig 2: A typical SAR interferogramme over parts of Jharia and corresponding height variation from 117 to 319 m (Input: Radarsat data of 21st Nov and 15 Dec)

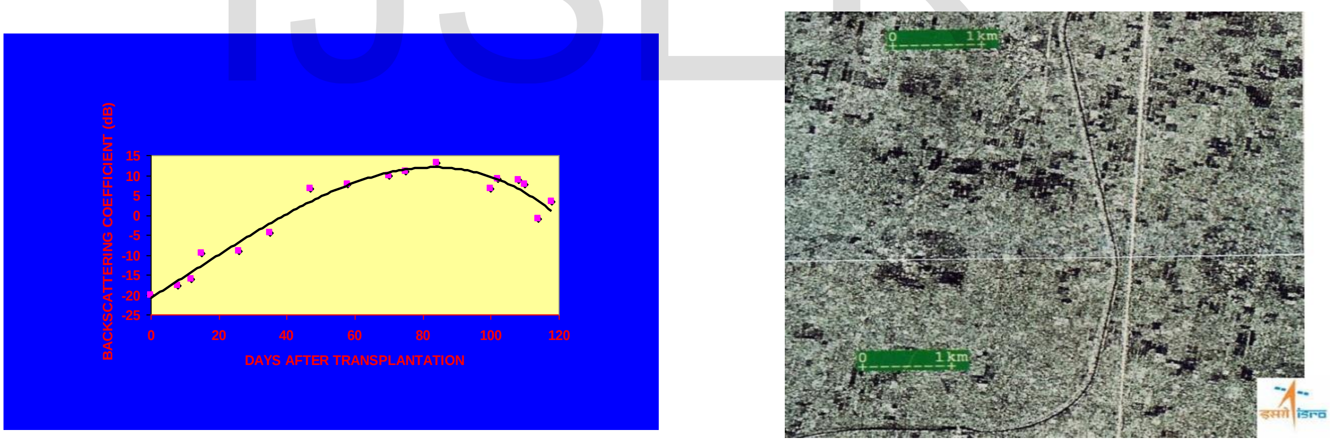

Fig3: (a) Typical crop growth profile at C-band for paddy (b) C-band Radarsat image showing paddy fields (Haryana)

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
Issn 2229-5518

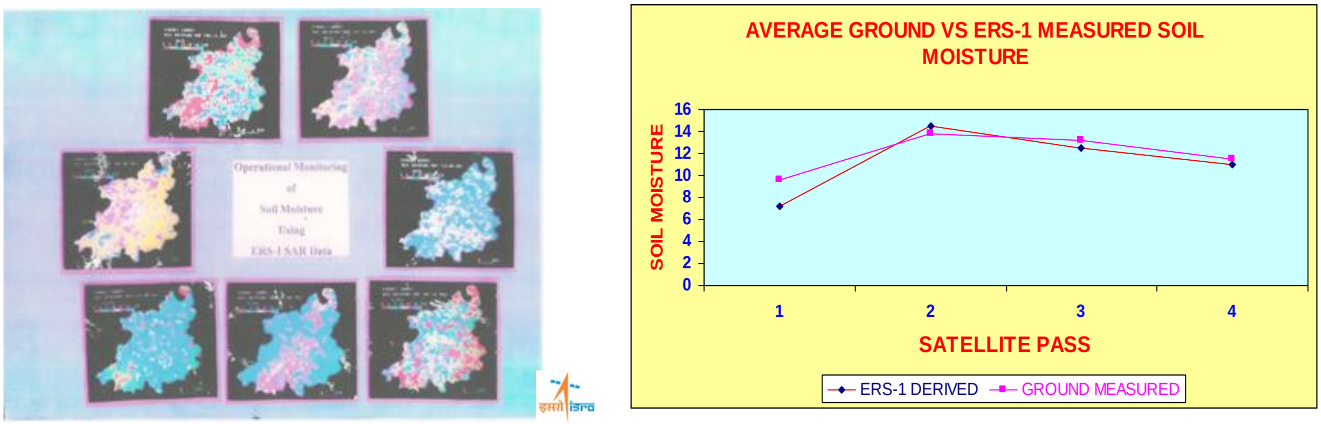

Fig 4: Temporal variation of soil moisture using ERS SAR data (Agra)

