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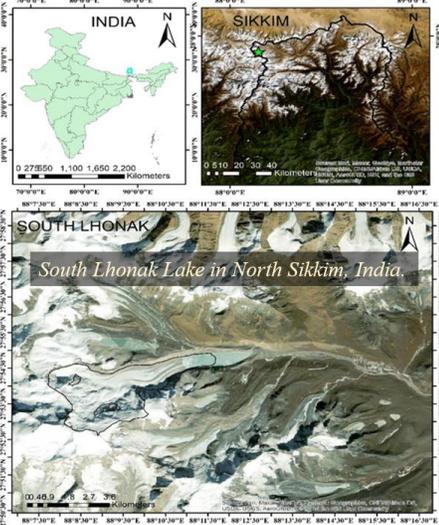Website: https://fac.iitg.ac.in/rbharti/

Lec 22 b: Geophysical Parameters of Snow-I: Part B

Hello everyone, welcome to lecture 22; this is the continuation of the first part. So, we were talking about the snow grain sizes, and then we also saw how hyperspectral remote sensing is being used by various researchers to identify the snow grain sizes. So, we will try to see some more details about this. So, this is our work from South Lhonak Lake, and because of the GLOF event, this particular area was studied.

So, South Lhonak Lake is a moraine-dammed glacial lake located in the northern district of Sikkim, India. The lake is elongated from east to west and situated at the tongue of South Lhonak Glacier. At an elevation of 5,200 mean sea level in the Lhonak Valley. So, the water that is coming to the South Lhonak Glacial Lakes is from these glaciers. After the lake burst on 4th October 2023, the length of the lake was reduced by 48.4 percent, as we have identified using the satellite data analysis.
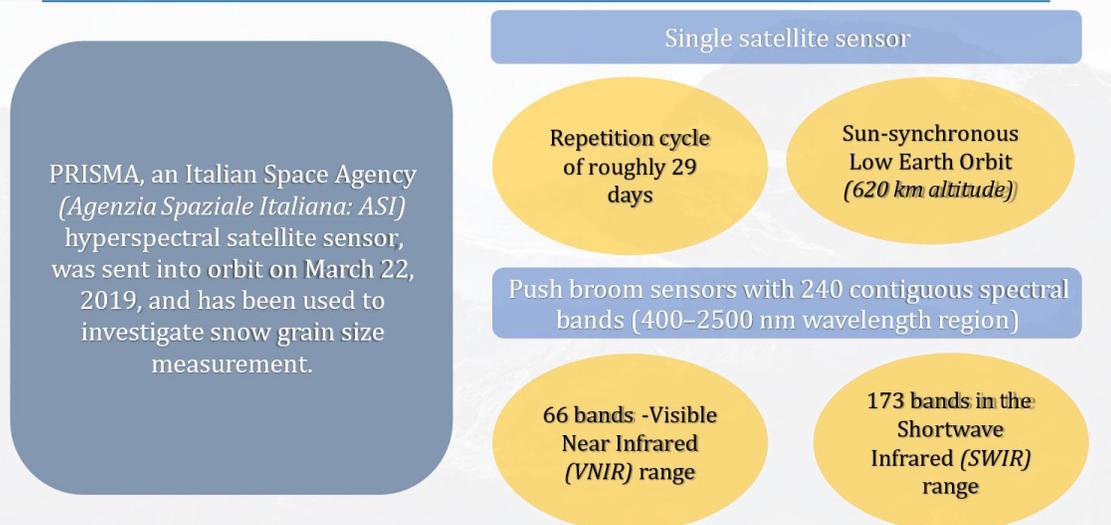
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Satellite Name & Product	Temporal Cycle & Spatial Resolution	Spectral resolution and Bands	Date of Acquisition
PRISMA-Hyperspectral Sensor: Sun-synchronous Low Earth Orbit (620 km altitude) & L2D (bottom-of-atmosphere reflectance)	~29 days & 30m *(swath of 30km)*	12nm; 240 contiguous bands (400-2500 µm), 66 VNIR & 173 SWIR	8th October 2023

