SUSTAINABLE MINING AND GEOINFORMATION

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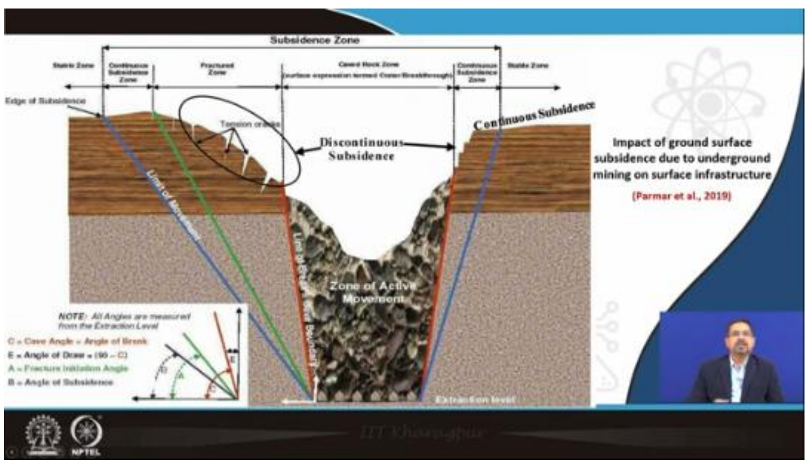
Week – 04

Lecture 16: Subsidence Detection

Thank you. Welcome, welcome to the lecture on Subsidence Detection. This is the first lecture of the fourth week. So, let us understand the concept in terms of subsidence as far as the mining sector is concerned and how much geoinformation benefits in terms of studies, assessment, and estimation as far as mining subsidence is concerned. So, remote sensing techniques, along with geoinformation, help in detecting ground subsidence, and in this lecture, we will discuss in detail the SAR interferometry, the data, techniques, methods, etc.

Monitoring subsidence due to underground mining and its impact on many other factors, such as infrastructure, surroundings, and even safety, is very important. So, that is why monitoring subsidence is very, very important. SAR interferometry techniques assist in understanding subsidence-related issues, such as water table changes and structural hazards, thereby enabling better mitigation strategies. So, we will understand what the different factors are that trigger subsidence and how they can be related or correlated, such as water table changes. or any changes as far as the structure or structural deformation or subsidence is concerned. We will also discuss integrating satellite data with ground-based observations, which helps improve reliability and thereby extends applications to diverse environmental assessments.

We will also take two case studies that use the integration of satellite and other observations, as well as another one in terms of SAR interferometry-based study for subsidence detection in two coal mining regions. So, let us understand the concept of subsidence and how a subsidence zone can form. Just have a look at this particular picture where the subsidence zone has been shown, along with the continuous subsidence zone, fracture zone, and the caved rock zone, which is the surface expression termed in terms of the crater or the breakthroughs. So, in the middle or the center of the picture or the diagram, the caved rock zone has been shown, which is the zone of active movement. Bordering this particular zone, the zone of active movement, red lines on both sides have been plotted, which is the line of break that is the boundary. And bordering these two, we have the line of movement, which is shown in terms of the blue lines. So, on either side, you can see the tension cracks, and on the lower left, in terms of C, E, A, and B, the cave angle.

