SUSTAINABLE MINING AND GEOINFORMATION

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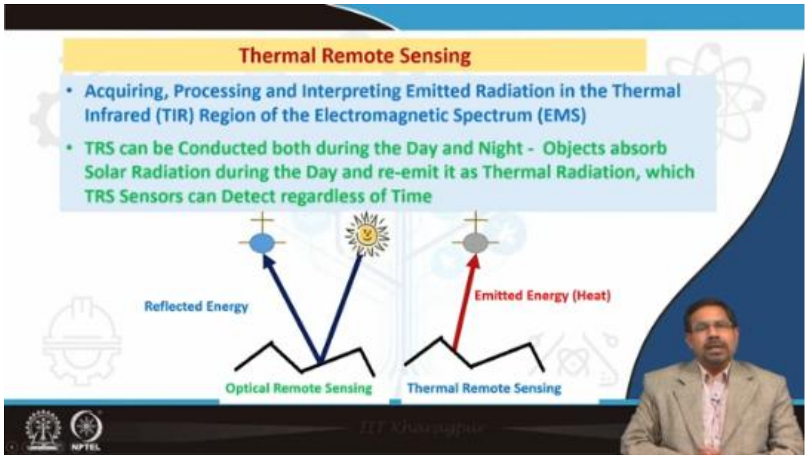
Week – 01

Lecture 05: Thermal/Column Concentration

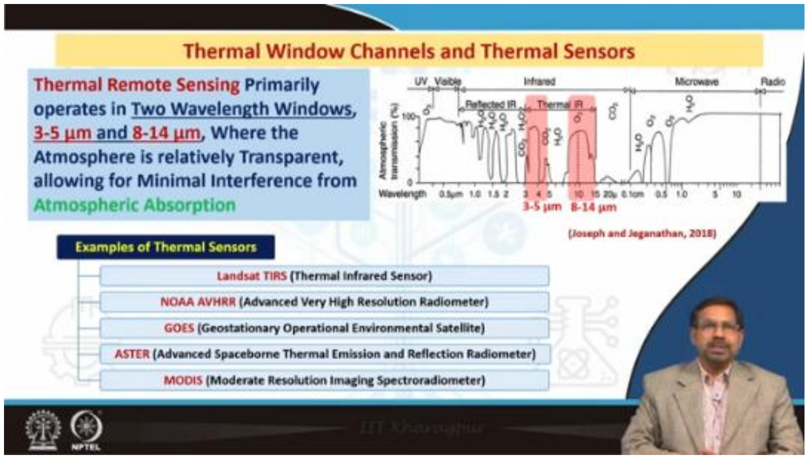
Welcome to the fifth lecture on thermal remote sensing. As we discussed in the first class, when we talk about thermal remote sensing, that means there is variation in terms of temperature. So that means we are going to measure the differences in terms of heat, moisture, or water content. So, let us see in terms of the concepts what we are going to cover; they fundamentally could be these three. One is we will discuss the principles of thermal infrared remote sensing and heat detection.

Then, we will also discuss the applications of detecting heat anomalies in mining operations, for example, spontaneous combustion in coal mines, and we will talk about the principles of column concentration, such as its utility in monitoring gas emissions from mines, for example, the detection of methane and other gases. On the right-hand side, I have put two black and white images. Those are taken from thermal sensors, and here you can very well see that the one which has a brighter tone is for higher temperature, and the one which has a darker tone is for lower temperature. So, these images are taken from the thermal infrared sensors. Let us understand the principles of thermal remote sensing.



