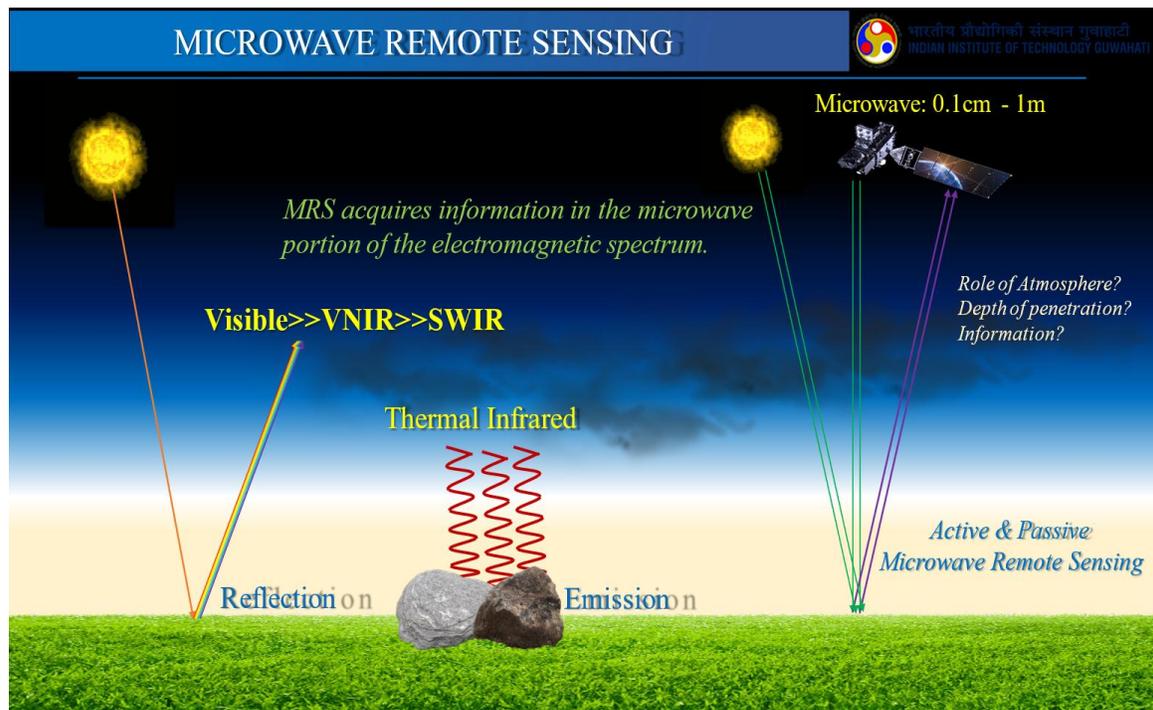


REMOTE SENSING FOR NATURAL HAZARD STUDIES

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Lec 24 b: Seismic Impacts on Himalayan Glaciers- Part B

Hello everyone, welcome back to the lecture. So, this is the second part. Here we will start with the basics of remote sensing, particularly microwave remote sensing, and how it can be used in seismic studies, especially for the Himalayan glaciers. So, let us try to understand the interferometry. I hope you remember this particular slide where we have explained the different parts of the electromagnetic radiation. To start with, we have visible, VNIR, and SWIR; then we have thermal infrared, and then we have the microwave remote sensing region.



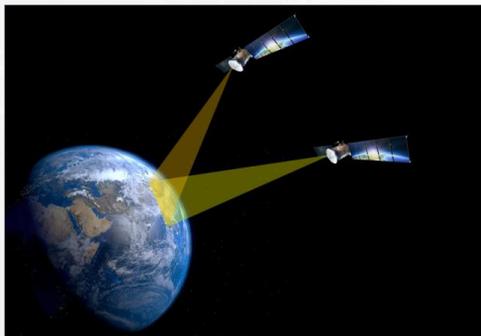
So, here in the microwave, we are utilizing this 0.1 centimeter to 1 meter wavelength range. So, here we can have both active and passive microwave remote sensing, and here you can understand the role of atmospheric depth of penetration and what kind of information it provides. So, when we talk about the atmosphere, since this is the longer wavelength region, it is free from scattering effects.

Then comes the depth of penetration as I mentioned in the previous few lectures, the depth of penetration is as equal to your wavelength that is a thumb rule we follow. So, when we talk about the depth of penetration here, it will be as good as the wavelength you are using in remote sensing. Then what kind of information does it have? So, as we have seen in visible, VNIR, SWIR, and even in the thermal infrared, we have information related to their chemical composition. However, when we talk about microwave remote sensing, more information will be related to its structure or geometry. So, here the chemical composition cannot be identified; however, we have other information that is required for other types of analysis that can be gathered using microwave remote sensing.

