Snowpack Properties Effects on Satellite Brightness Temperature and Emissivity Data

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ABSTRACT

Spatial variation of snow depth and Snow Water Equivalent (SWE) is an essential component in flood predictions and water resource management. Satellite microwave data can be used to estimate snowpack properties. Microwave Brightness Temperatures (Tbs) have been used by remote sensing community for estimations of snow depth and SWE. Snowpack properties (snow depth, density, and snow grain) highly influence the microwave scattering.

In this research, we investigate potential of microwave Emissivity data *(em)* in improving estimated snow properties (depth, water equivalent, and grain size). A microwave snow emission model from Helsinki University of Technology (HUT) was employed to generate the *(Tb)* and *(em)* which were evaluated with satellite microwave measurements. The comparison of Brightness Temperature *(Tb)* and Emissivity *(em)* data shows that over the deep and medium snow, Brightness Temperature *(Tb)* in 37GHz is a better estimator of snowpack while over the shallow and fresh snow, emissivities in 85GHz show higher capability in estimating of snowpack properties. In summary, using both *(Tb, em)* can results in higher accuracy of estimated snow properties.

Keywords: snowpack properties, passive microwave, remote sensing, snow emission model

1. INTRODUCTION

According to the Federal Emergency Management Agency (FEMA), floods are one of the most common hazards in the United States. A re-analysis of the National Weather Service (NWS) showed that flood damage has been despite local and federal efforts to mitigate floods. One of the most common reasons of floods is rainfall on the snow covered area. During the melting seasons precipitations tend to occur in the form of rain rather than snow. When rain accompanies melting snow, the melting process is accelerated, causing unpredicted floods. An adequate knowledge of snow is necessary for use in hydrological, meteorological, and hydro-climatological models for flood, weather forecasting, and water resource management. Snowpack is a complex medium with large spatial and temporal variability, which consist of several layers with different densities and grain size distributions.

The launch of earth observatory satellites in the mid-twentieth century and their capability to observe the earth on large scales encouraged the meteorologists and hydrologists all around the world to find alternatives for traditional methods of estimating snowpack properties.

For decades, visible satellite sensors such as Land Remote Sensing Satellite (LANDSAT), Multi-spectral Scanner (MSS), and LANDSAT Thematic Mapper (TM) were monitoring the Northern Hemisphere. But visible satellite sensors can detect snow cover only during cloud-free

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daylight condition without providing any information of snow depth or Snow Water Equivalent (SWE).

Contrary to visible band, microwaves can pass through precipitating clouds. This ability of microwaves is due to the fact that they have long wavelengths, which fact allows the wavelengths to pass through clouds. Satellite-borne passive microwave imagery started with the Nimbus program in 1963. By the launch of Nimbus 5 in 1972, the first microwave satellite imager was successfully positioned in space. The original mission of Nimbus was to map global rainfall rates, but shortly after the launch the mission evolved into mapping global sea ice coverage. Mapping the snow did not start until the launch of Nimbus 7 with a Scanning Multi-Channel Radiometer (SMMR) on board. SMMR multiple channels and their spectral difference permitted better detection of the land covered by snow. Using spectral difference between channels led researchers to the first global snow mapping algorithm [1]. The legacy of microwave imagery continued with the Defense Meteorological Satellite Program (DMSP) and the Special Sensor Microwave Imager (SSM/I). Having 7 channels and four frequencies, SSM/I became a very successful instrument, replacing its predecessor, SMMR.

Microwave radiation responds to snow properties such as density, depth, grain size, temperature, surface wetness, melting-refreezing cycles, and vegetation. Most of the algorithms previously used for estimating snowcover from spaceborne microwave radiometer are empirical formulas [1, 6]. These algorithms are restricted because they use regional empirical regression coefficients. It is also possible to develop inversion techniques by using ground-based experimental data and/or emission models. The benefit of the emission models is that the use of empirical coefficients can be avoided. Several models have been proposed in the literature to describe the relationships between snow parameters such as mean grain size, density, snow depth, etc., and electromagnetic quantities [7-9].

In this study we employed a model developed by Helsinki University of Technology (HUT). HUT is semi-empirical model which combines theory with results from measurements. The objective of this study is to investigate the potential of Emissivity data *(em)* in improving estimation of snowpack properties (depth, water equivalent) which are essential components in flood forecast.

