

## REMOTE SENSING FOR NATURAL HAZARD STUDIES

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### Lec 7b: Hyperspectral Data Acquisition and Processing-Part B

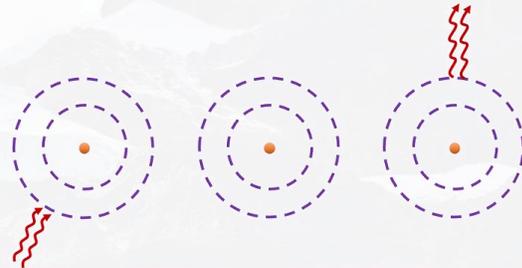
Hello everyone, welcome back to Lecture 7, part 2. So, we will continue the acquisition and processing of hyperspectral remote sensing data. So, we were talking about imaging spectroscopy. Now let us understand how these absorption features are produced by a particular target, why they appear in our spectra, and then only will we be able to use them efficiently to characterize a material. So, here you can see that this is one of the sample spectra. And here are these absorption features; as we understood, these are the characteristic absorption features of a given material, and these can be studied to determine whether it is x, y, or z material.

#### Electronic Process



- Absorption of photons of a specific wavelength causes a change from one energy state to a higher one.
- The emission of a photon occurs as a result of a change in an energy state to a lower one and can be observed in the VNIR wavelength region.
- When a photon is absorbed, it is usually not emitted at the same wavelength.
- For example, it can cause heating of the material, resulting in grey-body emission at longer wavelengths.

Electronic transitions produce broad absorption features that require higher energy levels and occur at shorter wavelengths.



Isolated atoms and ions have discrete energy states.

So, what causes these absorption features? So, there are two general processes which produce this kind of characteristic absorption feature. The first one is electronic, and the second one is vibrational. So, these electronic and vibrational processes are responsible for generating this kind of characteristic absorption feature for any given material or target. So, we will see them one by one. So, let us start with the electronic process. Electronic transition produces a broad absorption feature that requires higher energy levels and occurs

at shorter wavelengths. So, when we talk about the electronic processes, one thing that is important to note is that it is occurring at this shorter wavelength, So, this is in the shorter wavelength range. Now, here you have isolated atoms and ions which have discrete energy states, which is very clear from this. So, the absorption of photons of a specific wavelength causes a change from one energy state to another energy state.

So, what happens when there is a material with extra energy coming in the form of radiation or irradiance that is falling on this particular material? And let us say here you have the E1 energy level; because of this extra energy, what will happen is that it will change to E2. Now the energy level of this material has changed from E1 to E2 because of some external energy. So, to maintain equilibrium with the surroundings, what will happen? This has to come down to E1. on its own energy state. So, this extra energy will be released, and that will produce the characteristic absorption feature. The emission of a photon occurs as a result of a change in an energy state to a lower one and can be observed in the VNIR wavelength range. Now, when it is coming from E2 to E1, some extra energy that was present in the target will be released, and that will occur in the shorter wavelength range. So, here we are having this at the VNIR. When a photon is absorbed, it is usually not emitted at the same wavelength. So, when energy is absorbed by the target, it is released in the longer wavelength region. For example, it can cause heating of the material, resulting in gray body emission at longer wavelengths. So, we also talked about it earlier. Now let us see the crystal field effects, which are one of the electronic processes. Common electronic processes occur in the mineral spectra due to unfilled electron shells of transition elements like nickel, chromium, cobalt, iron, etc. The transition elements have identical energies in d orbitals in isolated ions.

The energy levels split when the atom is placed in the crystal field. So, that is why we are calling it crystal field effect. Crystal field describes the breaking of orbital degeneracy in transition metal complexes due to the presence of ligands or ions. Splitting of orbital energy states causes electrons to move from a lower level into a higher one. Now it is jumping from a lower one to a higher one. The energy levels are determined by the valence state of the atom, such as whether it is  $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$ , its coordination number, and its symmetry. The crystal field varies with crystal structure from mineral to mineral; thus, the amount of splitting varies, and the same ion, like  $\text{Fe}^{2+}$ , produces different absorption positions. So, now you can see that both  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  can be identified because of this crystal field effect. Now here you can see this is one of the example reflectance spectra of 2 pyroxenes showing the change in  $\text{Fe}^{2+}$  absorption band position and shape with composition. So, here you can see that the 1 micrometer versus 2 micrometer band position describes the pyroxene composition.

