**Introduction**

On the global scale, high albedo snow plays a major role in the earth's energy balance. Seasonal snow covers more than thirty percent of the earth’s land surface (Robinson et al., 1993). Also, an estimation of snowpack properties is significantly important at regional scales for various problems such as flood predictions and water resource management. The melting snow is responsible for the majority of spring

floods.

Many works has been done with Microwave interactions of snow at C-Band (5.5 GHz) or higher frequencies [1]–[5]. The relationship between HH and VV measurements is sensitive to dielectric and

roughness properties of the surface [10]–[14].

The Synthetic Aperture Radar (SAR) data algorithms (Shi *et al.* 1993, Shi and Dozier 1995, Singh *et al.* 2006, Singh and Venkataraman 2007, Niang *et al.* 2007, Singh and Venkataraman 2007) can be applied only for wet snow dielectric constant retrieval which can not be used for dry snow density estimation. When a snow pack is dry (at a temperature less than 0°C) microwaves easily penetrate the snow and the backscatter is largely a function of snow density. Singh *et al.* (2007) derived the empirical relationship between field measured snow density and ENVISAT-ASAR HH-polarization backscattering coefficient. They observed that this empirical relation becomes insensitive beyond snow density 0.35 g/cm3.

Interesting results have been obtained by Shi and Dozier (2000) using fully polarimetric L-band data from SIR-C/XSAR, obtaining snow density estimates. This algorithm maximizes the sensitivity to the incident angle and wave number while minimizing its sensitivity to the surface dielectric and roughness properties. This algorithm does not require a priori knowledge of the subsurface dielectric and roughness properties. It is insensitive to the SAR absolute calibration error but sensitive to the relative calibration error, especially at small incident angles (<30o). At large incident angles (>50o) this algorithm becomes insensitive to the effect of the SAR relative calibration error. This indicates that a better estimation accuracy of snow density can be obtained at larger incident angles than at small incident angles. This model can be applied over a large range of incident angles (10o-70o). The estimated snow density compared to field measurements shows an absolute RMSE of 42 kg m-3 and a relative 13% error. This model can be applied to seasonal snow cover when the snow is dry. Since the algorithm is based on the modification of the surface scattering problem, it can be applied where the subsurface is either rock or soil. However it cannot be applied where the subsurface is dominated by volume scattering, as may be the case with snow-covered firn. Niang *et al.* (2007) also developed a statistical inversion model which performs a simultaneous retrieval of the wetness and density using ENVISAT- ASAR alternating polarization data.

This section is concerned with the estimation of dry snow density from multi-polarisation SAR data. Dry snow is consisting of ice particles and air and contains no liquid water. Snow is a dielectric material and one important property of a dielectric material is its dielectric constant. The real part of the dielectric constant of dry snow (εds’) is a function of the snow density and the real part of the dielectric constant of air and ice. The real part of the dielectric constant of air is 1.0 and pure ice is 3.15 for frequencies from 1MHz to well above the microwave region (Evans 1965). Real part of ice dielectric constant (εi’) may be considered independent of both temperature (below 00) and frequency in the microwave region. However, the imaginary part of ice dielectric constant (εi”) exhibits strong variation with both parameters. Hence, in effect, the real part of the dielectric constant of dry snow (εds’) is governed by snow density (ρs) under natural dry snowpack conditions. Density of snow pack is an important parameter in snow hydrology. The most appropriate method for estimation of dry snow density is based on determination of dielectric constant at radio frequencies because in the range between 1 MHz and 10 GHz the real part mainly depends on density. The dielectric constant of dry snow in the density range between 0.05 and 0.5 g/c3 have been obtained by various authors (Cumming 1952, Ambach and Denoth, 1972, Nyfors 1982, Hallikainen *et al.* 1982, Tiuri *et al.* 1984, Achammer and Denoth 1994, Denoth 1994, Matzler 1996).

In microwave remote sensing modeling snow properties can be characterized by the dielectric constant. Shi and Dozier (2000) developed an algorithm for dry snow density retrieval using L-band HH and VV polarization SAR data, due to the unavailability of HH and VV polarization combination L-band SAR data (e.g. Advanced Land Observation Satellite-Phase Array L-Band Synthetic Aperture Radar) our test site or other under peak winter accessible condition test site for synchronous field measurement, we could not adopt this algorithm. And also world wide, there is no algorithm which we can apply directly to Himalayan snow covered region for dry snow density estimation, only basic investigation has been done in the context of snow density estimation for Himalayan snow covered region. Singh *et al.* (2007) studied the behavior of SAR BSC with field measured snow density and derived the regression relation between them. Singh and Venkataraman (2009) developed initial stage of inversion algorithm. Hence there is need to develop and explore inversion algorithm for dry snow density estimation over Himalayan snow covered region.