In initial stage of this study, we investigated sensitivity of snow parameters to *TB* and *em* of different SSM/I frequencies (19, 37,85GHz) and their scattering signatures. Then, we compared the performance of *Tbs* and *em* data in their potential in estimation of snowpack properties (depth, water equivalent, and grain size) using HUT model. At the end, we derive and qualitatively evaluate the time-series of snowpack properties estimated by T*b* and *em* microwaves.

2. STUDY AREA

The study area is in the Great Plains, North of the USA and south of Canada, located between 45N-52N and 96W-114W including, North Dakota, South Dakota, Western Minnesota, Eastern Montana, Sothern Alberta, Saskatchewan, and Manitoba (Fig 1). Great Plains have a long history of snow-melt related floods. The 1997 Red River flood in Grand Forks, North Dakota resulted in record-breaking flood devastation.

The northern Great Plains is an ideal laboratory for the development of passive microwave snowpack algorithms. The region has relief on the scale of the passive microwave sensors, 25km to 50km, and consists mostly of open prairie or farmland. Wintertime temperatures are generally quite cold for extended periods of time, which limits melt-freeze effects. The snowpack in this area is less than 1m deep; moderately cold; subject to wind drifting; and contains large annual variations and spatial variations on length scales of tens kilometers [10].

Figure 1. Great Plains, source: solpass.org.

3. DATASETS

3.1. Brightness temperature

Satellite microwave data used in this study are from Special Sensor Microwave Imager (SSM/I) on board the Defense Metrological Satellite Program (DMSP. The polar orbiter observes the Earth twice daily at four frequencies (19, 22, 37, and 85 GHz) and dual polarizations (H, V), with exemption of 22 GHz, which is vertical polarization only. The observing incidence angle is close 53°, and the fields of vie decrease from 43 km x 69 km to 13 km x 15 km [11]. Brightness Temperature *(Tb)* data are obtained from National Snow and Ice Data Center (NSIDC) in 25 km x 25 km spatial resolution (EASE-GRID format).

3.2. Emissivity

The Brightness Temperatures *(Tb)* measured by satellites is function of land emissivity *(e)* and surface/skin temperature. By removing the contribution of surface temperature so *Tb*, the remaining parameter *(e)* can have higher potential to monitor changes in snow properties. Microwave emissivities are estimated from SSM/I observations by removing the contributions of the atmosphere, clouds, and rain using ancillary data from International Satellite Cloud Climatology Project (ISCCP). Cloud-free SSM/I observations are first isolated with the help of collected visible/infrared satellite observations. Then the cloud-free atmospheric contribution is calculated from an estimate of the local atmospheric temperature-humidity profile (National Centers for Environmental Predication (NCEP) analyses). Finally, with the surface skin temperature derived from IR observation (ISCCP estimate), the surface emissivity were calculated for all the SSM/I channels [12].

3.3. Ground measurement

In the Northern Great Plains study region, National Climate Data Center (NCDC) in the USA and National Climate Data and Information Archive operated by Environment Canada make daily weather observations of temperature, precipitation, snowfall, and snowpack thickness. In this study, 28 stations in the USA and Canada were chosen to be used as the input of the emission model and to compare the snowpack properties variations with the pattern found in SSM/I observations.

4. SNOW EMISSION MODEL

The model used in this study was developed by Pulliainen in 1999 at Helsinki University of Technology (HUT) [7]. The HUT snow emission model is a semi-empirical approach based on radiative transfer. They assume the snow cover as a single homogeneous layer and the emission from the snow cover is a function of snow depth, snow density, snow grain size, snow temperature and, in the wet snow case, surface roughness of the air and snow boundary, and snow wetness.

The model also takes into account the emission emitted downward and reflected upward from the snow and soil boundary. To calculate this emission, the rough bare soil reflectivity model developed at the University of Bern, Switzerland was used. [13]. The dielectric constant of the soil was chosen to be 3.5+.1j from [14-15]. The basic assumption in the HUT snow emission model is that scattering is mostly concentrated in the forward direction. The passive microwave data and ground measurements were used as inputs to the model to calculate variations of snowpack properties spatially and temporally.

5. METHODOLOGY

As discussed before, different land parameters and snow properties influence the microwave emissions. In a simplified format, Tb recorded by satellite's sensor is influenced by land characteristics, surface temperature, snow depth, snow density, and snow grain size. Assuming the land characteristics do not change during the season, the changes in microwaves measured by satellite is originating from change in snowpack properties. These changes range from snowfall (depth increase) to snow melt (depth decrease) as well as snow metamorphic evolutions.