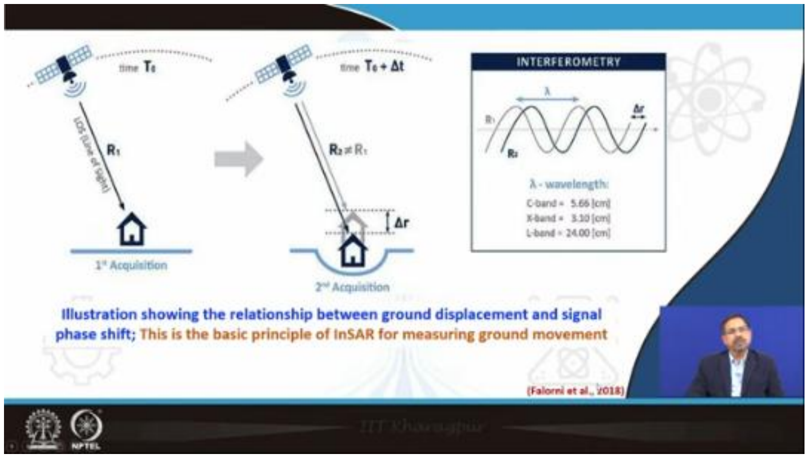


The angle of draw, the fracture initiation angle, and the angle of subsidence have been mentioned. So, this depiction has been taken from a study by Parmar et al., published in 2019. which talks about the impact of ground surface subsidence due to underground mining on surface infrastructure. So, we have already discussed in our second-week lectures about the SAR and also the interferometric SAR, that is, synthetic aperture radar, or in short, it is called INSAR. So, what is INSAR, and what is its utility as far as subsidence study or subsidence monitoring is concerned?

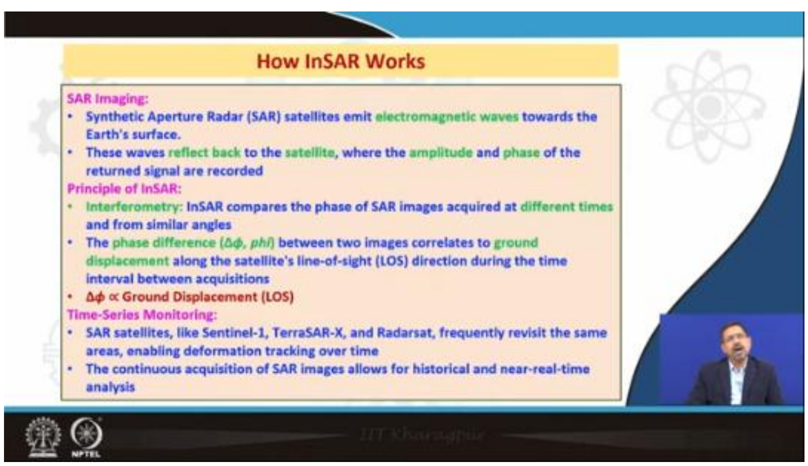
So, underground mining methods create subsurface voids, as we have seen from the previous picture. So, when activities, particularly underground mining activities, happen, they create a void or a vacuum because the ore or the mineral has been taken out. So, this subsurface void often leads to ground surface subsidence because there is a void. So, historically, subsurface or this subsidence mapping relied on numerical modeling techniques with limited spatial and temporal data. That is why the accuracy and also the usability are either restricted or, to a certain extent, compromised.

So, this SAR, along with the differential INSAR, So, INSAR and the differential INSAR, these are specialized remote sensing techniques that exploit phase information from the radar or the microwave images. which are captured at different times. So, the phase information is exploited that is captured using a slight time difference or time gap so that the ground deformation can be monitored, including the subsidence. So, deformation study helps in monitoring the ground subsidence. So, the working principle: SAR systems onboard satellites or aircraft send microwave or radar pulses to the Earth's surface. So, these phase differences between images are captured at different times, as we just mentioned.

Those reveal the deformation pattern, which we can measure in terms of the quantity of the subsidence at any particular mining site. Look at this illustration that shows the relationship between ground displacement and signal phase shift. On the right-hand side, the upper right-hand side, you can see the principle of interferometry. This is in terms of the bandwidth or the wavelength. Particularly, CXL is also mentioned in terms of centimeters, averaging 5.66. X-band is 3.1. Whereas L-band gives up to 24 centimeters. So, the phase and the difference in the phase are shown, which is the principle as far as interferometry is concerned. On the left-hand side, the time factor has also been mentioned in terms of t0, and the change in time is mentioned in terms of delta t.