So, here you can see the interferometric SAR configuration. So, when we talk about the SAR, which is synthetic aperture radar. It is a system with an interferometric configuration known as interferometric SAR or InSAR. So, it allows for accurate measurement of the radiation travel path because it is coherent.

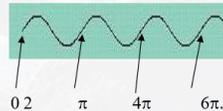
So, it is from two different positions, but they are looking at the same location. Measurement of travel path variation with respect to the satellite position and time of acquisition allows for the generation of a digital elevation model. So, this is widely used for digital elevation model estimation or generation. It can provide centimeter-level information related to surface deformation. High-resolution digital elevation models or surface change maps due to earthquakes, land subsidence, glacier movement, volcanic activity, and land use land cover changes are the prime applications of this interferometric SAR.

Interferometric SAR (InSAR)



- SAR interferometry needs at least,
 - (i) Two radars, or
 - (ii) Radar imaging from two places

- Phase is a measure of “how far the wave has travelled:



- In general, the relationship between phase and distance is $\phi = 2\pi d/\lambda$
i.e. if we have travelled by a wavelength ($d=l$) then the phase has changed by 2π .

Reference: Dr. Mathias (Mat)/Disney Mat) Disney
www.geog.oxl.ac.uk/~smdisney/disney

So, the SAR interferometry needs at least two radars; you can see here there are two radars and the radar imaging from two different places.

So, they are in different positions. So, the phase is a measure of how far the wave has traveled. So that will be identified like this. So, it is 0π , 2π , 4π , 6π . In general, the relationship between the phase and distance is as follows.

So, if we have traveled by a λ_d equal to L , then the phase has changed by 2π . So, the phase information is effectively random noise in a single SAR image because the phases are randomized by all the scattering on the Earth's surface. So, the phase image will be like this: However, if we view it from another position very close to the first, then the difference in phase tells us about the differences in distance. So, let us say this is the area, and here you have one. Radar, this is another radar; both are looking at the same position.

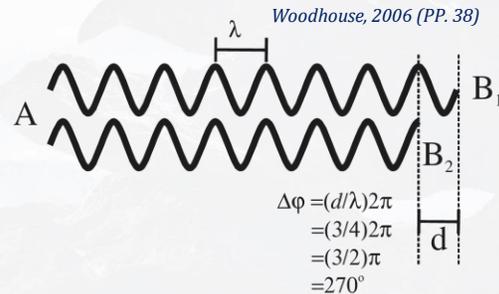
So, if you see a single image phase, it will be like this. But when we have the measurement from two different positions, we will have the phase differences, which can be used to identify the difference in distance. So, this is the basic configuration; here, you can see this is the arc where it looks. So, this is the topography now. Here, we have two radars. So, this is the first one, this is the second one, and the difference between these two is what your normal baseline. So, here, the difference between this position and this position is the parallel baseline, and the difference between these two will be the phase difference. We will be estimating using the satellite image. So, the image point is at the same location along this arc; the SAR phase difference is used to pinpoint the exact location of this. So, the difference between the two path lengths relates to the difference in phase of the received electric fields. I hope this basic configuration is clear to you. So, interferometry is used to generate two products. The first one is the coherence image, and the second one is the phase image. So, the phase image is also known as the interferogram. So, the entire image based on the phase information is known as the interferogram.

An image of coherence; here, you can see how we can interpret it. So, coherence near 1 means that the phase information is reliable. If the coherence value is less than or equal to 0.3, it means the image has low correlation. So, we will consider it as noise.

In this case, the phase information is not useful. So, when we say the phase of a SAR signal, we are again having the same information. So, each SAR image pixel contains a complex signal giving amplitude and phase information of the target. So, the amplitude is the strength of backscattered energy coming from the target, and the phase is the last fraction of the two-way travel distance. So, $(-\pi$ to $+\pi)$

Phase of a SAR Signal as a Measure of Relative Distance

- A phase of a microwave signal changes as the distance between the satellite and the target changes.
- Consider, the position of a point on ground is changed from B_1 to B_2 during the two satellite passes where the displacement d is less than λ .
- This difference in phase ($\Delta\phi$) is a direct measure of the difference in the length of the path from A to B_1 , versus A to B_2 , i.e., the distance d .



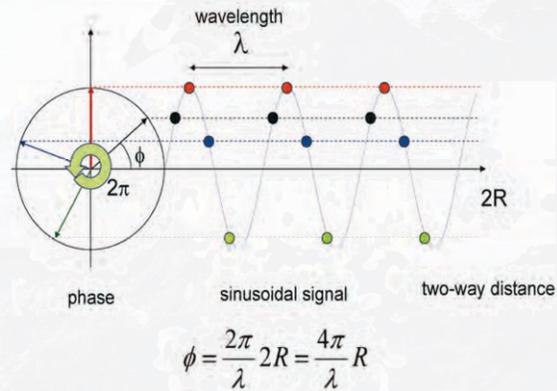
Here, a phase difference of $3\pi/2$ equates to a path length difference of $3/4$ of the wavelength. Subsequently, we can obtain the value for d using the value of λ provided $d < \lambda$.