Snow Grain Type	Grain Size
Frost	50 to 100 µm
Fine Grain Snow	200 µm
Medium Grain Snow	500 µm
Coarse Grain Snow	1 mm

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So, we have used the Prisma data, and this is a single satellite sensor that has been used, which has a repetition cycle of roughly 29 days. It is a sun-synchronous low Earth orbiting satellite. Push broom sensors are used here with 240 contiguous spectral bands, which are measured in the 400 to 2500 nanometer wavelength range. So, the 66 spectral bands are in the visible and VNIR wavelength ranges, whereas 173 bands are in the SWIR shortwave infrared range. The prism has a coherent spectral resolution of about 12 nanometers, a narrow bandwidth, and 30 meters of spatial resolution on a 30-kilometer swath width.

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Single satellite sensor

PRISMA, an Italian Space Agency *(Agenzia Spaziale Italiana: ASI)* hyperspectral satellite sensor, was sent into orbit on March 22, 2019, and has been used to investigate snow grain size measurement.

Repetition cycle of roughly 29 days

Sun-synchronous Low Earth Orbit *(620 km altitude)*

Push broom sensors with 240 contiguous spectral bands (400–2500 nm wavelength region)

66 bands -Visible Near Infrared *(VNIR)* range

173 bands in the Shortwave Infrared *(SWIR)* range

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We have used the Prisma L2D product, which was acquired on 8th October 2023, and it was downloaded from this particular website. So, you can simply register it, and then after that, you can download the datasets. So here you can see the basic details about this data, so the Prisma hyperspectral sensors that are being used here. This is the spectral resolution and the date of acquisition. So, in this study, we tried to identify different wavelength ranges.

So, we have reference grain sizes. So, we have used different grain sizes. So, the first one is the frost, fine grain, medium grain, and coarse grain. So, we tried to use this PRISMA data to classify our study area into different grain sizes. So, the used data was basically the L2D data, which was ortho-rectified and is an L1 product, which is nothing but the bottom-of-atmosphere reflectance.
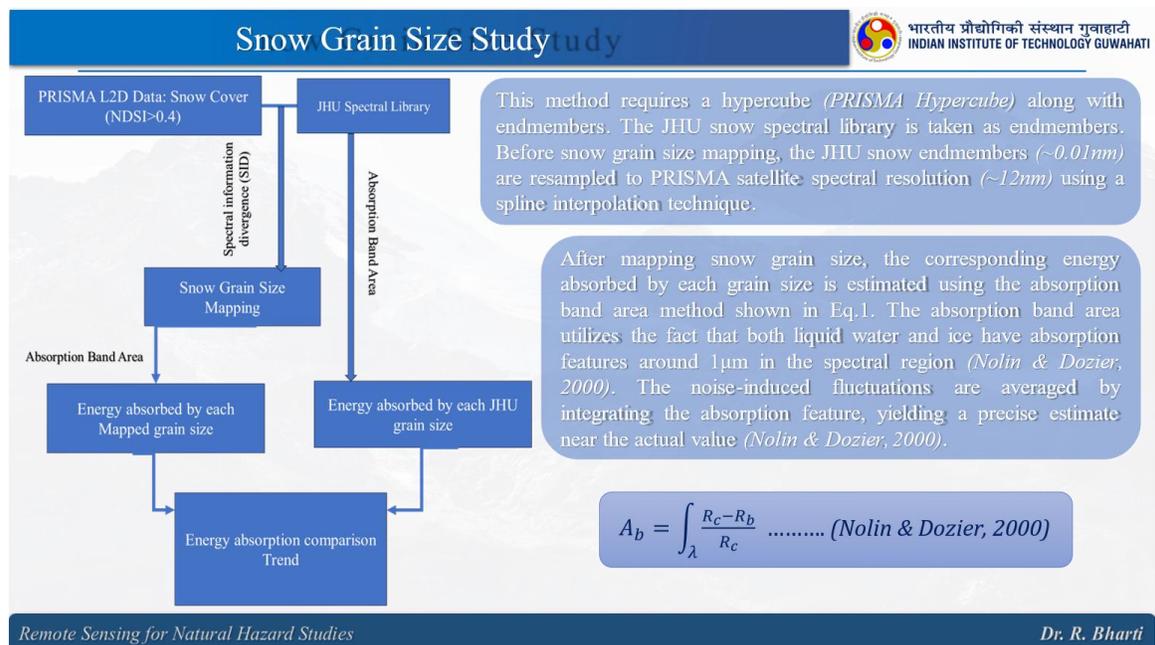
So, we have used that snow density here. which is 250 kilogram per meter cube and this is the methodology that have been used in our study. So here you can see that this method requires a hypercube. So here the hyperspectral data, also called a hypercube, has been used and then the GHU spectral library was referred to for the spectral signature of different grain sizes.