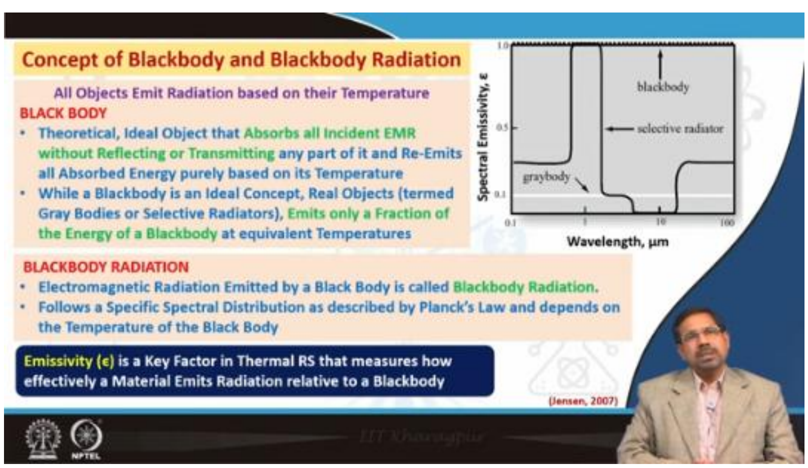
Thermal remote sensing involves acquiring, processing, and interpreting emitted radiation in the thermal infrared, which is abbreviated as TIR, the thermal infrared region of the electromagnetic spectrum. So, thermal remote sensing can be conducted both during the day and night. In fact, we are going to discuss that conducting thermal remote sensing at night has several advantages. So, objects absorb solar radiation during the day and re-emit it as thermal radiation, which the thermal remote sensing sensors can detect regardless of time. So, we have brought here two depictions: one is the reflected energy, and another is the emitted energy, to counter or to bring out the contrast between the optical and the thermal remote sensing.

As we know, in optical remote sensing, the reflectance is the rule; here, in thermal remote sensing, the emission or emissivity is the rule. So, with this, let us understand the window which is available to us for thermal remote sensing. So, thermal remote sensing primarily operates in two wavelength windows: at the region of 3 to 5 micrometers and at the region of 8 to 14 micrometers. So, that means within the infrared region. So, the atmosphere is relatively transparent, allowing for minimal interference from atmospheric absorption in these two windows.



So, basically, thermal remote sensing is done during or at these two wavelength windows: between 3 to 5 micrometers and 8 to 14 micrometers. On the upper right-hand side, we can see the absorption, the atmospheric transmission depicted in terms of percentage, and we have shown the range of the windows corresponding to thermal remote sensing at 3 to 5 and 8 to 14 micrometers. Some of the examples, as far as the thermal sensors are available, could be the Landsat TIRS thermal imaging remote sensing or thermal infrared sensors. Then we also have NOAA AVHRR. And also GOES, which stands for Geostationary Operational Environmental Satellite.

The ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer. And also, the MODIS has thermal sensors. We have many more also in the list. So, let us understand what a blackbody is and what blackbody radiation is. So, this understanding of blackbody and blackbody radiation is a must as far as the concept of thermal remote sensing goes.



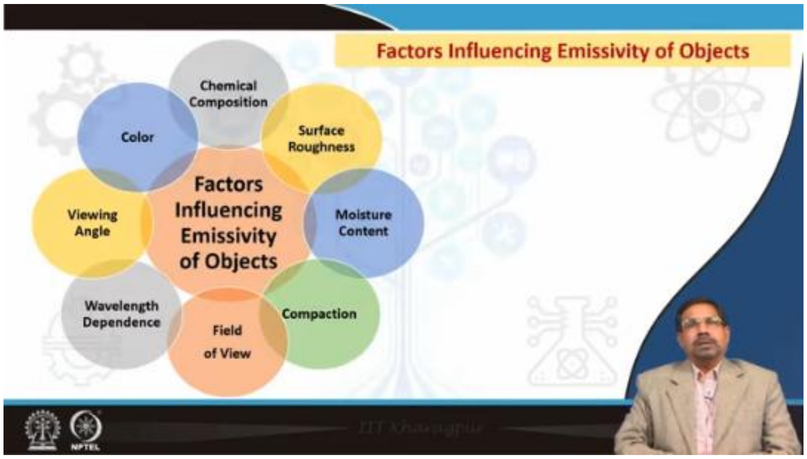
So, all objects, what happens? All objects emit radiation based on temperature. So, a blackbody is particularly a theoretical or, you could say, an ideal object that has the potential to absorb all the incident energy falling on it without reflecting or transmitting any part of it or any kind of re-emission. So that means all the absorbed energy is purely based on its temperature. So that means a blackbody is particularly a theoretical or an ideal object that absorbs all the incident energy falling on it without any reflection or transmission.

So, what happens is, while a black body is an ideal concept, real objects are termed as gray bodies, which we usually call selective radiators, those emit only a fraction of the energy of a black body at equivalent temperature. So, we really do not get the theoretical or ideal black bodies. So, that is why we take the real objects which are equivalent to that, having a small fraction of the energy of a black body at temperature equivalence. So now, what do we understand by radiation from a black body? So, the black body radiation can be understood as electromagnetic radiation emitted by a black body, which is called black body radiation.