In initial stage of this study, we investigated sensitivity of snow parameters to *TB* and *em* of different SSM/I frequencies (19, 37,85GHz) and their scattering signatures (19v,h-13v,h, 19v,h-85v,h). We used HUT model in this analysis. The model was fed with a constant density and temperature, and a range of grain size and snow depth to understand the variation of grain size versus snow depth and *Tb* versus *em*.

In the second stage, we compared the performance of *Tbs* and *em* data. Using HUT model we evaluated which channels and their "Scattering Signatures" have the highest potential in estimation of snowpack properties (depth, water equivalent, and grain size).

Finally, the snowpack properties we derived over 28 stations within the study area. The derived time-series monitors and evaluates the changes in snow properties during winter season 2003-2004.

6. RESULTS

6.1. Sensitivity analysis and performance in different microwave bands

In order to analyze sensitivity of microwave Tb and em to different snow parameters HUT model was used. Intially the input consisted of: constant density and temperature, a range of grain size (0.8-1.2mm) and a range snow depth (0-3m). The output of the model consisted of model produced Brightness Temperatures *(Tb)* and Emissivities *(em)*. Then the grain size was assumed a constant and a range of density (.01-.41 g/cm^3) was fed into the model to show the variation of density vs. snow depth and emissivity/brightness temperature.

Figure 1 illustrates the results for both brightness temperatures *(Tb)* and Emissivity data *(em)* for a snowpack with density of 0.3g/cm^3. It is shown that channel 85GHz (Fig 2a) and the scattering signatures of 19GHz-85GHz (Fig 2b) in both polarizations are highly sensitive to the changes in snow depth and grain size.

In other words, in 85GHz, *(Tb)* and *(em)* show high dependency to variations in snow depth and grain size. The sensitivity decreases where snow depth and grain size increase and pass a certain threshold. For instance, given the density of 0.3kg/cm^3, the 85GHz channel and the scattering signatures of 19GHz-85GHz are not capturing the increase of depth after 25cm. On the other hand, for a deeper snow, 37GHz (Fig 2a) and the scattering signatures of 19-37GHz (Fig 2b) are showing more sensitivity where the snow depth is higher than 25cm.

Similar behavior is observed between density, depth, and microwave scattering for a given grain size (Fig 3). Increase in density and depth increases the microwave scattering. Again, the sensitivity of microwaves is higher in high frequency band of 85GHz. This analysis indicate that, although, channels of 85GHz and 37GHz have the potential for estimating snowpack properties, but the microwaves are sensitive to density and grain size as much as they are sensitive to snow depth. Then, to reach the optimum answer in the retrieval, all snowpack characteristics must be solved simultaneously.

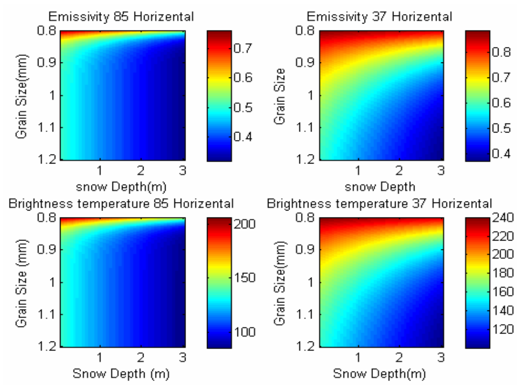

Figure 2a. Variation of brightness temperature and emissivity versus snow depth and grain size for 37H and 85H

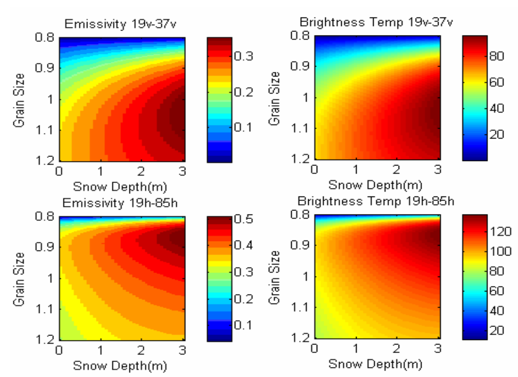

Figure 2b. Variation of brightness temperature and emissivity versus snow depth and grain size for 19V-37V and 19H-85H