For dry snow cover the backscattering from the snow surface may be neglected and the total backscattering is a combination of volume scattering from snow and surface scattering from the ground. Volume scattering from a shallow, dry snow cover (SWE <20 cm) is undetectable at C-band (5.3 GHz, 5.6 cm), because the backscatter is dominated by soil/snow scattering (Bernier *et al.* 1998).

Total backscattering from the snow is the sum of scattering from air-snow, volume scattering in the snow layer and scattering from the snow-ground attenuated by snow layer. Due to large penetration at C-band, in dry snow layer and the dielectric contrast at the air-snow boundary is small for dry snow, the reflection coefficient is quite small. Thus, most of the power incident upon the snow surface interface is transmitted across the boundary. Therefore the contribution due to multiple reflections off the upper and lower boundaries of snow layer may be ignored and due to same reason, the backscattering contribution of air-snow interface scattering from the total backscattering coefficient may be ignored for angles away from nadir. Backscattering coefficient is independent of snow surface roughness when the snow layer is dry. (This however, is not the case for wet snow, because of its higher dielectric constant). Because of the small dielectric contrast the roughness of the dry snow layer is not so important and the snow layer can be modeled as an inhomogeneous layer with a plane top boundary and a rough bottom boundary. The dry snow layer consists of air and randomly located ice particles of various sizes. Therefore the volume scattering in the snow layer is governed primarily by the size of the ice crystals compared to the wavelength. The ground contribution decreases as the snow depth (attenuation) increases (Ulaby *et al.* 1986, Shi *et al.* 1990). Therefore total backscattering coefficient for dry snow is the sum of two main components, i.e. snow volume backscattering and snow ground backscattering (Figure 3.46).

Under an assumption that snow surface has no significant air/snow interface scattering and angle of refraction remains constant in dry snow pack, total backscattering from the dry snow pack can be defined as

 (3.74)

**Air/snow = can be neglected**



**Air**

**Snow**

**Ground**



Snow volume =



= Snow Ground

Figure 3.46. Backscattering from dry snow covered terrain.

In equation (3.74) σt , σv and σsg are total backscattering, volume backscattering and snow ground interface backscattering coefficients respectively. ***pp*** is either VV or HH. *k* and *k*1 are the incident wave number in the air and in snow pack respectively. θi is incident angle and θr is angle of refraction.

The incident angle at air-snow interface and the angle of refraction in the snow layer and snow-ground interface can be related by the Snell’s law. The observable change of wavelength at different density of snow layers is found at L-band in (Shi and Dozier 2000) by comparing the difference between incident angle at air-snow interface and at snow-ground interface with different snow density (100 - 500 kg/m3). For a given snow density, incident angle at the snow surface causes the change in the incident angle in the snow layer. These changes are observed at L-band propagation wavelength by Shi and Dozier (2000). Therefore these changes can also be considered at C-band because C-band has lower penetration capability as compared to L-band. Hence C-band is more sensitive to above mentioned changes as compared to L-band. Since both the angle of refraction and wavelength shifts are only a function of the snow’s dielectric constant, which is mainly governed by the snow density, it is possible to estimate snow density by using C-band ASAR and RADARSAT-2 data.

Active microwave remote sensing has long promised the advantage of sensitivity to many snow parameters, ability to provide day or night imaging in all weather condition, a spatial resolution comparable with the topographic variation in alpine regions [4].