It follows a specific spectral distribution as described by Planck's law. So, we are now going to understand two or three basic laws that govern thermal remote sensing. Or the black body radiation, and this depends on the temperature of the black body. So, let us also have a look at the definition of emissivity. Emissivity is a key factor in thermal remote sensing that measures how effectively a material emits radiation relative to a black body.

So, that is a key factor in thermal remote sensing. So, this is also shown in the upper right diagram where the y-axis shows the spectral emissivity as epsilon or E, and the x-axis is the wavelength. So, we can see the black body, the gray body, and the selective radiator, which are also shown there. So, I would again repeat the definition of emissivity, which is a key factor in thermal remote sensing that measures how effectively a material emits radiation relative to a black body. So, it is in relation to a black body.

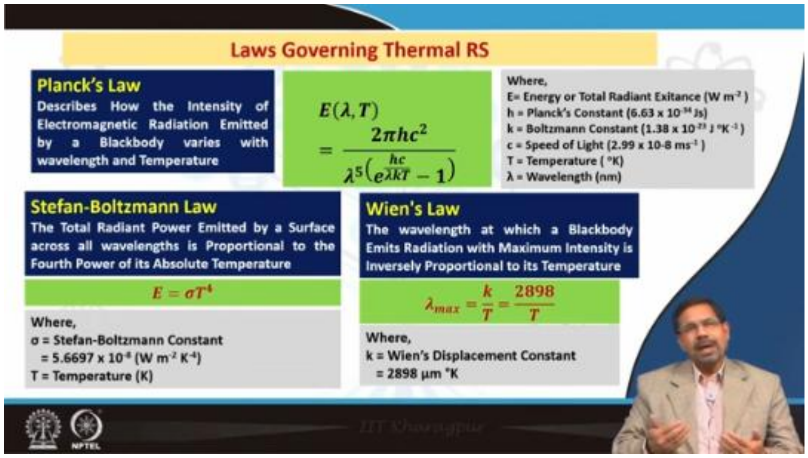
So, let us see the factors that influence the emissivity of objects. We have listed these eight factors that influence the emissivity of an object. So, the first is the chemical composition. So, different objects have different chemical compositions, and accordingly, their emissivity differs. And so does the roughness.



So, based on the roughness or the coarseness or smoothness of the surface, the emissivity also varies. Another, the third factor, is moisture content. If there is more moisture content, then the emissivity will be less, and vice versa. So, definitely, moisture content is also a very important influencing factor as far as emissivity is concerned. Then, how it is arranged, the compaction, whether it is loosely arranged or tightly arranged, so based on the compaction of the object, the emissivity also differs.

And the field of view from which angle the photography or the thermal remote sensing is happening, so that depends on the field of view, and it also influences the emissivity of objects. Now, the wavelength dependency. Yes, at which part of the electromagnetic spectrum the thermal remote sensing is happening, that also affects the emissivity of the object. And so also the viewing angle and the eighth factor, the last factor which is very important, is the color. What is the color, the external appearance, the physical appearance, or the phenological appearance of the object?

So, color also has an impact or has an influence on the emissivity of the objects. Now, let us recall some of the laws that govern thermal remote sensing. We all must have studied this in our physics classes. So, I have selected these three: Planck's law, Stefan-Boltzmann law, and Wien's law, or sometimes you call it Wien's displacement law. So, friends, Planck's law is very fundamental; it describes how the intensity of electromagnetic radiation emitted by a blackbody varies with wavelength and temperature.



So, look at the expression there,

$$E(\lambda, T) = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda kT}}-1\right)}$$

Where,

E = Energy or total radiant exitance (Wm^{-2})

h = Planck's constant (6.63×10^{-34} Js)

k = Boltzmann constant (1.38×10^{-23} JK^{-1})

c = Speed of light (2.99×10^{8} ms^{-1})

T = Temperature (K)

λ = Wavelength (µm)

Let us have a look at the second law that governs thermal remote sensing, which is the Stefan-Boltzmann law. So, many of us recall the Stefan-Boltzmann constant. So, the Stefan-Boltzmann law is defined as the total radiant power emitted by a surface across all wavelengths, which is proportional to the fourth power of its absolute temperature. The expression is this:

$$E = \sigma T^4$$

Where,

σ = Stefan-Boltzmann constant = 5.6697×10^{-8} (Wm^{-2} K^{-4})