So, here you can see how we can calculate the phase. If the phase of the transmitted signal is 0, then the received signal covering the distance of $2r$ shows a phase that is equal to $4\pi r$ by λ , and it will be in radians. So, the phase of the SAR signal as a measure of relative distance is something we have understood how it works. So, the phase of a microwave signal changes as the distance between the satellite and the target changes. Consider the position of a point on the ground that is changed from B_1 to B_2 during the two satellite passes, where the displacement d is less than λ .

So, here you can see that this is B_1 and this is B_2 , and the difference between these two is d . This phase difference is a direct measure of the difference in the length of the path from A to B. So, this is A, which is versus A to B_2 , which is the distance d . So, d can be calculated here. So, a phase difference of 3π by 2 equates to a path length difference of three-fourths of the wavelength; subsequently, we can obtain the value for d using the value of λ , provided d is less than λ .

Phase of a SAR Signal

- Each SAR image pixel contains a complex signal giving amplitude & phase info of the target.
 - ✓ **Amplitude:** strength of back-scattered EM wave
 - ✓ **Phase:** Last fraction of two-way travel distance ($-\pi$ to $+\pi$)
- If the phase of the transmitted signal is zero, then the received signal covering the distance of $2R$, shows a phase $\phi = 4\pi R/\lambda$ radians.



The interferometric synthetic aperture radar is the InSAR. So, here we have also seen the other diagram where we are generating the phase information from two different positions. So, an interferogram is generated by cross-multiplying pixel by pixel the first SAR image with the complex conjugate of the second one. So, the interferogram can be formed as this, where interferometric phase and interferometric coherence are used. So, now you have understood the basic principle of interferometry; how can we utilize this for the surface deformation study?

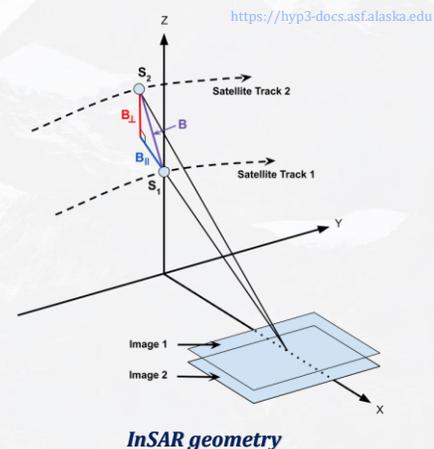
DINSAR FOR DEFORMATION MAPPING

Interferometric Synthetic Aperture Radar (InSAR)

- An interferogram is generated by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second (Bamler & Hartl, 1998).
- The interferogram can be formed as,

$$z_1 \cdot z_2^* = r_1 e^{i\phi_1} \cdot r_2 e^{-i\phi_2}$$

$$= r_1 \cdot r_2 \cdot e^{i(\phi_1 - \phi_2)}$$
- Here, $(\phi_1 - \phi_2) =$ Interferometric Phase
 $(r_1 \cdot r_2) =$ Interferometric Coherence



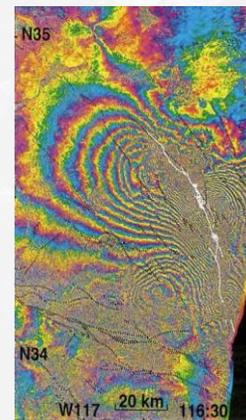
So, if ground movement occurs between two data acquisitions, the phase changes due to ground movement are given by this relationship, where we are using phase change due to topography and then satellite line-of-sight deformation. So, here is the pre-movement, this is the post-movement, and here the phase shift due to ground motion can be seen. So, the differential interferogram, this is the D-InSAR, interferogram from which the topographic contribution has been removed. An earthquake of magnitude 7.3 occurred on June 18, 1992, near the town of Landers in the USA. So, here is the interferogram.

DINSAR FOR DEFORMATION MAPPING



□ Differential interferometry for Seismic Deformation Mapping

- Differential interferogram: Interferograms from which the topographic contribution has been removed.
- An earthquake of magnitude 7.3 occurred on 18th June 1992 near Landers town of USA.
- ERS-1 images were used to create interferogram before and after the event which exhibited distinctive interferogram fringes – colorful contour-like patterns
- Each fringe (cycle of color change) corresponded to a change in distance between ground and satellite ~2.8 cm for C-band ERS satellite.