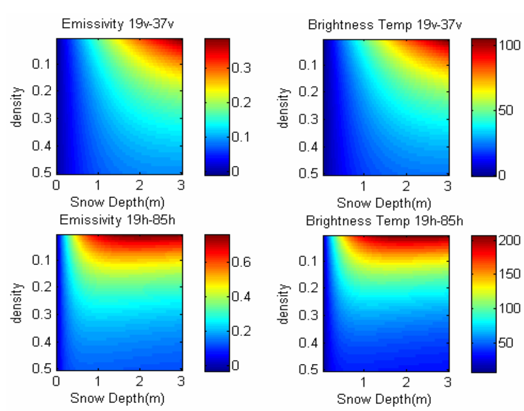

Figure 3. Variation of brightness temperature and emissivity versus snow depth and density for 19V-37V and 19H-85H

6.2. Comparison of brightness temperature (Tb) and emissivities (em) performance

The major difference between *(Tb)* and *(em)* is the skin temperature. In the *(em)* the effect of skin/surface, temperature and atmosphere/cloud are filtered out of brightness temperature [12]. The use of emissivities can potentially reduce the error originating from the effect of temperature in snow estimations. A comparison of the performance of *(em)* versus *(Tb)* data is shown in Figure 4a,b. The snow depth data are reported from the ground stations and the brightness temperature and emissivities are measured by satellite's sensor. The black points on the graphs represent the ground measured snow depth and its corresponding satellite *Tb, em* measurements. The curves are model-produced *Tb* and *em* for various snow depth and grain size.

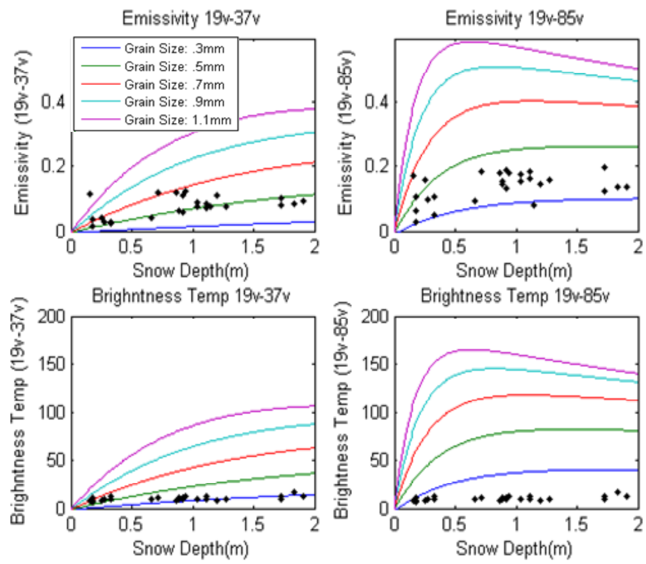

Figure 4a. Density 0.3g/cm^3, measured and modeled snow depth and the corresponding brightness temperature and emissivity.

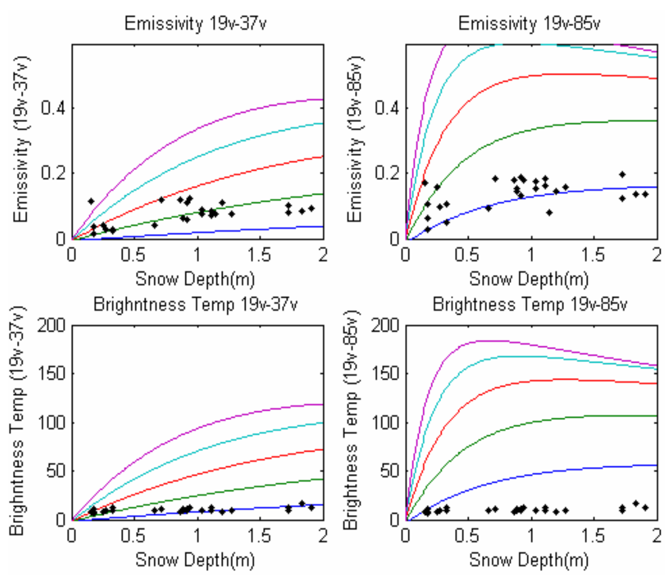

Figure 4b. Density 0.2g/cm^3, measured and modeled snow depth and the corresponding brightness temperature and emissivity.

Over the shallow snow, where snow depth is less than 0.3m, it is observed that in 85GHz the emissivity *(em)* data perform significantly better than *(Tb)* data. As shown in for the assumed density of 0.3kg/cm^3, estimated grain size in (Lat=49.92 & Lon=99.95) on 12/1/03 is equal to 1.15 mm which is in a reasonable range for grain size [16]. Unlike emissivities, the measured brightness temperatures are not showing satisfactory results in estimating snow using 85GHz. The high error in the results from brightness temperatures is associated from atmospheric effect in 85GHz. Similar behavior is observed for snow density of 0.2 kg/cm^3 (Fig 4b).