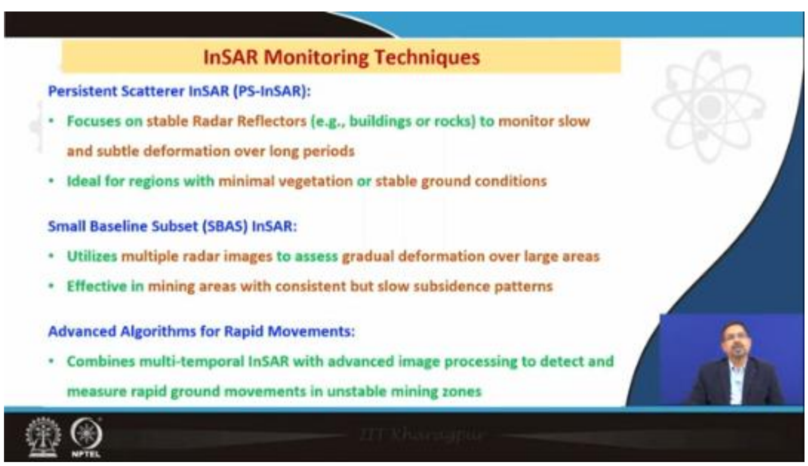
The first acquisition, as the line of sight, you can see a house. The right and the middle one show the deformation, which is a kind of deformation in terms of the object, the height, or the elevation. So, that is shown in terms of delta r. You can see two different signals, which go from the target and depict the signal phase shift. So, using the SAR interferometry principle, we can very well capture this deformation in terms of the signal phase shift. How InSAR works: the SAR imaging principles of InSAR and the time series monitoring. As far as SAR imaging is concerned, we already know that the SAR satellites emit EMR (electromagnetic radio radiations) or electromagnetic waves toward the Earth's surface. These waves, when radiated back in terms of backscatter to the satellite, record the amplitude and the phase of the return signal.



What is the principle of InSAR? Interferometry SAR (InSAR) compares the phase of SAR images acquired at two different times. You have a time delay or time difference from the same target with similar angles. This phase difference, which we can call Delta Phi between two images, So, this difference or delta Phi correlates to ground displacement, what is present on the ground in terms of the object, the displacement, or the deformation. This, along with the satellite's line of sight (sometimes abbreviated as LOS direction), occurs during the time interval between the two acquisitions. So, delta Phi is directly proportional to the ground displacement, which we sometimes also mention as LOS. So, what is time series monitoring?

Time series monitoring is such as like here we are using SAR satellite data synthetic aperture data or which is coming from Sentinel-1 or TerraSAR X-band or RadarSat. These satellites are the data coming from these satellites which frequently visit the same area enables us to track any kind of deformation, any kind of change in terms of elevation or the height over time. So, the continuous accusation of SAR images allows for historical and near real time analysis.

So, this is actually the beauty of the time series analysis. So, continuously if we acquire this SAR data that helps us in near real time analysis as well as a long term or a historical analysis in terms of the displacement or you can relate it to the deformation. So, INSAR monitoring techniques we can also divide into these three as far as PS-INSAR or SBAS and the advanced algorithm are concerned. So, the first one PS stands for persistent scatterer interferometric SAR. This monitoring technique focuses on stable radar reflectors such as mounted over building or rocks that allows monitoring slow and stable deformations over long periods.