T = Temperature (K)

Now let us look at Wien's displacement law. It is defined as the wavelength at which a blackbody emits radiation with maximum intensity, which is inversely proportional to its temperature. So, that means it is giving a relationship with the temperature.

$$\lambda_{max} = \frac{k}{T} = \frac{2898}{T}$$

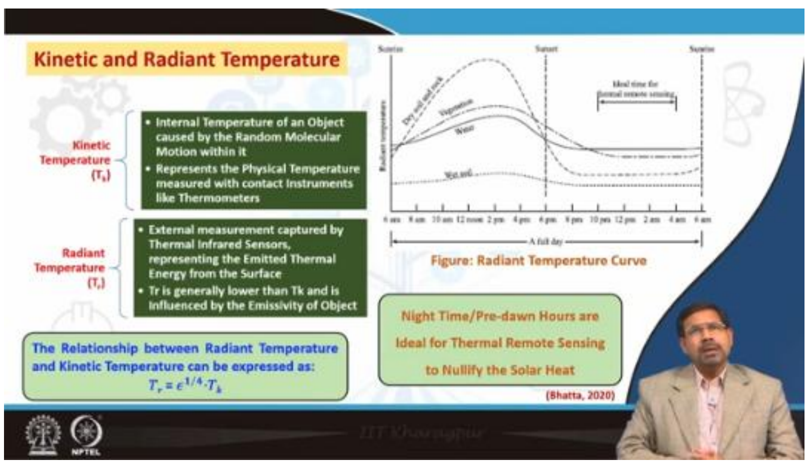
Where,

k = Wien's displacement constant = 2898 μm K

T = Temperature (K)

So, these are the three basic laws that govern or help us in understanding thermal remote sensing, the basics of thermal remote sensing.

Now let us also understand the kinetic and radiant temperature and the small difference between these two.



So, friends, the kinetic temperature is expressed as T_k, and the radiant temperature is expressed as T_r. So, what we understand, as far as the kinetic temperature is concerned, is that it is the internal temperature of an object caused by the random molecular motion within it. So, it represents the physical temperature measured with contact instruments like thermometers. In contrast, the other temperature, which is here as radiant temperature T_r, is the external measurement captured by thermal infrared sensors representing the emitted thermal energy from the surface. So, what happens is that T_r is generally lower than T_k and is influenced by the emissivity of objects.

Now, there is a relationship between the radiant temperature and the kinetic temperature, which is expressed as below.

$$T_r = \epsilon^{1/4} \cdot T_k$$

Where,

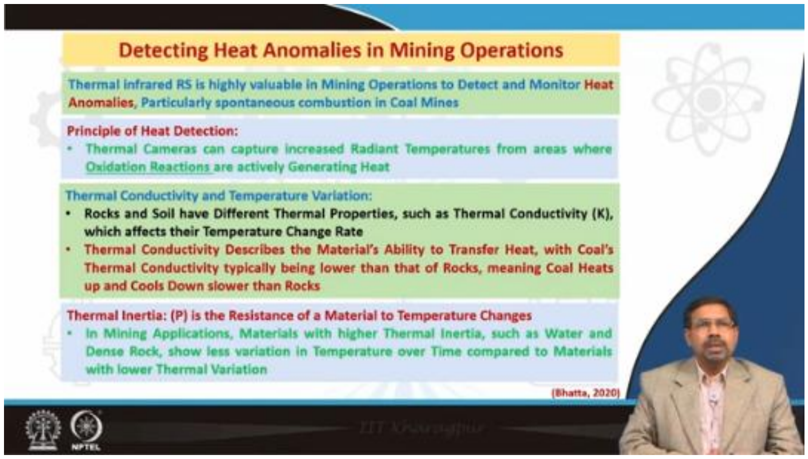
T_r = Radiant temperature

T_k = Kinetic temperature

Now, have a look at the right-hand side, the right-hand side portion. We have a diagram which talks about the radiant temperature curve, and on the x-axis, it has been shown across a full day or a diurnal scale, starting at 6 am in the morning and going up to 6 am the next morning. So, it is a 24-hour diurnal scale.