The results indicates that the range of grain size for emissivities (19GHz-37GHz & 19GHz-85GHz) for all densities is between 0.3mm-0.7mm and for brightness temperature is between 0-0.3mm.The comparison of the real measurements (ground and satellite) with the modeled results shows that the scattering signature (19GHz-85GHz) shows better results in emissivities rather than brightness temperature data. This confirms the fact that atmospheric effects influencing the brightness temperature *(Tb)* data will increase the error and using emissivity *(em)* data produces better results.

6.3. Time-series of snowpack properties and microwave (Tb, em) data

In the this approach, we investigate the seasonal behavior of derived snow grain size from the model using the measured snow depth, measured surface temperature, constant density, and brightness temperature/emissivity data from the satellite as inputs of the model. Generally, snow grain size tends to increase during the winter season. The aged snow average grain size could be three to four times larger than the fresh snow. The question is whether this fact can be used to quantitatively define a seasonal behavior for snow grain size. Figure 6 illustrates the behavior of the derived snow grain size with respect to snow depth, surface temperature, and SSM/I brightness temperature and emissivity for the whole winter season (Dec 1, 2003-Mar 31, 2004) at station 10 (Lat:53.31 & Lon: 113.56).

Snow grain size decreases when, the snow depth increases. This can be related to snowfall. Fresh snow has smaller grains which reduces the average size of the snowpack. Snow grain size derived from the model using the emissivity behaves the same for both channels (37 and 85 GHz). Snow grain size derived from the model using the brightness temperature for both channels follow the same pattern as the ones from the emissivity only with a smaller range of grain size. The results indicate the validity of grain growth assumption in to some extent but it fails to address it quantitatively as a function of time.

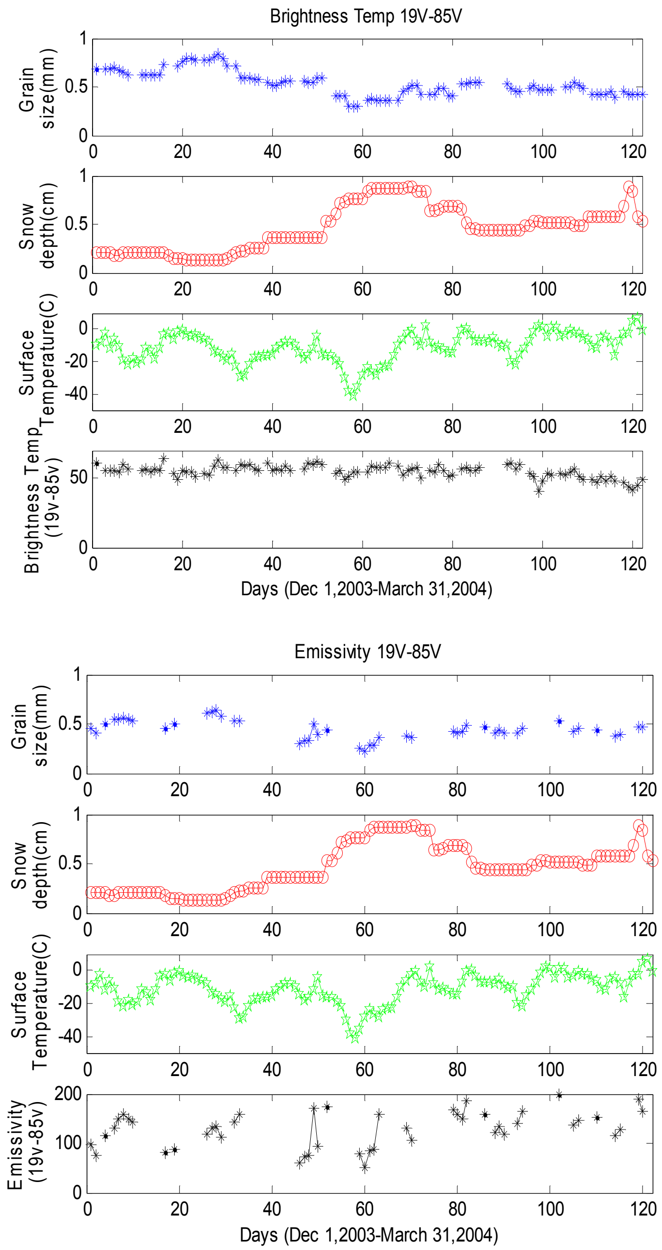

Figure 6. Time series of derived grain size, snow depth, snow temperature, *Tb,* and *em* emissivity of 19v-85v (bottom), brightness temp 19v-85v (top) at station (Lat:53.31 & Lon: 113.56).