So, here these two are the pyroxenes, and here, because of the change in  $\text{Fe}^{2+}$  absorption band position, the absorption positions are shifting or changing from one place to another, which can be used to identify these two very precisely in the spectra. Now this is the charge

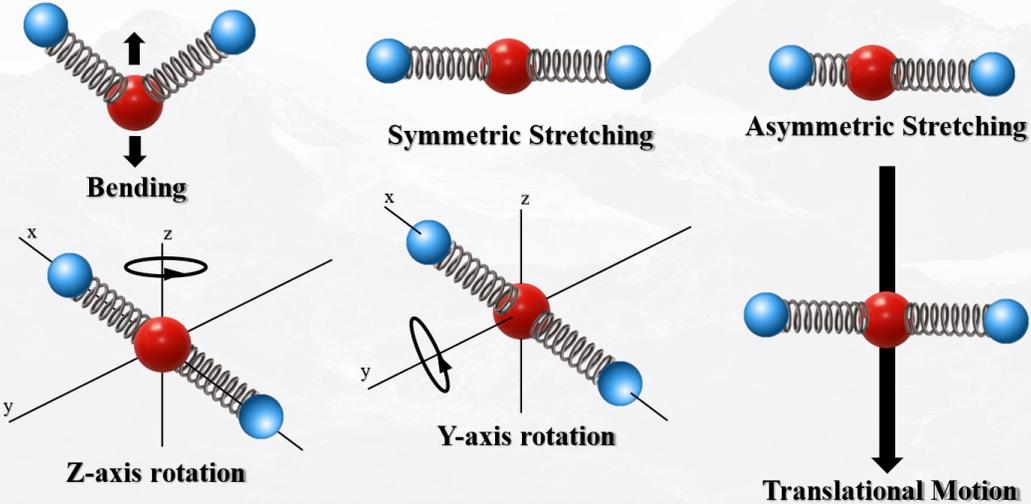
transfer; we also call it inter-element transition. The absorption of a photon causes an electron to move between atoms or between atoms and ligands. It can also occur between the same metal in different valence states, such as between  $Fe^{2+}$  and  $Fe^{3+}$ . In general, absorption bands caused by charge transfer are diagnostic of mineralogy.

Their strength is typically 100 to 1000 times stronger than the crystal field transition. Now, what we mean by stronger here is that we have one spectrum that has this kind of absorption feature. Now, we have another sample that has this kind of absorption feature. So, this is very strong compared to the two. So, when we talk about one particular material, the strength of charge transfer or inter-element transitions will be much stronger than the crystal field transitions, So, here you can see the reflectance spectra of Iron Oxide Hematite and Iron Hydroxide Goethite. So, here you see how these two appear in the spectrum. Now let us talk about the conduction band; in some minerals, electrons may have two energy levels: one is the conduction band, which is the higher level, and here the electron moves freely throughout the lattice. The second one is the valence band, to which lower-level electrons are attached to individual atoms. So, here they are moving freely throughout the lattice; here they are attached. So, this is a valence bond and this is a conduction bond, So, the difference between the energy levels, called the band gap, occurs in the visible region. So, here, if you see any absorption feature in the 400 to 700 nanometer and these are very characteristic and very clear, so we call it the band gap. So, we can find these conduction bands in 400 to 700 nanometer. This is one example where we have sulphur and cinnabar showing the conduction band in the visible wavelength region. So here are these two visible regions.

Vibrational Process



भारतीय प्रौद्योगिकी संस्थान गुवाहाटी  
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Bending      Symmetric Stretching      Asymmetric Stretching

Z-axis rotation      Y-axis rotation      Translational Motion

Remote Sensing for Natural Hazard Studies

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Now, the color center in a few minerals shows color due to absorption by color centers. A color center is caused by irradiation and solar UV radiation; crystals in nature have lattice

defects that may produce discrete energy levels. So, this is called a color center because of the color center, you will also have the absorption feature in the visible and the VNIR wavelength regions. Now, the second process is the vibrational process. So, here the bonds in a molecule or crystal lattice are like springs with attached weights; the whole system can vibrate.

So, let us assume you have two masses attached to each other with a spring. Now what happens if you hold one and just push little bit of the second mass what will happen these two will start vibrating. So, this can vibrate in this direction also, or like this, because these are connected with a spring. The same way the bonds in a molecular crystal lattice are like springs with attached weights, where the whole system can vibrate and the direction can be seen here in this particular figure. The frequency of vibration depends on the strength of each spring and its mass.