On the x-axis, and on the y-axis, the radiant temperature has been shown. And we can very well see that for different features like dry soil, rock, vegetation, water, and wet soil, you can see the curve varies differently. And for the first portion, the first half, the left-hand side, it is the sunrise to sunset, which means the day period, and the second half is for the night period. And friends, we can very well see the influence of sunlight, which means during the daytime with respect to the same feature, whereas in the nighttime, they have a different radiant temperature. So, the nighttime or the pre-dawn hours are ideal for thermal remote sensing because what happens is that the solar impact or the solar heat impact is nullified.

So, we should try to do a lot of remote sensing or thermal remote sensing in the pre-dawn or nighttime because those hours nullify the solar heat impact. Otherwise, if we are doing it during the daytime, then we have to consider the impact that is coming because of the solar heat. So, let us see how the heat anomalies are detected and their applications in the mining industries. The thermal infrared remote sensing is highly valuable in mining operations to detect and monitor heat anomalies, particularly spontaneous combustion in coal mines and others. Any variation that is happening because of temperature heat variation or heat anomalies has an application as far as the thermal infrared remote sensing is concerned.



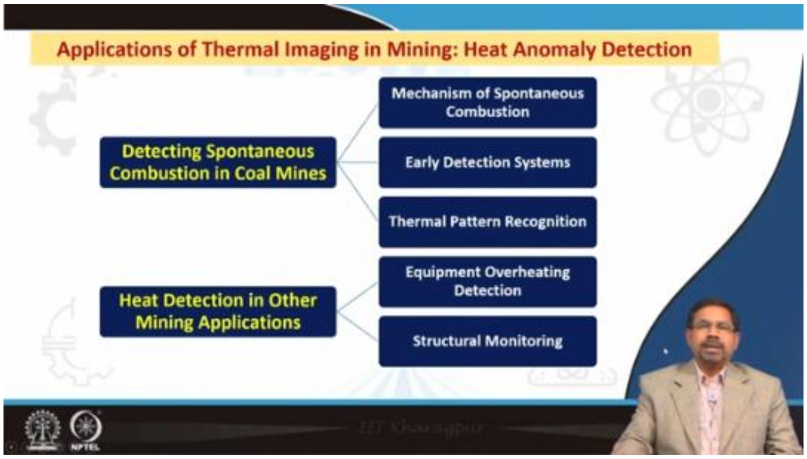
That varies across different mining industries. We often take the example of coal mines where a lot of activities happen and we have a lot of variation. In terms of different activities that have a link to heat anomalies. Now, the principle of heat detection: the thermal cameras can capture increased radiant temperature or, I would say, the variation in the radiant temperature from areas where the oxidation reactions are actively generating heat. So, the thermal cameras are very sensitive to capturing the radiant temperature, which is originated due to the oxidation reactions that actually generate a lot of heat.

Now, the thermal conductivity and the temperature variation. Let us see as far as the rocks and soils. There are various rocks and soils. They have different thermal behaviors. They have different thermal properties, such as thermal conductivity, which affects their temperature change rate.

Different soils or rocks have different thermal conductivities, which is why their rates of temperature change vary. This thermal conductivity describes the material's ability to transfer or conduct heat. For example, with coal or other materials, the thermal conductivity is typically lower than that of rock. So, if we take coal as an example, the thermal conductivity of coal is much lower than that of rock. What does it mean?

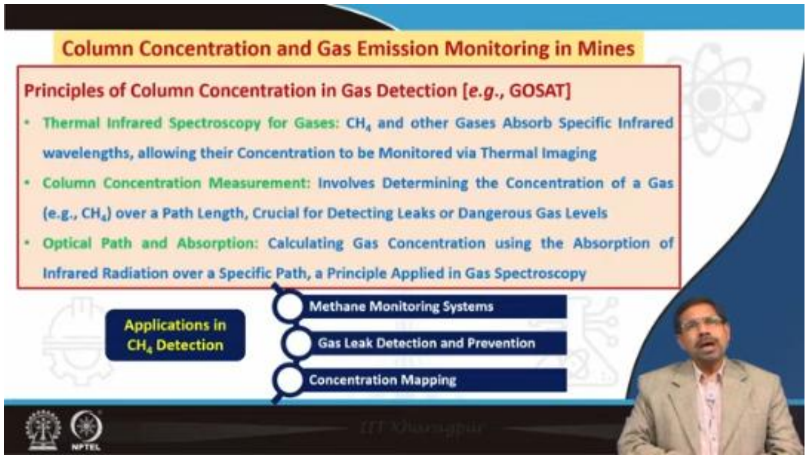
It means that coal heats up and cools down more slowly than rocks. So, thermal conductivity is one of the most important behaviors as far as the material or object is concerned. Now, let us understand thermal inertia, which is abbreviated as P. So, P is the resistance of a material to temperature changes. In mining applications, materials with higher thermal inertia, such as water and dense rocks, show less variation in temperature over time compared to materials with lower thermal inertia. So, inertia is another important factor where materials with higher thermal inertia show less variation in temperature compared to materials with low thermal inertia, okay.