Before snow grain size mapping, the GHU snow end members are resampled to PRISMA satellite spectral resolution, which is basically 12 nanometers, but the GHU library has a 0.01 nanometer sampling. So, we have to convert it to 12 nanometers so that it will match the PRISMA satellite data. After mapping snow grain size, the corresponding energy absorbed by each grain size is estimated using the absorption band area method. So, the equation is shown here.

The absorption band area utilizes the fact that both liquid water and ice have absorption features around 1 micrometer in this spectral region. The noise-induced fluctuations are averaged by integrating the absorption feature, yielding a precise estimate near the actual value, where AB is the absorption band area, RB is the reflectance spectrum, and RC is the continuum-removed spectrum. So, that has been used in this equation. The equation within the integration is called the scaled band depth. The energy absorbed by mapped snow grain sizes and GHU snow end members is compared to see the trend among the mentioned snow grain sizes.

In the absence of in-situ snow spectra, this absorption band area method is chosen as a validation technique, taking GHU snow grain size spectra as our reference data. So, when we cannot visit the site and do not have any information from the surface, then in that condition, this is a very good method to validate.

$$NDSI = \frac{Green - SWIR}{Green\_SWIR} \quad \text{................................ (1)}$$

$$NDFSI = \frac{NIR - SWIR}{NIR + SWIR} \quad \text{................................ (2)}$$

$$S3 = \frac{NIR(Red - SWIR)}{(NIR + SWIR)(NIR + Red)} \quad \text{................................ (3)}$$

$$SCI = \frac{[reflectance(470nm) - reflectance(590nm)]}{[reflectance(470nm) + reflectance(590nm)]} \quad \text{... ... (4)} \qquad \textit{(Negi et al. (2010))}$$

$$s = m_v[1; -0.5; 0; 0] + m_s[1; \cos(2\alpha); \sin(2\alpha)\cos(\delta); \sin(2\alpha)\sin(\delta)] \quad \text{.............. (5)}$$

where s = [s1; s2; s3; s4] is the Stokes vector, m_v is volume scattering power, and m_s is surface scattering power.

The threshold for each snow index is based on *Saptarshi et al. 2022.*

SAR backscattering values are obtained using Polarimetric Techniques.

The NDSI threshold for snow cover is generally taken to be 0.4 in the literature for snow cover. The default value of 0.05 is taken as the threshold for SID-based snow grain size classification. The SID-based classification shows that the majority of the grains in the study area had coarse and medium grain sizes, with much less frost and fine grain size present in comparison. So, here you can see that 31 percent is medium grain size and 61 percent is coarse grain, whereas the fine and frost are 2 to 6 percent. So here you can see the spatial distribution of different grain sizes present in the study area that have been identified. So, the GHU spectral library at satellite resolution is shown here, and we have different spectra: the B to E continuum removes a spectrum of fine granular, medium granular, and coarse granular snow whose y-axis is the continuum-removed spectra. So, you can see the continuum removed is here; the 1 is the maximum value, and all the

spectra are coming from the 1. Then the scale absorption depth of the snow grain size is given in the f, whose y-axis is the scale band value and x-axis is the wavelength. The vertical line parallel to the y-axis is at a wavelength equal to 1.03.