Now let us assume you have one spring, and here you have put a very small mass. Both sides of it, and you try to vibrate it; you put in some extra energy. So, this will vibrate and immediately it will stop, but if you attach a bigger mass here and try to vibrate this, it will not stop easily; it will take time to stop, and then it can vibrate in all these directions, So, here you can see some of the vibrational processes. So, bending is possible here; this is attached to these masses. Here, this is symmetric; this is asymmetric; here, z-axis rotation, y-axis rotation, and translation motion.

So, with an animation, I will try to show you how they appear. So, 3D animation of the symmetric stretching; this is symmetric stretching. Here, it is asymmetric stretching, scissoring, and rocking. Wagging. So, here you see how they vibrate. So, it is like a spring, and with this spring and the masses, how they are behaving and how they are vibrating. So, here this is the twisting right. So, here you can see that the rocking is very easy to understand with this animation. So, when we talk about the vibrational process, we talk about the fundamentals. So, the fundamentals can be identified using this concept. So, this is  $3N-6$  for a molecule with  $N$  atoms. When we talk about the vibrational processes, the fundamentals are very, very important; they can be measured or calculated using this  $3N-6$  for a molecule with  $N$  atoms. So,  $N$  can be known,  $N$  can be identified, and then you can use this, and then you will get the fundamentals. Overtones and combinations occur at roughly multiples of the original fundamental frequency. So, this is fundamental. If a molecule has vibrational fundamentals at  $V_1$ ,  $V_2$ ,  $V_3$ , then it can have overtones at approximately  $2V_1$ ,  $3V_1$ , or  $2V_2$ . And combinations at approximately  $V_1$  plus  $V_2$ ,  $V_2$  plus  $V_3$ ,  $V_1$  plus  $V_2$  plus  $V_3$ , or so on. Subtraction is also possible. So, like  $V_1$  plus  $V_3$ , minus  $V_2$ . So, all of these are possible. So, we have fundamentals and overtones. And then we have a combination. So, these are roughly multiples of the original fundamental. Overtones and combinations are 30 to 100 times weaker than the last; hence, the feature will be more difficult to sense. The feature means that the absorption feature will be very difficult to

identify.

## Vibrational Process



- Fundamentals ( $\nu$ ):  $3N-6$  for a molecule with  $N$  atoms,
- Overtones and combination: Occur at roughly multiples of the original fundamental.
- If a molecule has vibration fundamentals  $\nu_1, \nu_2, \nu_3$ , then it can have overtones at approximately  $2\nu_1, 3\nu_1, 2\nu_2$  and combinations at approximately  $\nu_1+\nu_2, \nu_2+\nu_3, \nu_1+\nu_2+\nu_3, \dots$
- Subtractions are also possible

e.g.  $\nu_1+\nu_3-\nu_2$ .

Vibrational absorptions occur at longer wavelengths. So, this is SWIR and MIR – Mid-Infrared. So, earlier we had the electronic processes which are in the visible and SWIR and here we have this in SWIR to MIR. So, here we have deep and narrow characteristics. So, that will help us to precisely identify the characteristic absorption feature. For example, the water molecule, which is  $H_2O$ , has  $N=3$ . So, there are  $3N-6$ ; remember  $3N-6$ , and if we calculate this, it will be 3, so 3 fundamental vibrations will be available for a water molecule. Now, here you can see we have calcite and dolomite. Comparison of calcite and dolomite spectra in the MIR shows a small band shift due to changes in the composition between the two minerals. Now, because of the change in the composition, but very similar to each other, you can easily see how they are different, and it can be easily identified when we go for the spectroscopy, the level change in reflectance of calcite is higher than that of dolomite because calcite has a smaller grain size.

So, if you want to go and learn more about hyperspectral remote sensing and the basics, I suggest you read this imaging spectrometry, and our paper that hyperspectral remote sensing and geological application which is available in the web. So, you can refer to them as covering the very fundamentals of hyperspectral remote sensing. So, when we talk about hyperspectral remote sensing, we are basically collecting the spectra in the form of images.