So, these three things are also very important in terms of thermal conductivity, thermal inertia, and the anomaly. Let us also see the various applications of thermal imaging in the mining sector, particularly as far as heat anomaly detection is concerned. So, we have shown it in two parts: detecting spontaneous combustion, for example, in coal mines, and heat detection in other mining applications. So, the detection of spontaneous combustion in coal mines can be studied under these three parts or types. One is the mechanism of spontaneous combustion, which we can understand by detecting this.



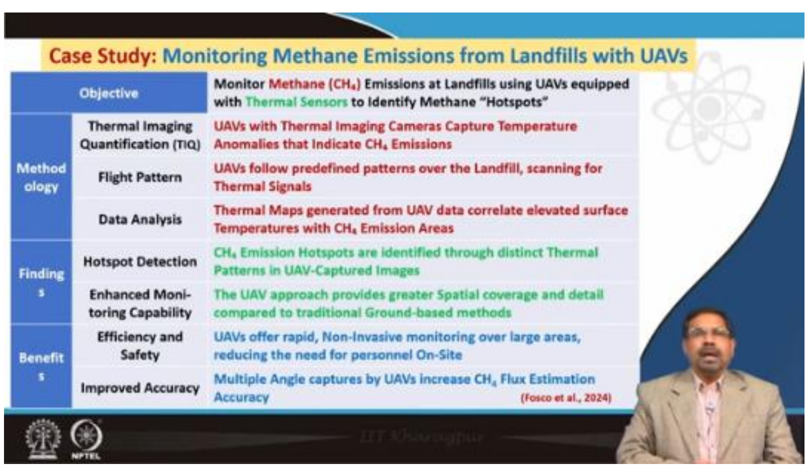
We can also go for an early detection system and understand the thermal pattern. So, the recognition of the thermal pattern is also important, and that comes from detecting spontaneous combustion. Now, let us talk about heat detection in other mining applications. They could be from equipment due to overheating, which can be detected, and also by monitoring the structure. So, these are the two broad types of applications as far as heat anomaly detection is concerned in the mining sector.

Now, friends, let us also have an understanding of column concentration and gas emission monitoring in mines. We have various sensors that also follow this principle of column concentration in monitoring gas emissions from different sources, including the mining sector. So, the principles of column concentration in gas detection are these three. One is thermal infrared spectroscopy for gases, the second one is column concentration measurement, and the third one is a kind of optical path and absorption. So, let us see thermal infrared spectroscopy for gases, particularly methane and other gases, which observe specific infrared wavelengths, allowing their concentration to be monitored via thermal imaging, which essentially falls under thermal infrared spectroscopy.



As far as column concentration measurement is concerned, it involves determining the concentration of a gas, for example, methane and others, over a path length, which is crucial for detecting any leakage or dangerous gas, what you say, leakage, emission, or flow. So, the third type is optical path and absorption, which calculates the gas concentration. It uses the absorption of infrared radiation over a specific path. That is why it is called optical path and absorption. So, the gas concentration is calculated using the absorption of infrared radiation over a specific path.

So, this is the principle which is applied in gas spectroscopy. So, friends, the applications, as far as methane gas detection is concerned, are discussed. So, methane monitoring systems, gas leak detection, monitoring, and concentration mapping. So, these are the various applications as far as the column concentration of any gas, including methane, is concerned, particularly in the mining industry sector. Now, let us have a look at a case study that has been done using the thermal sensor which was equipped on a UAV platform.



We have already understood that the unmanned aerial vehicle is at our mercy in terms of when and where we want to fly it, and at what height. So, UAVs have that advantage. So, this case study talks about monitoring methane emissions from landfills using UAVs or unmanned aerial vehicles. So, the objective, methodology, major findings, and benefits are discussed here in this slide. So, the objective of this study was to monitor methane emissions at landfills using UAVs equipped with thermal sensors to identify methane emissions from the landfill site.