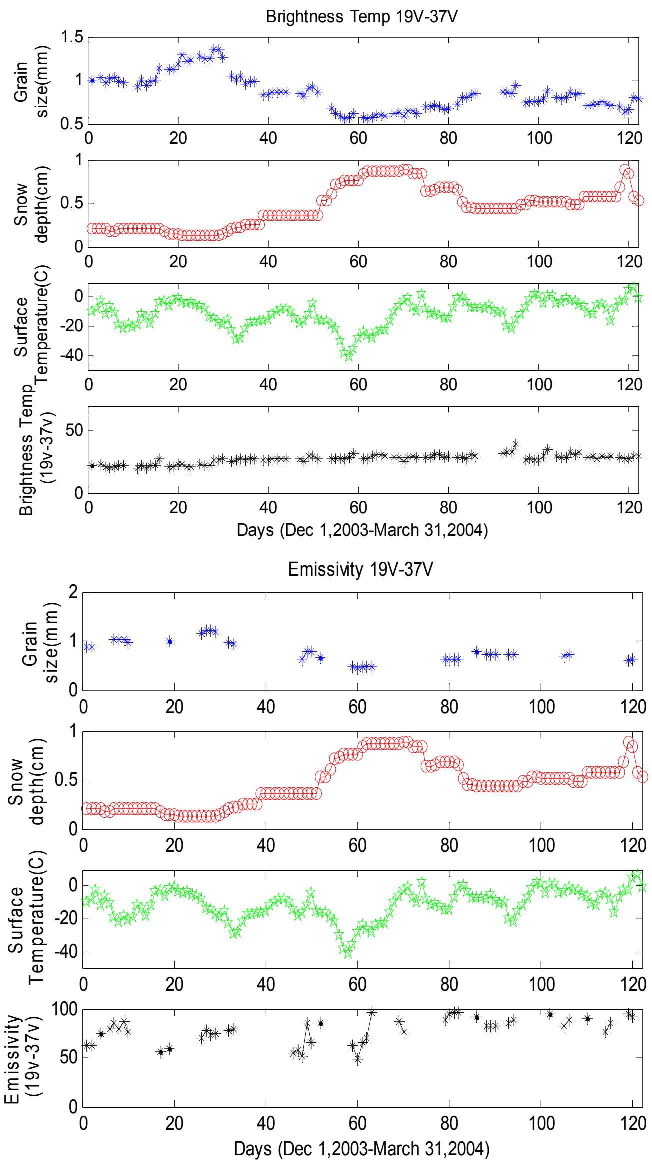

Figure 7. Time series of derived grain size, snow depth, snow temperature, *Tb,* and *em* emissivity of 19v-37v (bottom), brightness temp 19v-37v (top) at station (Lat:53.31 & Lon: 113.56).

7. CONCLUSIONS

In this study we explored the potential of satellite microwave emissivity *(em)* and brightness temperature *(Tb)* data in estimation of snow properties (snow depth, water equivalent, and grain size). The results from brightness temperature and emissivity was analyzed and compared. Variation of snow grain size, density, and frequency were derived from the model and was compared in different channel of brightness temperature and emissivities. The results shows that average snow grain size decrease when snow depth increase. The changes in average snow grain size over the layer can be explained by snow fall. Fresh snow has a smaller grain size. When snow fall happens, it increases the depth of snow but the average grain size will be decreased. The increase in the snow grain size can be associated with snow metamorphism. When snow melts the processes of metamorphism accelerates increasing the size of the snow grains.

The comparison of Brightness Temperature (*Tb*) and Emissivity *(em)* data shows that the grain size derived from emissivity data indicates emissivities at high frequency (85 GHz) and brightness temperature at low frequencies (37 GHz) are very sensitive to the presence of snow on the ground for very low snow depth. Then, over the deep and medium snow, Brightness Temperature *(Tb)* in 37GHz is a better estimator of snowpack while over the shallow and fresh snow, emissivities in 85GHz show higher capability in estimating of snowpack properties. Qualitatively, using both *(Tb, em)* must results in higher accuracy of estimated snow properties.

8. ACKNOWLEDMENT

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