Now we will continue this discussion. So, the collected spectra are the response of the materials present in that particular pixel. I hope you learn how a particular characteristic absorption feature is produced by the material. So, it is basically because of the electronic and vibrational processes once we have the response of the material, and that is getting captured by our sensor. So, the sensor is storing them in different pixels depending on their

position, and we will have imaging spectrometry or spectroscopy, which we also call hyperspectral remote sensing. So, the collected spectra are the response of the material present in that particular pixel. If the spatial resolution is 1 by 1 kilometer, recorded reflectance is the average response of the material present within the field of view. So, when we talk about satellite remote sensing, we have one detector, for example, that is looking at the ground and then it is covering this particular area, So, this particular area can be 30 by 30 meters, or it can be 1 by 1 kilometer, or it can be centimeter by centimeter level, So, depending on the field coverage or the ground coverage, this whole area is being captured, and whatever energy is coming from this 30 by 30 meter area is being averaged, and you are storing it as one single DN value. So, if you have 30 by 30 meters, 1 kilometer by 1 kilometer, or 15 centimeters by 15 centimeters. You will have that much area covered at the ground level, So, if I am getting only one value, we should have the smaller pixel size because we are going to use this spectral information to identify the material.

Now, can you imagine it at the field scale? Can you find one particular material present in 30 by 30 m or 1 km by 1 km? It is very difficult. Sometimes we get it, but sometimes what happens is that you have different material present within the field of view. So, these many targets or objects will be present, and all of them are reflecting based on their chemical composition, and they are getting averaged, which will be stored as one single DN value. So, in such a situation, it is very difficult to identify the composition of the material present in the field of view of the satellite image, whether it is at the meter level or kilometer level. Coarser spatial resolution introduces mixing of spectral signatures within the field of view.

I have a figure that can explain this particular concept. In nature, it is very difficult to find one type of object or material covering 1 km by 1 km, 90 m by 90 m, or 30 m by 30 m. The effect of grain size and geometry is also significant in hyperspectral remote sensing data. Let us say I have A, B, and C: three materials, and my satellite has a 30 by 30-meter spatial resolution, So, let us say this is one pixel.

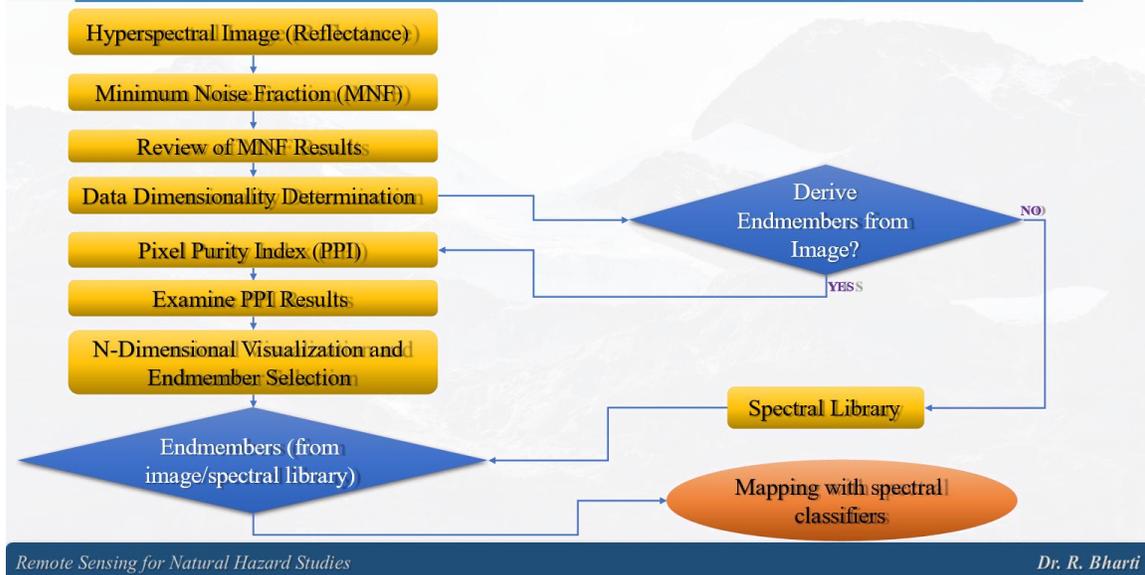
Now A is present like this. And we also have A, B, C, and D; they are present like this. Now, if we change the orientation, so this is A, B, C, D, this is also possible; the proportion will remain the same, but the orientation and the geometry are changing here, which will also have some effect on the spectra. But remember, this will change the intensity of the spectra, but it will not change the position of the characteristic absorption feature because the materials are the same, So, here we are talking about the grain size and geometry and why this intensity is important because, let us say, if this is x and let us say this is y. So, if these two are present in one pixel, let us say 50-50; x and y, you will have the output reflectance spectra like this. So, all of them are present with this same strength of the absorption feature because this is one line of 0 to 1 reflectance, and from here we will see how much absorption is happening, and this will calculate the area under the curve and then we will say how much x is present and how much y is present. So, in such a situation, this grain size geometry will also play a critical role. So, the spatial resolution is very, very