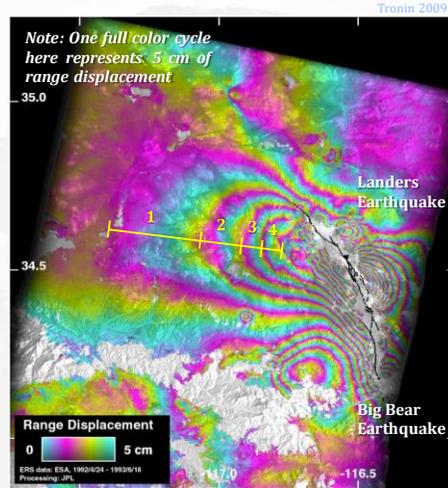
Differential interferogram of Landers Earthquake (Images used: 24 Apr 92 & 18 Jun 93

ERS-1 images were used to create interferograms before and after the event, which exhibited distinctive interferogram fringes and colorful contour-like patterns. Here, you can see these fringes. Each fringe corresponds to a change in distance between the ground and satellite that is about 2.8 centimeters for the C-band ARS satellite. So, this is from this paper.

The lander earthquake created a large surface rupture, as evidenced in the interferogram, with a right-lateral sweep. So, here you can see a maximum displacement of approximately 4 meters and 6 meters at 10 kilometers and 40 kilometers distance, respectively, can be estimated by counting the fringes in the interferogram. So, the Big Bear earthquake, occurring 3 hours later, lacked a surface rupture but was visible in the interferogram. As circular fringes south of Lander. So, here, the interferogram is very useful in earthquake studies

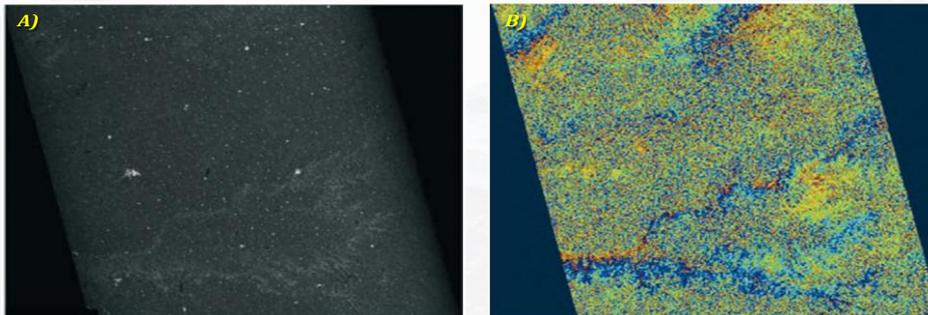
□ Landers Earthquake

- Landers Earthquake created a large surface rupture, as evidenced in the interferogram, with a right-lateral slip.
- Maximum displacements of appx 4 m & 6 m at 10 km and 40 km distance respectively, can be estimated by counting the fringes in the interferogram.
- The Big Bear Earthquake, occurring 3 hours later, lacked a surface rupture but was visible in the interferogram (as circular fringes south of Landers).



So, you have seen the interferogram and how it is coming for different seismic events. The source of error in an interferogram that we also need to understand before we go into the application. The sources of error in an interferogram primarily arise from environmental, geometric, and instrumental factors, which include atmospheric disturbances, spatial and temporal decorrelation, orbital errors, unwrapping errors, instrumental noise, and processing artifacts. So, these can also introduce errors in your analysis. So, when we talk about the sources of error, particularly decorrelation, temporal decorrelation plays a critical role here. So, changes in surface properties, for example, vegetation growth and soil moisture between data acquisitions, reduce coherence and affect phase accuracy. Then, spatial decorrelation is caused by geometric differences in radar look angles due to baseline separation between acquisitions, especially over rough terrain.

□ Latur Earthquake



A) ERS-1 amplitude image of the Latur region. B) co-seismic interferogram created from 23 February 1993 and 26 October 1993 ERS1 images.

On 30 September 1993, a case of the Latur earthquake struck the Latur region of India, a predominantly agricultural area dotted with small cities and villages. ERS-1 images were used to obtain a co-seismic interferogram. However, the images showed mostly incoherent results because of the change in the soil moisture. So, the main cause of coherence loss was decorrelation, which hindered effective denser analysis. The earthquake occurred during the monsoon season; thus, heavy rains altered surface properties and reduced radar coherence. Then the affected region is primarily agricultural, further lowering coherence; changing vegetation and wet soil contribute to signal decorrelation. Further cities and villages retain coherence despite the large-scale destruction. Radar signals in urban environments may come from stable structures where buildings might remain identifiable even when damaged.

So, that is the advantage of your DInSAR. So, here is an example from the Latur earthquake. So, here A is the amplitude image of the Latur region, and B is the co-seismic interferogram created from the 23rd of February 1993 and the 26th of October 1993 ERS images. So, you can see here. Then, we have the sources of error again: the atmospheric disturbances. The atmospheric phase noises are introduced in the interferogram due to tropospheric and ionospheric path delays.