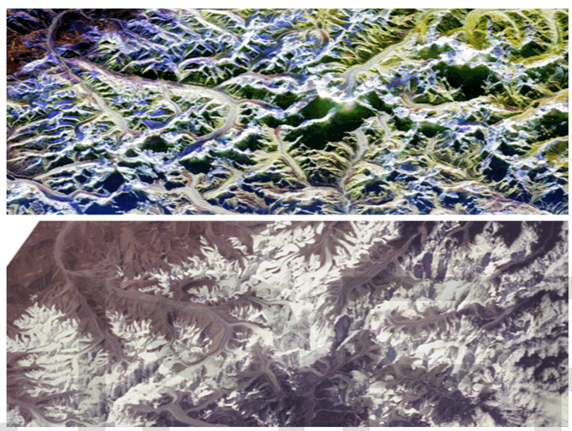

Fig 5: Peak of mount Everest (8848 m) at centre of image (28 Degree N , 86.9 Degree E)
(70 Km * 38 Km) R:Lhh,G:Lhv,B:Chv Curving and branching feature of both images are Glaciers (blue, purple, red, yellow, white: due to variability in roughness and water content)

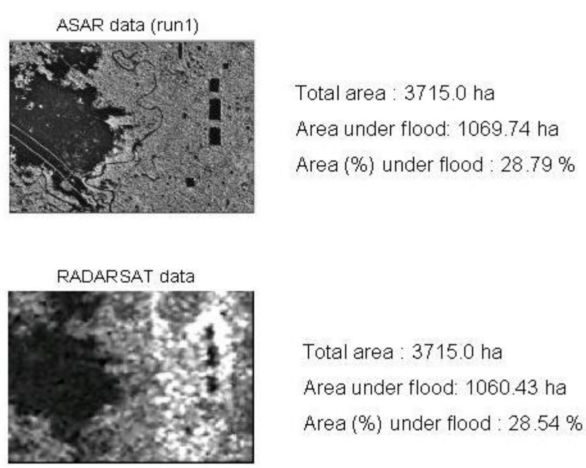

Fig 6: Typical signature of floods in SAR image (parts of Darbhanga)

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
Issn 2229-5518

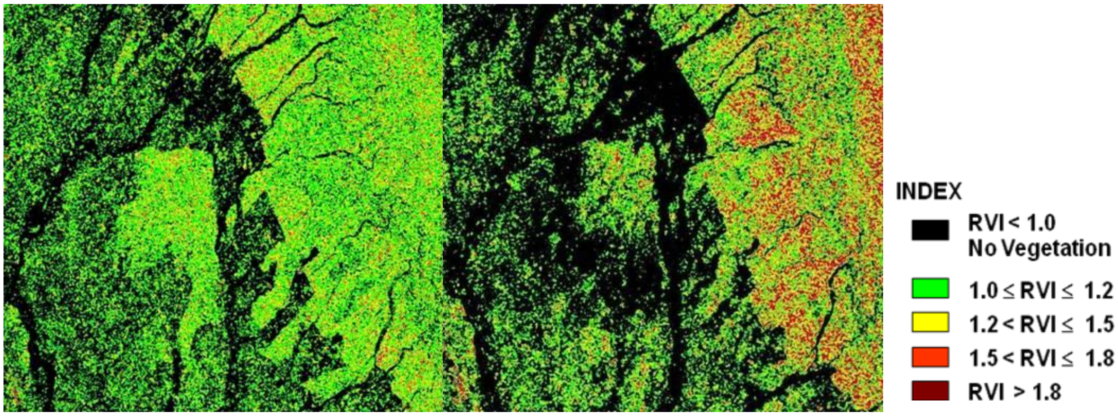

Fig. 7: C-and L-band SAR images over parts of Tarai region displaying radar vegetation index

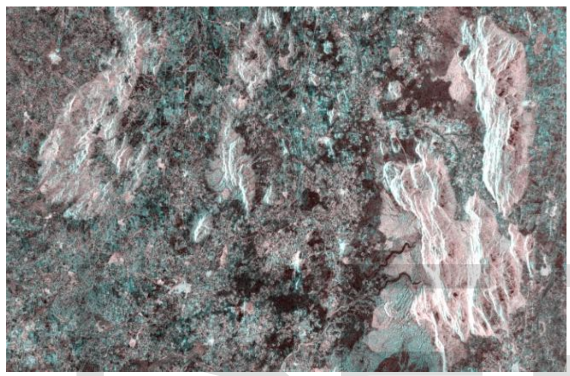

Fig 8: L-band SAR FCC showing Rocky Hills (Granite) over parts of Jalore Dist., Rajasthan (B: HH, G: HH, R: HH)