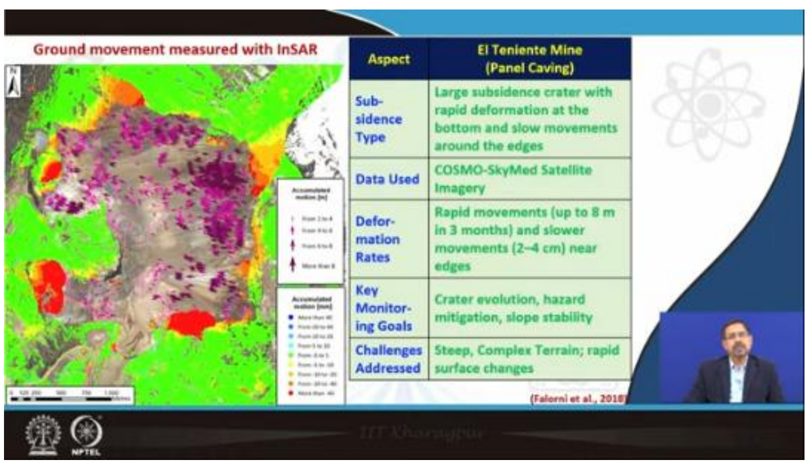
So this is this kind of persistent scattering in terms of INSAR persistent scatterer INSAR helps or provides ideal platform for regions with minimum vegetation or stable ground conditions. Let us move to the next one as far as the insert based monitoring technique is concerned is small baseline subset or we say SBAS insert monitoring. So this SBAS monitoring helps or I say utilizes multiple radar images to assess gradual deformation over larger areas so this is very effective as far as the mining areas with consistent but slow subsidence pattern is concerned so that we can calculate the rate of subsidence which is which otherwise goes undetected as far as the very slow level of subsidence so this small baseline subset is useful in that And the third one is the advanced algorithm for rapid movements.

This algorithm combines multi-temporal insert with advanced image processing such as machine learning or artificial intelligence. Detect and measure rapid growth movements in unstable mining zones. So, in a sense, the rivers are complementary to SBAS. In SBS, we monitor slow subsidence, but here, this advanced algorithm helps to detect and measure rapid ground movement in unstable mining zones. These three monitoring techniques, as far as the SAR interferometry is concerned, is used for subsidence or deformation monitoring. So, as far as the applications in mining operations are concerned, we can study them in terms of regular operational planning, hazard assessment, environmental and socio-economic impact analysis, and complementing other existing traditional methods. So, as far as operational planning is concerned, SAR interferometry generates, or the InSAR-generated subsidence maps help in guiding mine planning to identify areas with different risk levels—high risk, low risk, and so on.

And that is how it informs different mitigation measures or mitigation strategies as far as regular operational planning is concerned. The hazard assessment—yes, in terms of hazard assessment, we need early detection so that we can plan any kind of early detection if possible, as far as the subsidence or the deformation is concerned. It helps in preventing or developing safety measures that will prevent accidents. So, hazard assessment detects—

the InSAR-based method helps in detecting pre-collapse deformation patterns in block caving and longwall mining setups so that you can plan if it is detected early or in advance. This kind of deformation, then, allows us to plan early and take appropriate measures to arrest such collapses. Then, coming to the third one, as far as the environmental and socio-economic impact analysis Here, it tracks subsidence-related environmental damage such as water table changes, sinkholes, etc.

Thereby, it assesses the impact on nearby communities, infrastructure, and the ecosystem as a whole. All these three complement traditional methods. So, if these are integrated with ground-based surveying systems such as GNSS and extensometers, this will enhance data reliability and also improve resolution as far as spatial and temporal aspects are concerned. Now, The picture or the image on the left-hand side demonstrates the ground movement, which is measured using such techniques as far as InSAR image or SAR interferometry is concerned. And here, the accumulated motion has been shown in terms of millimeters, and the upper arrow kind of things which go from 1 to 4, 4 to 6, 6 to 8, and more than 8 millimeters, whereas the Accumulated motion, in terms of millimeters, is shown from more than 40 millimeters to up to minus 40.