So, that means we can understand it has a lot of applications, including methane emissions from solid waste or landfill sites. So, the thermal imaging quantification methodology has been applied, which is abbreviated as TIQ. So, what happened? The thermal imaging quantification flight pattern and data analysis. In terms of TIQ, UAVs with thermal imaging cameras capture the temperature anomalies that indicate methane emissions.

So, the thermal imaging cameras were mounted on the UAV platform to capture the temperature anomalies, which later indicated the methane emissions. The UAVs followed predefined patterns over the landfill, scanning for thermal signals. So, when flown on a defined or predefined pattern over the landfill, it scanned and captured the thermal signals across a defined or predefined path as far as the UAV is concerned. Then, the data that was captured was used to derive or generate the thermal maps, which correlated the elevation surface and temperature with methane emission areas. So, this well gave us the variation in the surface temperature, which has a good correlation as far as the methane emission is concerned.

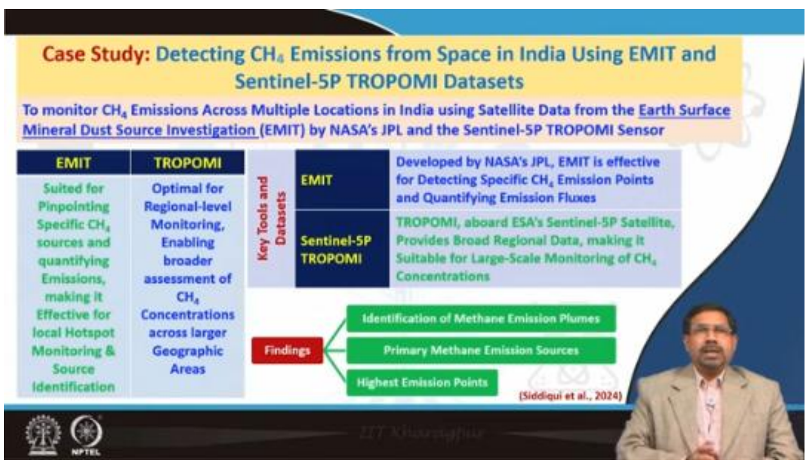
So, the important findings could be one: the hotspot detection. So, where there is more emission of methane. So, we define it as the hotspot. So, the methane emission hotspots were identified through distinct thermal patterns in the images that were captured using the UAV. The enhanced monitoring capability, that means the UAV approach, provides greater spatial coverage and detail, which are useful for comparison.

to traditional ground-based methods. So, when you mount the thermal sensor on a UAV, we have the option of flying it over a region. So, that means we get coverage over an area, which is not possible through traditional ground-based methods. So, we have control in this way that wherever or whenever we feel that there is methane emission over an area, it could be a landfill, a mining site, or from different sources. We can fly or mount the thermal sensor on a UAV and fly over the area.

So, we have that option with us. So, as far as the benefits are concerned, the efficiency and safety. UAVs offer rapid, non-invasive monitoring over larger areas, reducing the need for personnel on site. So, we need some people on site, but it helps us in giving rapid coverage in a non-invasive way. And it is also very cost-effective.

And also, it gives us very high, what you say, accuracy. So, multiple-angle capture is possible using UAVs. So, that can give us increased methane flux estimation accuracy. So, if you have multiple If you have availability in terms of data take, we can fly it across multiple angles so that we will have more coverage, which is useful for more accurate estimation of greenhouse gases, including methane.

So, methane emission or any greenhouse gas emission from the thermal sensors is possible over the mining sites. And the second case study goes in terms of detecting methane emissions from space in India using EMIT, that is, Earth Surface Mineral Dust Source Investigation. Which is by the sensor by NASA JPL and also the Sentinel-5P TROPOMI sensor. Let us have a look at this study. The two sensors, EMIT Earth Surface Mineral Dust Source Investigation by NASA JPL.