**1.**

@article{stiles1980active,

title={The active and passive microwave response to snow parameters: 1. Wetness},

author={Stiles, William H and Ulaby, Fawwaz T},

journal={Journal of Geophysical Research: Oceans (1978--2012)},

volume={85},

number={C2},

pages={1037--1044},

year={1980},

publisher={Wiley Online Library}

}

**2.**

@article{ulaby1980active,

title={The active and passive microwave response to snow parameters: 2. Water equivalent of dry snow},

author={Ulaby, Fawwaz T and Stiles, William H},

journal={Journal of Geophysical Research: Oceans (1978--2012)},

volume={85},

number={C2},

pages={1045--1049},

year={1980},

publisher={Wiley Online Library}

}

**3.**

@article{ulaby1984snowcover,

title={Snowcover influence on backscattering from terrain},

author={Ulaby, FAWWAZ T and Stiles, W Herschel and Abdelrazik, Mohamed},

journal={Geoscience and Remote Sensing, IEEE Transactions on},

number={2},

pages={126--133},

year={1984},

publisher={IEEE}

}

**4.**

@article{rott1987possibilities,

title={Possibilities and limits of synthetic aperture radar for snow and glacier surveying},

author={Rott, Helmut and M{\"a}tzler, C},

journal={Annals of Glaciology},

volume={9},

pages={195--199},

year={1987}

}

**5.**

@article{rott1988study,

title={Study on SAR land applications for snow and glacier monitoring},

author={Rott, H and M{\"a}tzler, C and Strobl, D and Bruzzi, S and Lenhart, KB},

journal={ESA Contract No},

volume={6618},

year={1988}

}

10

@article{ulaby1990radar,

title={Radar polarimetry for geoscience applications},

author={Ulaby, Fawwaz T and Elachi, Charles},

journal={Norwood, MA, Artech House, Inc., 1990, 376 p. No individual items are abstracted in this volume.},

volume={1},

year={1990}

}

11

@book{fung2010microwave,

title={Microwave scattering and emission models for users},

author={Fung, Adrian K and Chen, Kun-Shan},

year={2010},

publisher={Artech house}

}

12

@article{oh1992empirical,

title={An empirical model and an inversion technique for radar scattering from bare soil surfaces},

author={Oh, Yisok and Sarabandi, Kamal and Ulaby, Fawwaz T},

journal={Geoscience and Remote Sensing, IEEE Transactions on},

volume={30},

number={2},

pages={370--381},

year={1992},

publisher={IEEE}

}

13

@article{dubois1995measuring,

title={Measuring soil moisture with imaging radars},

author={Dubois, Pascale C and Van Zyl, Jakob and Engman, Ted},

journal={Geoscience and Remote Sensing, IEEE Transactions on},

volume={33},

number={4},

pages={915--926},

year={1995},

publisher={IEEE}

}

14

@article{shi1997estimation,

title={Estimation of bare surface soil moisture and surface roughness parameter using L-band SAR image data},

author={Shi, Jiancheng and Wang, James and Hsu, Ann Y and O'Neill, Peggy E and Engman, Edwin T},

journal={Geoscience and Remote Sensing, IEEE Transactions on},

volume={35},

number={5},

pages={1254--1266},

year={1997},

publisher={IEEE}

}

Reference from Gulab thesis

@inproceedings{niang2007new,

title={New inversion method for snow density and snow liquid water content retrieval using C-band data from ENVISAT/ASAR alternating polarization in alpine environment},

author={Niang, M and Dedieu, Jean-Pierre and Durand, Yves and M{\'e}rindol, L and Bernier, Monique and Dumont, M and others},

booktitle={Proceedings of the 2007 ENVISAT Symposium},

year={2007}

}

* Snow density is an important physical feature that influences the thermal, mechanical and optical properties of snow layers
* slope stability calculations for avalanche prediction (Hirashima et al., 2009; Brun et al., 1989)
* snow hydrology (Rango and Martinec, 1995; Jonas et al., 2009; Sturm et al., 2010).
* These studies show that snow density is a complex parameter that can vary spatially, temporally and vertically within the snow pack profile
* Seasonal densification of snow packs is caused by wind erosion, melt-refreeze events, compaction and snow metamorphisms acting in response to internal temperature and moisture gradients (Sommerfeld and LaChapelle, 1970; Colbeck, 1982). Wind erosion, for example, physically reshapes snow crystals to more sphere-like grains that can pack closer together. Similarly, the presence of liquid water (Brun, 1989a; Marshall et al., 1999) and destructive snow metamorphisms occurring when vertical temperature gradients are weak (Colbeck, 1982), also result in smaller, rounded grains.
* Melt-freeze processes (Gray and Male, 2004) have long been implicated in snow densification,
* The real part of the relative dielectric constant Ed' was found to depend almost solely on the density. No difference was found between coarse old snow, aged snow, new fine grained snow, undisturbed snow, and prepared snow.