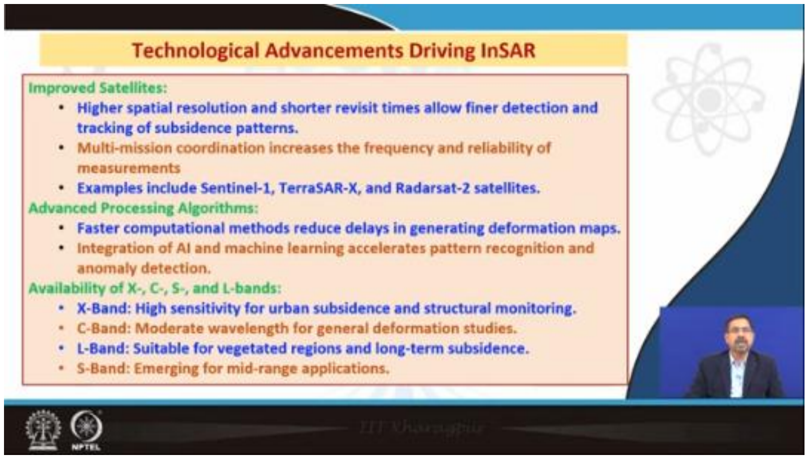


So, plus or minus 40 millimeter kind of accumulation motion can be studied or could be measured. This particular study has been done by Falorni et al published in 2018. So, what they did the subs the subs of the subsidence type particularly large subsidence crater with rapid deformation at bottom and slow movement around the edges could be detected. The data used this Falroni et al they have used the COSMO SkyMed satellite imagery and study the deformation rates.

So, rapid moment up to 8 meter in 3 months could be observed and slower moment up to 2 to 4 centimeter near the edges could be detected. So, this is what actually we need in terms of the deformation or in terms of the subsidence. So, at the edges if we can see the slow moment to the tune of 2 to 4 centimeter whereas the rapid moment over 3 months period goes up to 8 meter. So, 2 to 4 centimeter to 8 meter in the edges and the rapid moment dimension. This itself helps us in understanding the subsidence pattern which comes from the deforestation rates.

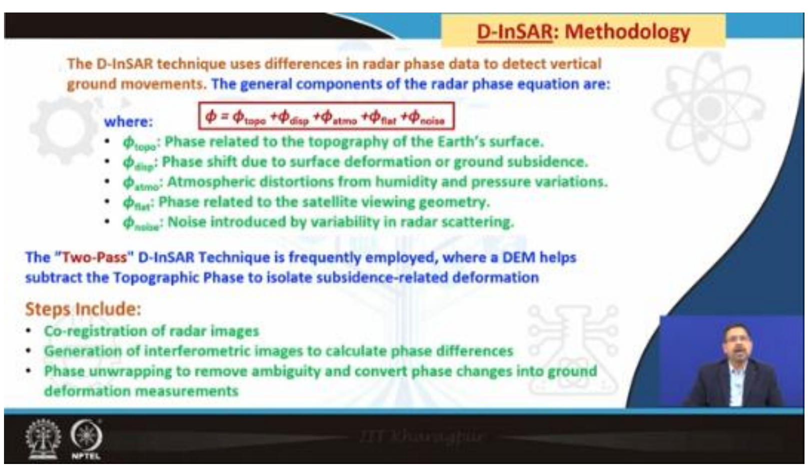
So the key monitoring goals, the evolution of the craters, the hazard mitigation, slope stability, these are the activities which can be very well catered or addressed using the INSAR based studies. So the challenges there are these in survey studies are also associated with some challenges such as it has limitation as far as very steep slope is concerned, very complex terrain is concerned and rapid extremely rapid surface change is concerned. So, we are also we need to understand this and know that yes there is the availability of this technology along with modeling and very precise integration of other data which is coming from the ground can help us in monitoring the deformation rate. which can be as low as 2 to 4 cm near edges, which can be as high as up to 8 m in 3 months. So, you can say close to 3 m in 3 months in terms of rapid moment.

And now let us see the technological advancements that drive SAR interferometry. We have improvements in the satellites, advanced processing algorithms, and also the availability of all these datasets in terms of the low to higher wavelength X, C, and L bands. So, we have improved satellites, particularly higher spatial resolution with shorter revisit time, allowing for finer detection and tracking of subsidence patterns. Multiple mission coordination increases the frequency and reliability of measurements. Examples include Sentinel-1A, 1B, and TerraSAR-X, which provide X-band data, while the radar set gives us C-band data. So, we have all these datasets available, and they can be well integrated using data processing algorithms. These advanced processing algorithms help in computing. So, faster computational methods and faster computing help reduce the delay in generating deformation maps.