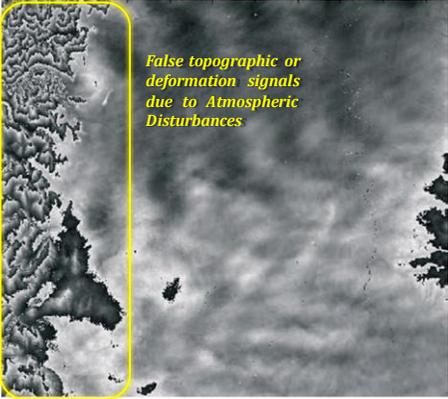
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❑ Tropospheric Delay

Ferrati et al, 2007

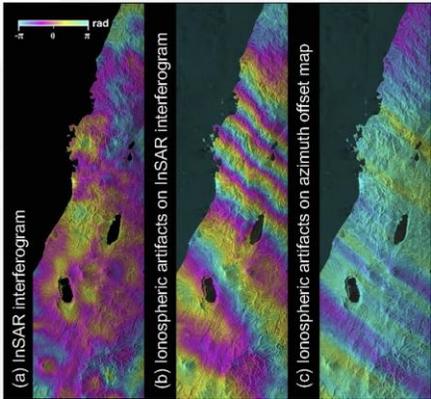


False topographic or deformation signals due to Atmospheric Disturbances

ERS interferogram over Pianura Padana, Italy.

❑ Ionospheric Delay

Zhang et al, 2022



The ionospheric effect on InSAR data

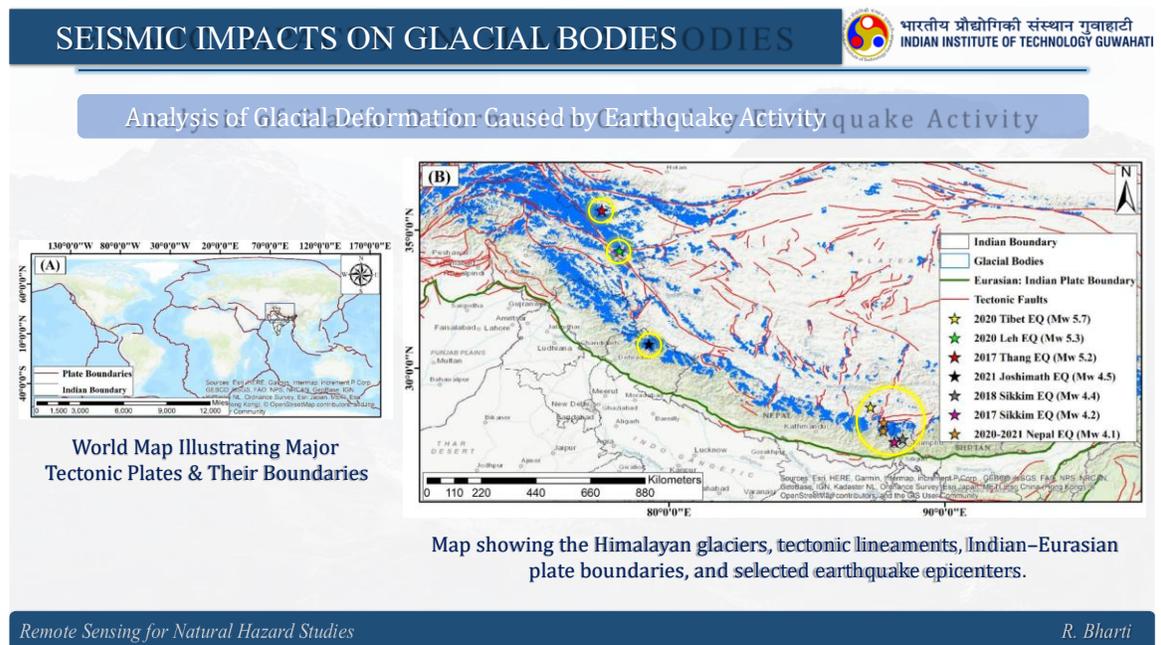
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And, when we say tropospheric delay, when SAR images are acquired at different times with varying atmospheric conditions, radar signals travel along different paths through the atmosphere. So, the atmosphere will have a role here; it is caused by variations in temperature, pressure, and humidity, leading to path length differences. So, here the scattering is not considered because we are talking about the longer-wavelength regions.

Then, ionospheric delays particularly affect L-band SAR due to ionospheric fluctuations, which cause phase shifts.