important and critical when we talk about hyperspectral remote sensing data analysis. Because one pixel is producing this kind of spectrum, which represents a bigger area on the ground, it is very hard to find one type of material in that particular field of view. So, it can be a mixture of materials. So, when we talk about the ideal condition, let us assume that we have one particular target that is available in, let us say, 30 by 30 meter. or 1 kilometer by 1 kilometer. Now, we have this source that is eliminating this, and it is getting reflected or emitted—emission will be measured here. So, the collected spectra are the responses of the material present in that pixel. In this example, I used only one type of object or material within the field of view of this particular sensor.

So, in such a situation, it is very easy that you will get only a spectrum that represents quartz. But in another condition or the natural condition, this is the scenario where 1 pixel has many objects or materials, and they are available in different orientations and geometries. So, what will happen in such a situation is that you will find this kind of spectra, and this will be a mixture of all x, y, z, a, b. So, this is the problem with hyperspectral remote sensing: one pixel representing the ground is actually large, and one type of material is not present within meter or kilometer levels; because of that, you are facing the nonlinear mixing problem. So, here you see if my material is present in such a way that x, y, z, a, and b are all present here.

So, you are getting a spectrum. So, you can do this; you can give weightage depending on the area, and then you will get this kind of spectra. But when you have the nonlinear combination of all these materials present within the field of view, then what kind of spectrum you are getting is very hard to interpret and hard to quantify. So, what we do is assume in hyperspectral remote sensing data analysis that the material present within the field of view of my sensor is linearly mixed. So, we try to avoid this nonlinear unmixing; we try to go with the linear unmixing problem. And this linear unmixing will give you the combination of all these materials present within the field of view, and then you can quantify their composition; you can quantify their presence in the pixel.

So, let us talk about the spectral mixture analysis: how do we do it? So, let us assume that you have identified a particular mineral. Let us say this is quartz using the conventional method. So, you go with XRD, and then you can say that this is quartz. Now, once we have this Quartz, it is also present within the field of view of my image. So, this is 1 pixel; 50 percent is Quartz and 50 percent is Mica. So now we have also identified mica through the conventional techniques. Now we are very sure that this particular study area and these particular locations have 50% Quartz and 50% Mica. Now, we go to the field, collect the Quartz sample from here, collect the Mica sample from here, analyze them, and confirm whether they are Quartz or Mica. Then, based on the satellite data, we will see in which particular pixel it is coming, and then we will see whether it is 50 percent or 50 percent.



This is just to understand the concept. Now, once you have that, then you have a spectroradiometer. With the spectroradiometer, you will produce 1 spectrum for the quartz and 1 spectrum for the mica, Now, if it is 50 percent, 50 percent, I can just simply do this in Excel itself. In Excel, we will have the wavelength, quartz, mica, and then the pixel spectra, let us say. So, this is  $\lambda_1$ ; let us say this is  $r_1$ , this is  $r_{m1}$ , this is  $r_2$ , this is  $r_{m2}$ , and this is  $\lambda_2$ . Now, we know that this particular pixel has 50 percent quartz and 50 percent mica. So, I can simply do this:  $r_1$  into 0.5 plus  $r_{m1}$  into 0.5. So, in that way, you will produce the combination of these two spectra, which represent this particular image. So, this is the kind of analysis we have to do when we talk about spectral mixture analysis. So, we have almost characterized all types of mineral rocks that are present, including the soils, using the spectral measurements. Now, there are a few libraries available from different sources that have different minerals, rock, and soil spectra that can be considered in the spectral mixture analysis. So, the identification of pure minerals through field investigation or conventional techniques is necessary.

Measurement of the representative spectral signature of minerals or pure materials is also important. Sometimes a single material feature object can exist in several forms due to changes in the composition or state, which result in different spectral signatures. Then we will go for the spectral library. SMA is a technique to determine the proportion of different features of known material objects.

SMA uses the spectra of known materials from the spectral library. So, here when we talk about the pure spectra of a particular material, let us say if we collect the spectra of pure quartz, we will call this the true representation of quartz. So, then we can call it an endmember. So, the spectral endmembers are the pure spectra that are used as a reference

to deconvolve the measured spectra into known materials. Endmembers can be described as pure spectra for a specific image or area.