So, if you have good computational tools and algorithms, we can process the data quickly and produce deformation maps in a very short time period—near real-time scale. So, the integration of AI and machine learning accelerates pattern recognition and anomaly detection. So, these kinds of advanced processing algorithms are used to automate subsidence level detection as soon as the data is captured by the sensor. You pass it through the algorithm, and you get the subsidence. And availability—as you know—all the different data, particularly SAR data, is available at different wavelengths. So, you can capture different activities that have different levels in terms of high to low, moderate, and different suitability.

Now, let us move to differential InSAR. So, having understood the applications of InSAR interferometry as far as subsidence level is concerned, let us move to the differential aspect. So, the differential InSAR technique uses differences in radar phase data to detect vertical ground movement. It uses the differences in the radar phase data. So, general components of the radar phase equations could be these five φ's (1, 2, 3, 4, 5).



$$\phi = \phi_{topo} + \phi_{disp} + \phi_{atmo} + \phi_{flat} + \phi_{noise}$$

where**:**

ϕ_{topo}: Phase related to the topography of the Earth's surface.

ϕ_{disp}: Phase shift due to surface deformation or ground subsidence.

ϕ_{atmo}: Atmospheric distortions from humidity and pressure variations.

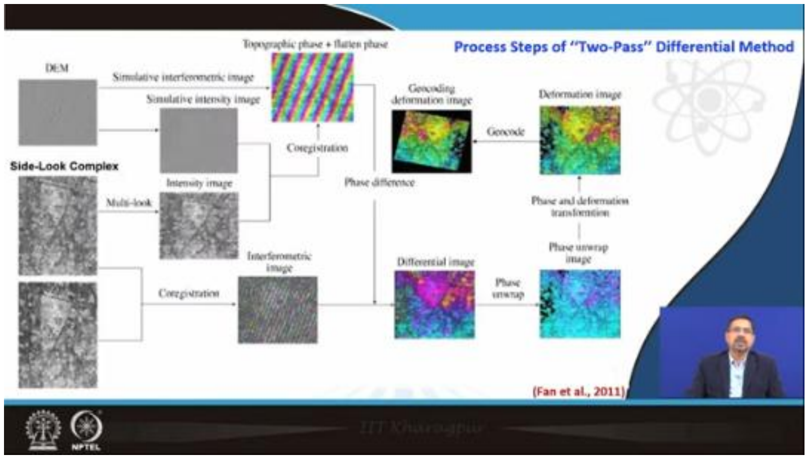
ϕ_{flat}: Phase related to the satellite viewing geometry.

ϕ_{noise}: Noise introduced by variability in radar scattering.

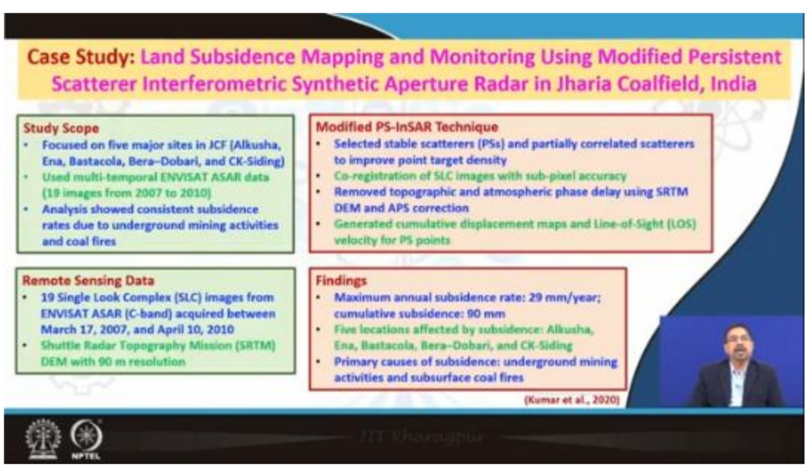
So, the first phase, related to the phi topo, indicates the attributes of the phase related to the topography of the Earth's surface. The phi displacement indicates the phase shift due to surface deformation or ground subsidence. The phi atmosphere is related to atmospheric distortions from humidity and pressure variations. And phi flat is related to the phase, the phase related to the satellite viewing geometry. And the fifth one, phi noise, indicates the noise introduced by variability in the radar scattering.