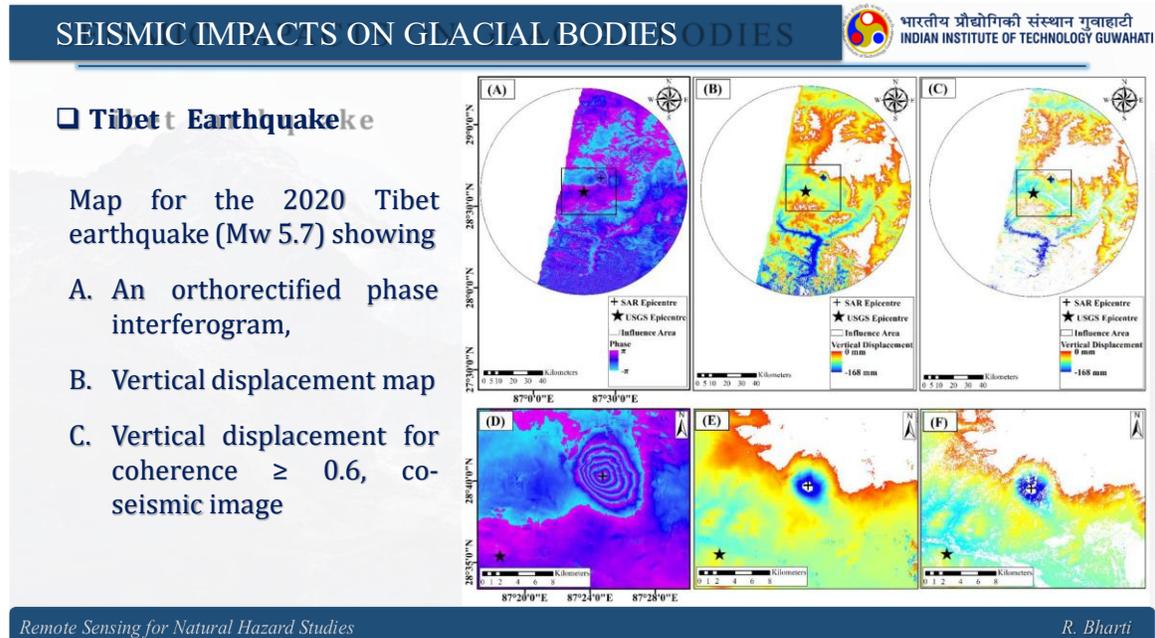
Then we have the example of the tropospheric delay and the ionospheric delay. So, you can see the false topography or deformation signal due to atmospheric disturbances, and here is the ionospheric effect on InSAR data that is given. Other sources of error include orbital errors, inaccurate satellite position, or altitude, which can introduce phase errors leading to misinterpretation of the surface displacement. Then, unwrapping error phase unwrapping, the process of converting wrapped phase to absolute displacement, can introduce discontinuities if coherence is low or gradients are steep. Instrumental noise, thermal noise, and sensor-specific instabilities can introduce random or systematic errors.

Processing artifacts, errors during image co-registration, filtering, or interpolation may affect phase reliability. Now, let us try to understand the seismic impacts on glacial bodies and how we can study them using remote sensing. So, the analysis of glacial deformation caused by earthquake activities. So, here you can see the world map illustrating major tectonic plates and their boundaries, and here you can see the different earthquakes that have occurred for this reason. So, it has a history of earthquakes.



So, this map shows the Himalayan glacier tectonic lineaments, Indian Eurasian plate boundaries, and selected earthquake epicenters. And the epicenter with a higher magnitude, which you can see is greater than 4, we have considered here. So, earthquakes are considered based on their closeness to the glacier-covered region here. So, if they are near the glacier's body, only then are they considered. So, the earthquake is considered to have a magnitude varying between 4.1 and 5.7 with various hypocenter depths. These

events are chosen to maximize the potential to observe the glacier's seismic response through remote sensing datasets.



So, when we had the 2020 Tibet earthquake. Here, the 2020 Tibet earthquake of magnitude 5.7, having a hypocenter depth of 10 kilometers, is used for analysis.

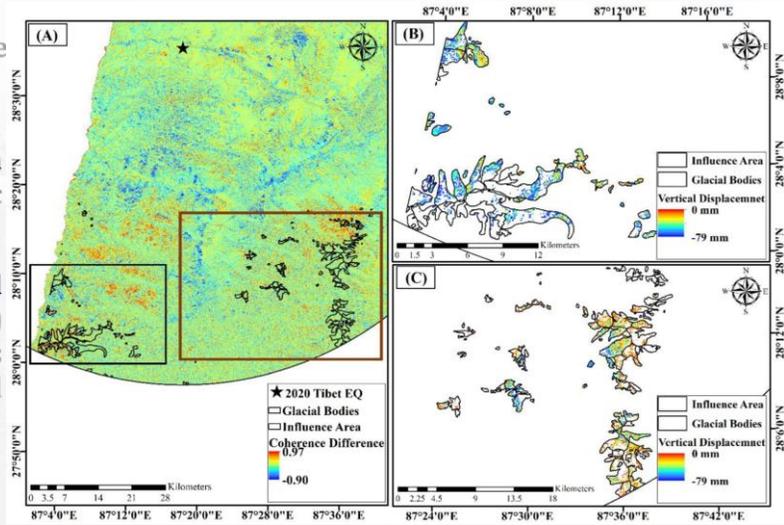
The DInSAR-derived vertical displacement ranged from 0 to minus 168 millimeters, indicating surface subsidence. So, the minus will be subsidence. Glacier bodies near the epicenter showed a mean displacement of minus 38.9 millimeters, and vertical displacement ranged from 0 to minus 79. So, subsidence was more prominent here. Earthquake-induced surface changes varied with terrain type and proximity to the epicenter, with reduced coherence near glacier moraines and lacustrine areas, while changes in peripheral glacial bodies remained moderate. So, that is based on the analysis of the microwave dataset.