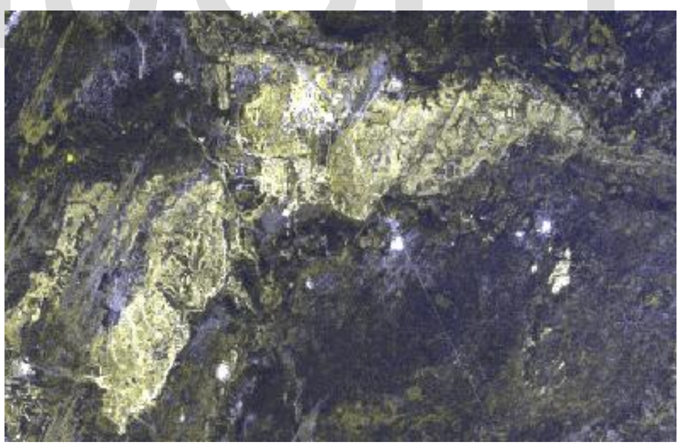

Fig 9: Sub- surface lime stone (bright color) at L-band near Ramgarh- Sanu region, Rajasthan

International Journal Of Scientific & Engineering Research, Volume 4, Issue 12, December-2013
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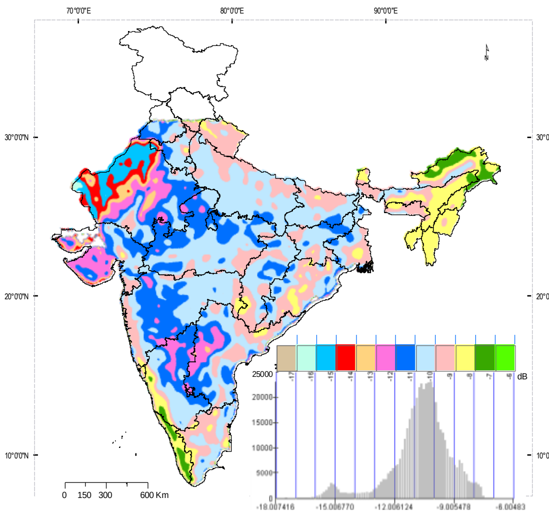

Fig 10: C-band scatterometer data for regional variability

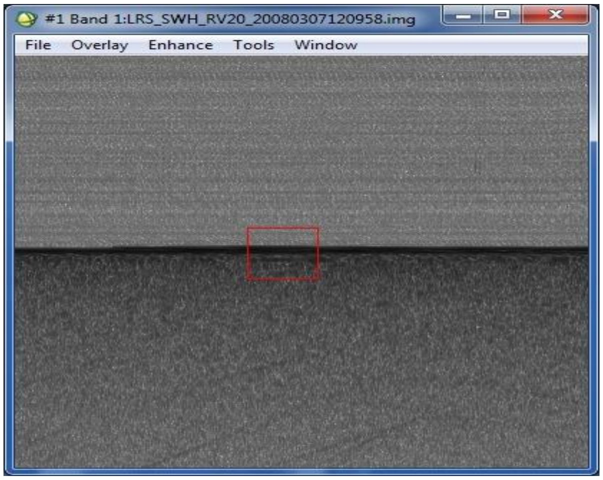

Fig 11: A typical subsurface reflector scene in Radargram

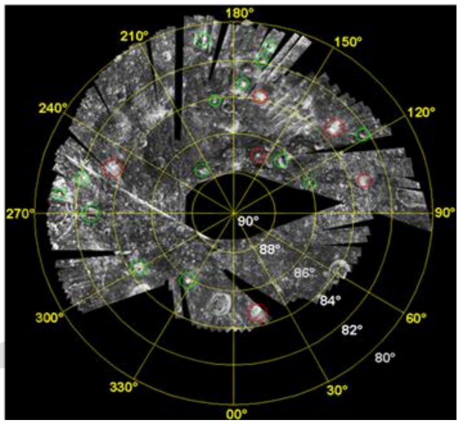

Fig 12 : Lunar Craters in south pole region: Green circle indicating presence of water ice


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