So, all these components of the radar phase equation go as phi, which is equal to the summation of all these five attributes, as far as the change, subsidence, variation, and variability are concerned. Now, the two-pass differential interferometry technique is also being used frequently, where a DEM helps subtract—sorry—subtract the topographic phase to isolate subsidence-related deformation. Subtract the topographic phase to isolate subsidence-related deformation. So, if you have two different layers, this kind of two-pass differential interferometry is very useful because you have a DEM that helps in subtracting the topographic phase to isolate the subsidence related to deformation. So, the steps in terms of two-pass differential SAR interferometry are: first, co-register the SAR data and generate the interferometric images to calculate the phase difference.

Then, phase unwrapping is done to remove ambiguity, thereby converting the phase changes into ground deformation measurements. So, here the process of the two-pass differential SAR interferometry method is shown. On the left-hand side, you can see the DEM, and then you have an SLC, which you call single-look complex images. So, which is coming from the multi-look, and you go for a registration so that both of them match each other—core registration in terms of the location and the particular pixel—so finally, you generate the interferometric images.



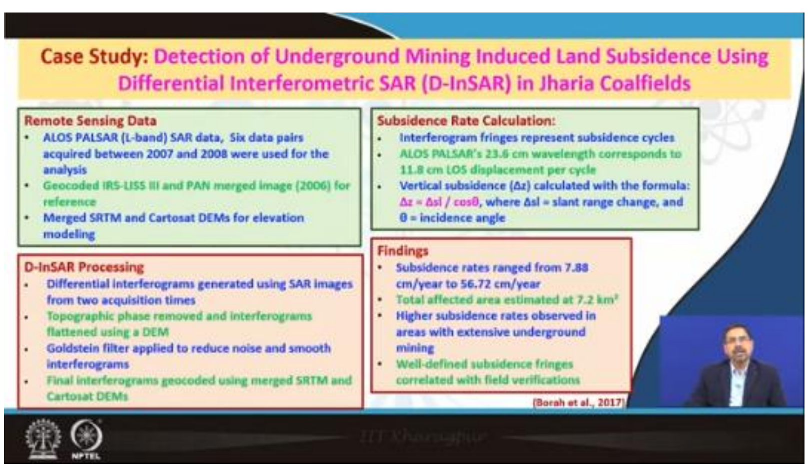
and based on the topography phase and ah phase unwrapping technique you come out with phase difference method you come out with a differential image then you go with a phase unwrapping approach so that the phase unwrap images is generated and finally the phase the deformation transformation image is generated which gives you the deformation in terms of variation as far as the millimeter or centimeter level unit is concerned. So, the advantage of differential INSAR is it gives high density of measurement points frequent visits with satellite data archives non-intrusive monitoring no need for ground instrumentation it is very very sensitive so sensitivity level goes up to millimeter in contrast to centimeter as we discussed in terms of SAR interferometry and the cost it is it reduces the cost because reduces dependency on the ground based observation so there thereby it saves the energy and the manpower resources Now let us have a look at the two case studies the first one given by Kumar et al in 2020 it is on the land subsidence mapping and monitoring using modified persistent scatter interferometric SAR and this first study has been done in Jharia coal field mine.



So, the scope is focused on five major sites and used multi-temporal ENVSAT ASAR data. Nineteen images have been picked from 2007 to 2010 and the analysis was done that showed consistent subsidence rates due to underground mining activities and coal fire. So, the remote sensing data, side looking complex images, SLC data from ENVSAT, which is a C band microwave radar from ERS, from European Space Agency, ESA, acquired between March 2007 to 2010. And SRTM, DEM was used, which was available at 90 meter resolution. Then the technique as far as the technique is concerned the modified PS interferometry SAR technique was used.