So, here you can see the map for the ‘2020 Tibet earthquake of magnitude 5.7; the epicenters have also been considered. So, this is from the SAR, and this is from the USGS, and here the vertical displacement is given; the influence area is marked with this boundary. And you can see the vertical displacement, which is between 0 and -168; here it is 0 to -168 again.

□ Tibet Earthquake

(A) Difference between pre- and co-seismic coherence,

(B, C) The vertical displacement (mm) within glacial bodies derived from unwrapped phase interferogram



So here, this A represents the difference between pre- and co-seismic coherence, and here you can see the coherence difference is between minus 0.9 and 0.97. B and C, the vertical displacements are given, which are for the glacial body. So here you can see the range. So, we have seen the example of glacial bodies and how they behave during an earthquake for a particular event, and how remote sensing datasets are used to estimate their vertical or horizontal displacement. So, when we talk about the glacial lake and how it behaves, we will try to understand that here. So, the glacial lakes are especially vulnerable due to their high altitude, sediment-laden surroundings, and potential for seismic-induced liquefaction.

Earthquakes in the Himalayas can trigger secondary hazards such as landslides, glacial lake outbursts, floods, and moraine dam breaches. So, here you can see the glacial lakes if they are on the verge of bursting, and at that time, if you have a tremor. Then that will lead to the subsequent hazards. These hazards pose a significant risk to downstream settlements and infrastructure. So, the earthquake can destabilize moraines and the surrounding slope, potentially triggering a lake outburst.

Here, we have understood these processes; this is calving, and because of this calving, when it falls, there will be overtop, and because of that, you will have a GLOF kind of situation downstream. So, surface shaking reduces shear strength, especially in the fine-grained lacustrine sediments. Because of that, you will have more vulnerability toward the GLOF landslides, which can fall into the lake, creating displacement waves and overtopping and breaching natural dams. So, these are the natural glacial lakes. The actual impact varies depending on local topography, lake volume, and seismic intensity.

The role of remote sensing for hazard assessment, particularly synthetic aperture radar.

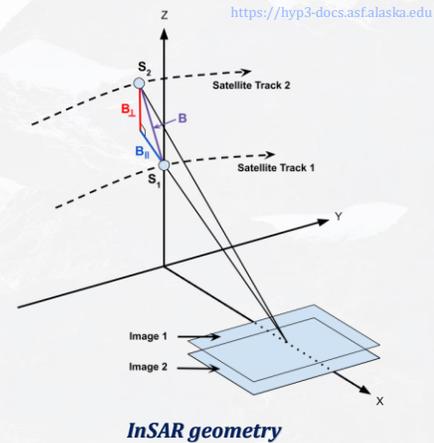
□ Interferometric Synthetic Aperture Radar (InSAR)

- An interferogram is generated by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second (Bamler & Hartl, 1998).

- The interferogram can be formed as,

$$\begin{aligned} z_1 \cdot z_2^* &= r_1 e^{i\phi_1} \cdot r_2 e^{-i\phi_2} \\ &= r_1 \cdot r_2 \cdot e^{i(\phi_1 - \phi_2)} \end{aligned}$$

- Here, $(\phi_1 - \phi_2) = \text{Interferometric Phase}$
 $(r_1 \cdot r_2) = \text{Interferometric Coherence}$



Interferometric SAR is a powerful tool to detect ground deformation post-earthquakes. In such situations, InSAR can identify centimeter to millimeter scale surface shifts using phase differences in SAR image pairs. Because we are talking about the InSAR interferometric SAR, two images are captured from two different locations. Optical sensors like Landsat 8 help to monitor changes in surface moisture via indices such as TDLI that can be used to identify how a particular area is behaving when a seismic event occurs. So, remote sensing offers timely, repeatable, and scalable hazard monitoring in harsh terrain that we have understood.