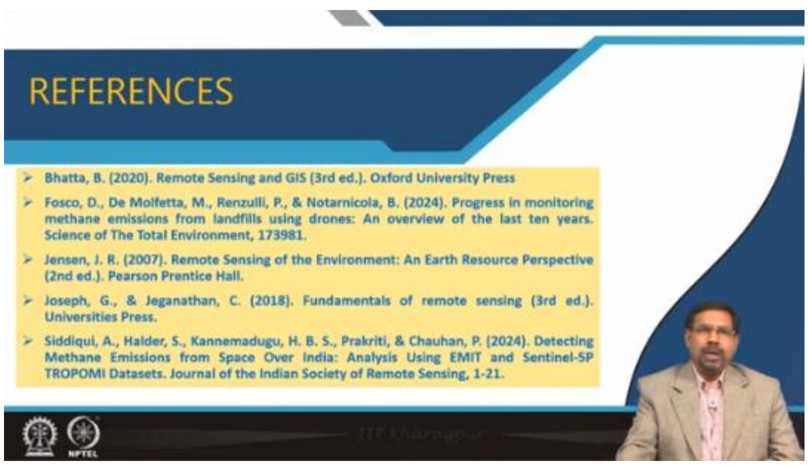


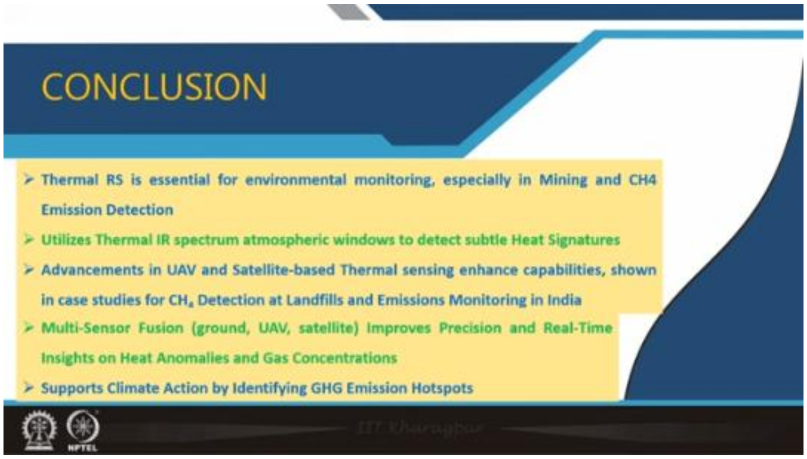
It is suitable for pinpointing specific methane sources and quantifying emissions, making it effective for local hotspot monitoring and source identification. Whereas the TROPOMI, which is mounted on Sentinel-5P of the Copernicus program by the European Space Agency. The TROPOMI sensor is optimal for regional-level monitoring, enabling broader assessment of methane concentrations across larger geographical areas. So, larger means it is giving us what you might call the global scale. So, the key tools and datasets used in this study are for EMIT; the NASA JPL-developed EMIT is effective for detecting specific methane emission points and quantifying emission fluxes, whereas the

TROPOMI, which is mounted on the 5P satellite, provides broad regional data, making it suitable for larger-scale monitoring of methane and other greenhouse gases.

So, the main findings of this study, given by Siddiqi et al., published in the year 2024, are the identification of methane emission plumes, the primary methane emission sources, and the highest emission points. Friends, as far as COP28, which happened last year in Dubai, the negotiators discussed and agreed upon having more studies and understanding of the well-mixed greenhouse gases. Because, next to carbon dioxide, methane is the most dominant greenhouse gas and it also has a higher Global Warming Potential (GWP). So, in the future, we are going to see more and more studies investigating methane and nitrous oxide. So, thermal remote sensing, in that way, is going to be very important including monitoring over the mining areas of the mining industries.

We have referred to these five references for this particular talk, and let us conclude the discussion we had about these five points. Thermal remote sensing is essential for environmental monitoring, especially in mining and methane emission detection. It utilizes the thermal IR spectrum atmospheric windows to detect subtle heat signatures within the range of 3 to 5 and 8 to 14 micrometers in the EMS. So, these are the two windows we mostly use as far as thermal infrared remote sensing goes.





So, the advancements in UAV and satellite-based thermal sensing enhance capabilities shown in case studies for methane detection at landfills and emissions monitoring in India and other sites across the globe. Multisensor fusion using all ground-based, UAV-based, and satellite-based methods improves precision and real-time insights on heat anomalies and gas concentrations, including methane and other greenhouse gases. We will be seeing a lot of studies as examples in our future classes. So, we conclude that thermal remote sensing or thermal infrared remote sensing supports climate action by identifying greenhouse gas emission hotspots. Thank you very much.