This was selected to as far as stable scatter and partially correlated scatters are concerned to improve point target density. Then co-registration of this SLC images was done using sub means was done and up to sub pixel level accuracy within pixel and the any kind of topographic and atmospheric phase delay was removed using the SRTM-DEM and some kind of APS correction was done. This allowed generation of cumulative displacement maps and the line of sight velocity for the PS points that helps in giving you the subsidence level. So, the findings maximum annual subsidence rate was found to be 29 millimeter per year cumulative subsidence was up to 90 millimeter. So, 5 locations affected by this was found.

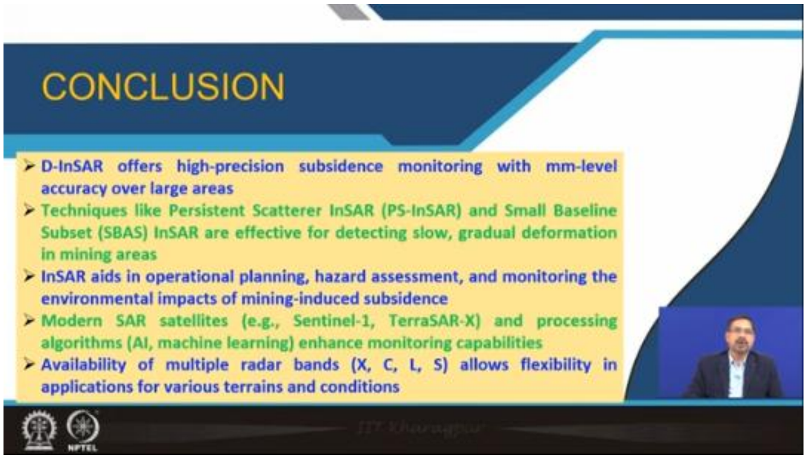
The primary causes were also attributed to underground mining. Here is another study on the same Jharia coal field mine, published by Bora et al. in 2017, that detected underground mining-induced land subsidence using differential SAR interferometry. So, here instead, ALOS-PALSAR L-band data was used—6 pairs—and this study was also conducted during 2007 to 2008. And the geocoded IRS-LISS 3 and the PAN data of 2006 were merged to that. So, you got a merged SRTM and Cartosat-DEM for elevation modeling.



And this is as far as the differential interferometry data processing is concerned. This was generated using SAR images from two acquisition times; the topographic phase was removed, and interferograms were flattened using a DEM. So, a Goldstein filter was applied to reduce noise and any kind of smoothing as far as the interferograms are concerned. So, final interferograms were geocoded using merged SRTM and Cartosat DEMs was generated. So, now based on this, the subsidence rate was calculated.

So, interferogram fringes represent subsidence cycles. ALOS-PALSAR 23.6-centimeter wavelength corresponds to 11.8-centimeter LOS displacement per cycle—that was the finding. And the vertical subsidence delta z was calculated using the formula: delta z is equal to delta SL upon cos theta, where delta sl is the slant range change and theta is the incident angle. So, the four important findings of this study: subsidence rates range from 7.88 centimeters per year to 56.72 centimeters per year. So, the total affected area was estimated at 7.2 square kilometers.

Whereas, higher subsidence rates are observed in areas with extensive ground mining. So, this study well defines the subsidence fringes correlated with the field verifications. So, these 6 references are utilized for this study. And now coming to the conclusions. The conclusions: the differential SAR interferometry offers high-precision subsidence monitoring up to the millimeter level.



The techniques, persistent scatterer (PS-InSAR) and SBAS (small baseline subset InSAR), are effective for detecting slow, gradual deformation as far as mining edges are concerned. InSAR or SAR interferometry aids in operational planning, and modern SAR satellites combine different datasets using AI and machine learning to enhance monitoring capabilities. So, the availability of all these datasets from SAR platforms enables us in terms of subsidence studies, or you can say, on a real-time basis with maximum accuracy—the accuracy level goes up to the millimeter. Thank you very much.