SEISMIC IMPACTS ON GLACIAL BODIES

□ Temporal Difference Liquefaction Index (TDLI)

- The TDLI is defined as:

$$TDLI = \frac{SWIR_{pre} - SWIR_{post}}{SWIR_{pre} + SWIR_{post}}$$

- Positive TDLI values indicate an increase in soil moisture, suggesting potential liquefaction or cyclic mobility near glacial lake margins.
- Negative values represent drying or reduced moisture, typically implying lower seismic-induced instability.
- Combined with coherence analysis from SAR data, TDLI enhances the reliability of seismic impact assessments around glacial lakes.

So, the temporal difference liquefaction index (TDLI) is very, very important here. The temporal difference liquefaction index is designed to assess earthquake-induced changes in soil moisture using satellite data. So, utilizing the SWIR band, which is between 2.11 and 2.29 micrometers, is effective in detecting variations in soil moisture.

The TDLI is calculated using pre- and post-earthquake reflectance values to identify possible liquefaction-prone zones. This method enables large-scale non-invasive assessment of seismic impacts on terrain stability in high-risk glacier and sedimentary regions. So, without reaching that location, you can have such an analysis that will provide you with more information about the vulnerability of that area to earthquakes. Temporal difference liquefaction (TDLI) can be defined as this, where we are using the SWIR wavelength region. So, the positive TDLI value indicates an increase in soil moisture, suggesting potential liquefaction or cyclic mobility near glacial lake margins.

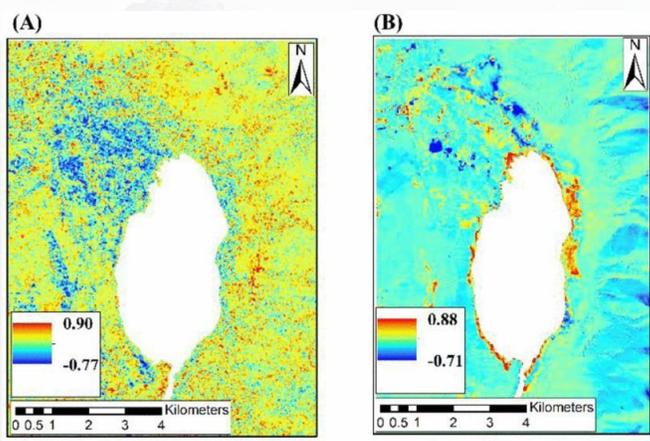
Negative value represents drying or reduced moisture, typically implying lower seismic-induced instability. Combined with coherence analysis from SAR data, TDLI enhances the reliability of seismic impact assessments around glacial lakes.

SEISMIC IMPACTS ON GLACIAL BODIES

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Case Example - 5.7 M_w Tibet Earthquake, 2020

(A) (B)



- Combined with coherence analysis from SAR data, TDLI enhances the reliability of seismic impact assessments around glacial lakes.

Maps showing (a) pre- and co-seismic coherence difference, and (b) TDLI

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For example, the 5.7 magnitude earthquake in Tibet that occurred in 2020. So, we have used the interferometric SAR and then identified how vulnerable this area is to the impact of seismicity.

So, this is one example from the Tibet earthquake that occurred in 2020. So, here we have combined this SAR data with the TDLI. To identify the seismic impact on the glacial lakes. So, combining these two will enhance reliability. So, here is the map showing pre- and co-seismic coherence differences and TDLI values.

This is another example from the Gorkha Earthquake of 2015. So, here you can see that over 4,300 co-seismic and post-seismic landslides were recorded, but no major GLOFs were observed. The spatial distribution of landslides closely correlated with slope peak ground acceleration and geologic structure, and here you can see the locations marked are Kathmandu and Gorkha, and here you can see the magnitude is 7.3; here it is 7.8. Remote sensing played a key role in rapidly mapping the affected region and assessing the risk evaluation.

So, long-term monitoring and risk reduction. So, continuous satellite monitoring enables the detection of evolving risk in glacier regions, and we all know how important it is to monitor the glaciers and the snow areas. Integration of SAR, optical, and DEM data allows for multi-hazard assessment. Post-earthquake. Early warning systems for GLOF rely heavily on near-real-time remote sensing updates because we are trying to bring all the real-time data sets together so that our model will be more accurate and will predict near-future hazards. Regional hazard zonation supports planning and emergency preparedness in vulnerable areas. Seismicity particularly poses a multifaceted threat to glacial lakes through direct shaking and cascading hazards. Remote sensing technologies have revolutionized how we detect, monitor, and assess such impacts. Case studies from Nepal and Tibet demonstrate the potential and challenges of satellite-based hazard analysis. Continued research and technology integration are vital for mitigating future disasters in the Himalayan region. These are some of the references that we have used in this lecture. So, if you are interested, you can refer to these papers; you will find more details about the impact of seismicity on glacier bodies or glacier lakes and how remote sensing, particularly the microwave remote sensing datasets, is used to assess the impacts.

Thank you very much.