They are the purest pixels in that particular image. So, what we do is, in the image itself, we also have to identify which pixels are covering one type of material on the ground, and their response, their spectra, will be considered as pure spectra, which we also call endmembers. So, difficulties in selecting the endmember sometimes arise because the endmember cluster is not present in an image larger than the pixel size due to the spatial resolution. Endmembers are not truly constant in an image and sometimes create a mismatch between the defined endmember and its actual form on the ground. Non-linearity due to shadow will result in additional information in this spectrum, which can cause confusion when selecting that particular pixel as an endmember. Sometimes, inherent variability in nature, such as rain and growing cycle phases, makes it difficult to match the endmember with actual pixel composition.

So, these are some practical problems. Now, assume the estimation of each image pixel's composition. Each pixel contains information about the proportion and spectral response of each component, brightness, which can be your DN value, radiance, or reflectance, which is captured by the sensor. The value of an image pixel is a linear combination of the percentage of each end member and the brightness of the pure sample of that end member. The spectral proportion of the endmember shows the proportion of the area covered by the feature on the ground. Most of the pixels contain some measurable amount of the endmember. So, these endmembers are not very easy to identify because in nature, 1 pixel is what we are capturing from space at 30 m spatial resolution, 90 m, or 1 km spatial resolution.

It will be very hard for us to identify a single material present in the field of view. So, that is why we have to very rigorously find a pixel that has a representation of one type of material or object. So, when we go for the spectral mixture analysis, we have one spectrum from the image which is unknown; we do not know the composition, but we should have some sort of information from the field about what kind of minerals, rocks, or soils are present in that area. Accordingly, the standard measured spectra by some other agencies or people can be used here as a reference. So, the library spectra are the pure spectra of, let us say, quartz, mica, feldspar, or maybe any standard material, and my pixel will have the combination of these 1, 2, 3, 4, 5, 10 materials. So, those will be available, or should I collect that information from different spectral libraries? Then different combinations of spectral libraries will be generated. So, let us say I have x, y, z, a, b, c, and d. These are the materials that I am expecting to present in my study area. So, what I will do is generate the linear combination of these materials. So, first we will go with 1% of x, 1% of y, 1% of z, and like that we will go until we complete it to 100%.

Then we will change these values, these weightages, and then you will have that many combinations, and then we will try to match it with the pixel spectra, how they are matching

or how well they are representing this absorption feature, So, that is how the spectral mixture analysis is done. So, with this, we will be able to say that this particular pixel has ABC, DEF, or GEF material, So, this library will be generated with this spectroradiometer, as I mentioned before; there are pure spectra measured by different agencies that are available, and they can be used here as your library spectra. For that, we are taking the help of the spectroradiometer. Now it is very important to note that when you are generating the spectra for the library, you should take care of the spectral range, spectral sampling, and number of spectral bands that are measured here and from space.

Because here we have the measurement at 0.1 nanometer, and here you have the 10 to 20 nanometer intervals. So, you have to take care of the number of spectral bands, the number of samplings, and the spectral range. So, let us say here it is from 350 to 2500; here it is 400. So, you have to match this spectral range, you have to match the spectral sampling, and then, once you do that, the number of spectral bands will be equal for both measurements. Then these two can be used here. And then this spectral analysis can be done. So, when we talk about hyperspectral data analysis, specifically the analysis of the hypercube or the satellite hyperspectral data, this is the flow that we have to follow. So, initially we have to convert the DN to radiance and radiance to reflectance; then we have to go for the minimum noise fraction to identify the inherent data properties, which are the unique information measured by our sensor and the additional information that is repeated. So, data redundancy will be removed, as well as the noise, and then we will use this endmember, which can be from your spectroradiometer. If you have a spectroradiometer, then you can go with this. If you do not have them from the image itself, you have to derive the endmember, and here you will follow this pixel purity index, and then from there, you will do the endmember selection.

Once you have the endmember, it does not matter whether it is from an image or from an instrument; both can be used together to go for the mapping of a specific material or classifying the image. Once you have the endmember from the image or library, that can be used further to analyze the hyperspectral remote sensing data. And then further, you will classify this hyperspectral data, and you will come up with different classes or categories that represent mineral rocks, soil, different types of land use, land cover, or different types of manmade materials present in that particular study area. So, with this, I will end this lecture, and we will continue this course with Lecture 8.

Thank you very much.