So, from this study, we found that the coarse-grained size of snow has the lowest reflectance, while frost has the maximum reflectance. When the grain radius rises, both the reflectance spectrum and the continuum-removed reflectance drop, while the scaled area of the absorption feature grows with the grain size, which is correlated with the absorption efficiency. In other words, a change in the grain size helps to identify the surface features of snow, such as melt and snowpack energy balance. When the absorption depth of each grain size was investigated using continuum removal, it was observed that in part of the 1.03 micrometer spectral region, there are two more prominent absorption depths that are near 1.5 and 2 micrometers.

However, these two new wavelengths are susceptible to water vapor and carbon dioxide absorption. So, they are excluded from the grain-size mapping. So, here we have some further box plots. Which shows the absorption band area for each snow grain size; the marked value shows the GHU snow spectral energy absorbed by each snow granule and frost and here, the underlying snow should have been exposed to the surface following the GLOF occurrence, and this grain size should generally be considered coarse grain, as this analysis of the surface layer demonstrates.
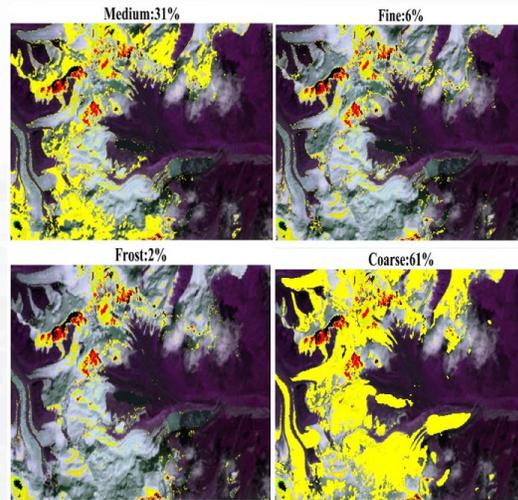
So, I wanted to show you an example of how hyperspectral remote sensing can be used in snow grain size mapping. To summarize this work, the snow grain size mapping for the South Lhonak Glacial Lake region has been studied using PRISMA data. The spatial subset of the hyperspectral data has been confined to the study area; the whole image was not used.

Snow Grain Size Study

The NDSI threshold for snow cover is 0.4, generally taken in the literature *(Marshall & Oglesby, 1994; Awasthi & Varade, 2021)*.

The default value of 0.05 is taken as the threshold of SID-based snow grain size classification.

The SID-based classification shows that the majority of snow grains in the studied area had coarse and medium grain sizes, with much less frost and fine grain size present in comparison.

Snow grain size mapping using the SID method. The yellow color is overlayed on the true RGB composite PRISMA data. Fine granular snow-6%, Frost-2%, Medium granular snow-31%, Coarse Granular snow-61%.

Medium:31% Fine:6% Frost:2% Coarse:61%

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The SID method, utilizing the Prisma and JHU snow spectral library for fine, frost, medium, and coarse granular snow, has been employed for snow grain size mapping. To characterize the snow surface characteristics, including melt area and snowpack energy balance, the absorption band area method is applied to map the snow grain size. The wavelength range centered at 1.03 is suitable for understanding grain size. So, remember that this is the main conclusion. The energy absorbed by the mapped snow grain size is consistent with GHU snow grain size spectra and Himalayan field circumstances of melting in the ablation period of October. Now, we will try to understand how remote sensing can be used in the study of snow contamination.

So, the snow contamination refers to the presence of various pollutants and foreign materials mixed with it. Here you have different examples from our field, and to just understand the basics, you see this is fresh snow; it is not contaminated here on the left-hand side. So, whatever energy is falling here, the maximum energy will get reflected, but when it comes to this contaminated one, what will happen is that a lesser amount of energy will be reflected back. So, if you talk about the total energy budget here, ideally, this should reflect that our atmosphere or our Earth system will not have any additional energy because of this contamination. They were supposed to reflect, but they are not reflecting.

So, they are appearing in the dark, and the albedo has been reduced. So, if the albedo is reduced, more absorption will occur, and that will lead to the melting of these glaciers or the snow. Snow is considered contaminated when foreign materials are deposited or mixed with it, accelerating melting and significantly impacting the snow cover's radiative balance. Such enhanced melting rates result in a reduction in freshwater sources at the

catchment level. In optical remote sensing, snow contamination is widely studied using a normalized difference index called the snow contamination index.

This is based on the finding that the impact of snow contamination diminishes with wavelength and is most noticeable in the visible spectrum, which is 0.3 to 0.7, or sometimes 0.4 to 0.7 micrometers.

However, the study of snow contamination using optical remote sensing is hindered in the Himalayan terrain due to enduring cloud cover in the region. That is why we have explored the potential of SAR data in such studies, and here we have used the Sentinel-1 dataset because it has the capability to measure in all weather conditions. So, this particular study focuses on the SAR backscattering behavior at the C-Band of clear and contaminated snow for March 2022 in a part of the eastern Himalayas in Arunachal Pradesh, India. An attempt has been made to utilize Landsat 7. So, we have also used optical data here and Sentinel-1 to study the snow contamination.

Snow contamination can accelerate melting and significantly impact the radiative balance of the snow cover, which we have understood in terms of how it behaves when there is a change in the albedo. According to them, understanding the connection between the cryosphere, the atmosphere, and the climate depends on how snow impurity affects snow albedo reduction. Furthermore, the deposition of black carbon accelerates the melting of the snow because nowadays we have more pollution, and if there is a wind circulation that brings the black carbon from the mainland to these higher altitudes. That will get mixed with the snow, and then we will have more impurities and contamination. Resulting in a decrease in freshwater sources at the catchment level, it will also increase the melting.

So, for this, we have selected Arunachal Pradesh, and here you can see these stars where we have conducted our field investigation to identify different types of snow, which are shown in these figures. So, for this, we have used synthetic aperture radar data. So, we have Sentinel-1, which is dual polarimetric VV and VH, that is being used. SLC interferometric wide IDW swath mode data is used; this is basically the C-band data, and the spatial resolution is 5 by 20 meters. The date of acquisition is 3rd September 2021, and the next one is 14th March 2022.

As I mentioned earlier, we have also used the optical data, so we have the multispectral data from Landsat 9 level 1 data, and the 11 bands were used here. The spatial resolution of this is 30 meters, and the date of acquisition is 14th March 2022, which matches with our Sentinel-1 data. So, for that, we have used NDSI, NDFSI, and S3 band indices, and then finally we have used the SCI. So, the threshold for each snow index is based on Saptarishi et al. (2022).

Synthetic Aperture Radar (SAR) data

Sentinel-1A, dual polarimetric (VV/VH), SLC Interferometric Wide(IW) Swath Mode

C-band (5.405GHz/5.55cm)

The central latitude and longitude are 29.25˚N and 93.06˚E respectively

Spatial resolution of 5×20 m

Date of Acquisition: 03 September 2021, 14 March 2022.

S. No.	Snow Covered Scene	Snow Free Scene	Temporal Baseline
01.	S1A_IW_SLC__1SDV_2 0220314T234622_20 220314T234649_042 324_050B9B_C585	S1A_IW_SLC__1SDV_20 210903T234625_2021 0903T234652_039524 _04ABBB_D87D	192 days

Multispectral Data

Landsat 9 Level 1, 11 bands (Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS)).

Central Latitude and Longitude are 28.87° N and 94.90° E respectively

Spatial resolution of 30 meters (visible, NIR, SWIR); 100 meters (thermal -B10&B11); and 15 meters (panchromatic -B8)

Date of Acquisition: 14 March 2022, Cloud Cover: 12.77%.

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SAR backscattering values are obtained using a polarimetric technique. So, here, the polarimetric SAR has been used. So, as I mentioned in the previous slide, Sentinel-1 is the polarimetric data. So, that has been used, and based on that, the contaminated and clear snow was mapped, and here, the polarimetry has been utilized.

So, you can see the VH and VV that have been used to identify. For the snow contamination, snow and non-snow areas have been seen. So, how are the backscattering values changing? So, this statistical analysis has been performed to finally arrive at a decision on how the backscattering coefficient can be used in identifying contaminated and non-contaminated snow. So, the snow condition in terms of snow contamination is studied using multispectral L9 and SAR S1 datasets for the Mechuka region in Arunachal Pradesh, India. The range of SARP backscattering for snow and non-snow regions is obtained using the resultant snow cover map.

The snow-covered region has comparatively lower backscattering than non-snow areas. So, this can be seen in any of the microwave datasets. The contaminated snow has a comparatively higher backscattering value than that of clear snow. So, now we have concluded that the contaminated snow has a comparatively higher backscattering value. The average wetness for both snow classes ranges from 3 to 5 percent of volume, in contrast to the visible electromagnetic wavelength region, where contaminated snow exhibits a lower reflectance value than clear snow; the SAR backscattering for contaminated and clear snow exhibits.

Opposite features in the microwave region of the C-band. It is observed from the analysis that the key parameters influencing SAR backscattering over contaminated snowpacks are the local incident angle, snow wetness, and surface roughness. So, these three are

used. Now we will talk about the snow depth. So, the snow depth refers to the vertical distance from the surface to the ground.

So, assuming this is the lowest surface where we have rocks and soil. So, in that case, this will become the depth of the snow. Snow depth is a critical parameter for understanding the extent and volume of snowpack, which plays a key role in hydrological studies. It is an essential indicator for assessing snow water equivalents. It provides valuable insight for water resource management because the thickness is greater if the depth is greater, which indicates it has more potential to supply water over time.

Snowmelt forecasting and various hydrological applications require this snow depth information. Under these circumstances, monitoring snow conditions has proven to be especially useful using satellite remote sensing techniques. The snow parameters have previously been retrieved by researchers employing a variety of optical and radar remote sensing datasets. Particularly, optical remote sensing encounters challenges in foggy conditions prevalent in snow-covered regions for much of the year. In contrast, radar remote sensing functioning within the microwave spectrum, specifically PLC and X-band, offers an advantage by acquiring images even under cloud cover.

So, the factors that are affecting the snow depth are snowfall, temperature, wind, and solar radiation. The next is rainfall, the liquid, then snow density, and finally, it is topography. So, together they work on this system, and then they define or control this snow depth. So, how do we measure it in the field? So, one example is the manual measurement, which is the simplest: you go to the field, put in a snow stake, and then you measure how much it has accumulated in the last year or in the last season.

So, for that, you need to have a reference point. In another, we have the automated measurement. So, here we are using different sensors that send the pulses and then measure the height of this particular area. So, we have known the value for the last year from there; how much accumulation has occurred that can be identified. So, here you can see we call it a snow stake, but with the advancement in technology, we are also using ultrasonic or laser sensors mounted over the snowpack. The sensor emits pulses and measures the time it takes for the echo to return from the snow surface, thus determining the distance to the snow.

By knowing the sensor height, the snow depth can be calculated. So, as I mentioned, it will send the pulses, then it will reach it, and then they will derive the change in the storage. So, for this snow depth study, we have done fieldwork where we tracked 96 kilometers and reached the Rathong Glacier. Where We have tried to install the snow stake, and that is a manual snow stake. So, you can see this is during the ablation period. So, this surface does not have snow, but this is part of the main glacier body. So, this is the Rathong Glacier. So, here we have tried to install it, and every year we have to collect

information on how much precipitation has occurred with respect to last year or last season. So, this is how we are trying to approach this snow depth, but apart from that, we have also used remote sensing techniques to estimate the snow depth information, which we validate using our field data. So, with this, I will end this lecture, and we will continue the application of remote sensing, particularly in depth studies, in the next part. Thank you very much.