# Remote Sensing: Principles and Applications

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## Lecture – 14
## Radiation reaching sensor - Part 2

Hello everyone, welcome to today's lecture on the topic, the radiance reaching the sensor. Last lecture, we started discussing about what are the different paths in which radiance can reach the sensor. We saw 5 different paths as given here in this slide.

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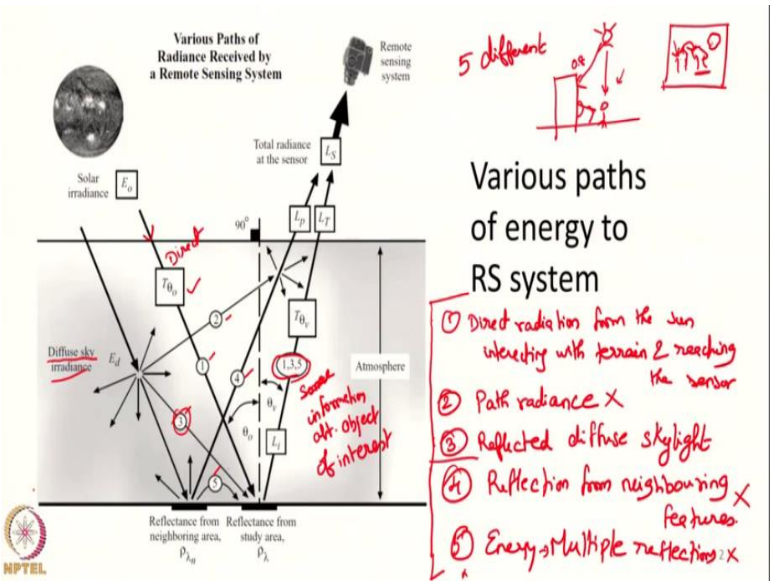

Various paths of energy to RS system

① Direct radiation from the sun interacting with terrain & reaching the sensor
② Path radiance ×
③ Reflected diffuse skylight
④ Reflection from neighbouring features ×
⑤ Energy → Multiple reflections ×

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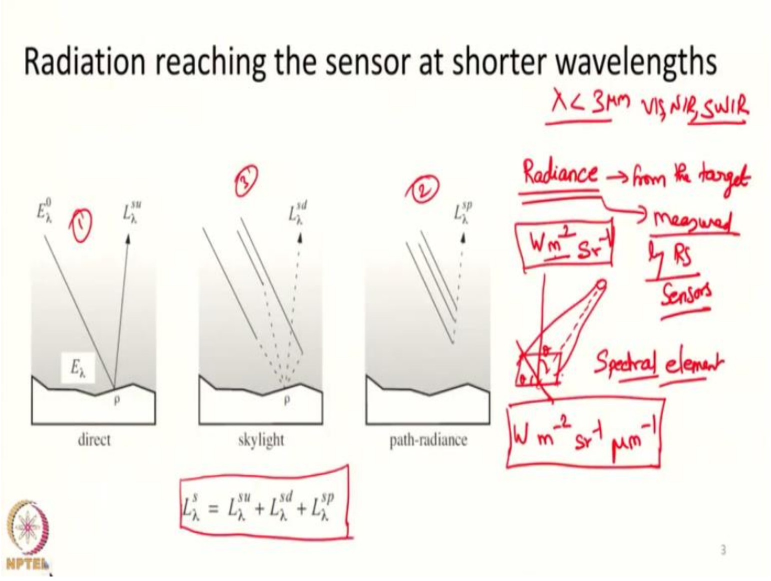

Radiation reaching the sensor at shorter wavelengths

$\lambda < 3 \mu m$ VIS, NIR, SWIR

Radiance → from the target → measured by RS Sensors

$\boxed{W m^{-2} sr^{-1}}$

$\boxed{W m^{-2} sr^{-1} \mu m^{-1}}$

$$\boxed{L_\lambda^s = L_\lambda^{su} + L_\lambda^{sd} + L_\lambda^{sp}}$$

We just went through what are these 5 paths in which energy can reach the sensor. Then we neglected 2 out of it. And we started to look at 3 major components of energy that will reach the sensor, especially in the shorter wavelength domain that is λ less than 3 micrometers. Then we started calculating each and every path separately. We started with path 1 that is the energy from the sun interacting with the terrain reaching the sensor.

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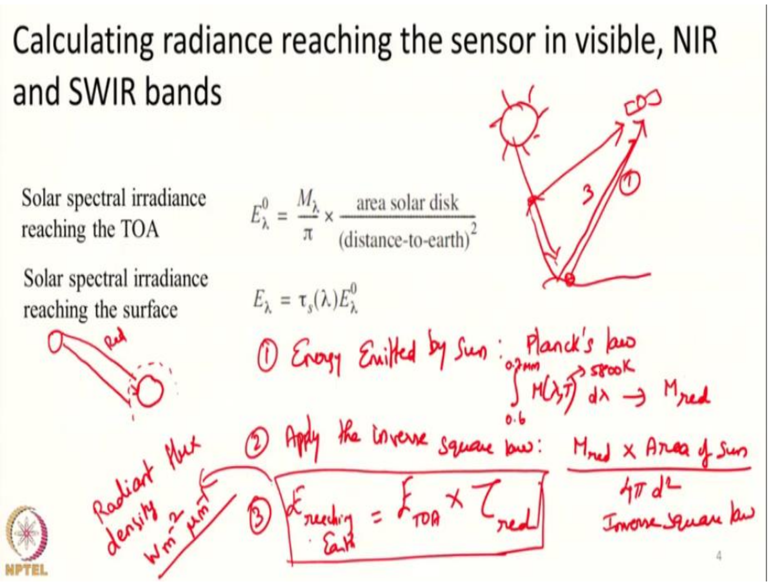

Calculating radiance reaching the sensor in visible, NIR and SWIR bands

Solar spectral irradiance reaching the TOA $E_\lambda^0 = \frac{M_\lambda}{\pi} \times \frac{\text{area solar disk}}{(\text{distance-to-earth})^2}$

Solar spectral irradiance reaching the surface $E_\lambda = \tau_s(\lambda) E_\lambda^0$

① Energy Emitted by Sun : Planck's law $\int_{0.6}^{0.7\mu m} M(\lambda, T) \, d\lambda \rightarrow M_{red}$ (T → 5800K)

② Apply the inverse square law: $\frac{M_{red} \times \text{Area of Sun}}{4\pi d^2}$ Inverse Square law

③ $\boxed{E_{\text{reaching Earth}} = E_{TOA} \times \tau_{red}}$

Radiant flux density $Wm^{-2}\mu m^{-1}$

There we calculated the energy coming in from the sun as 3 different steps like first we calculated using Planck's law what is the energy emitted by sun within that particular wavelength. Then we calculated how much of the energy will reach the top of atmosphere using inverse square law. After that, we apply the atmospheric transmissivity to that radiance at top of atmosphere for calculating the irradiance at the earth surface.

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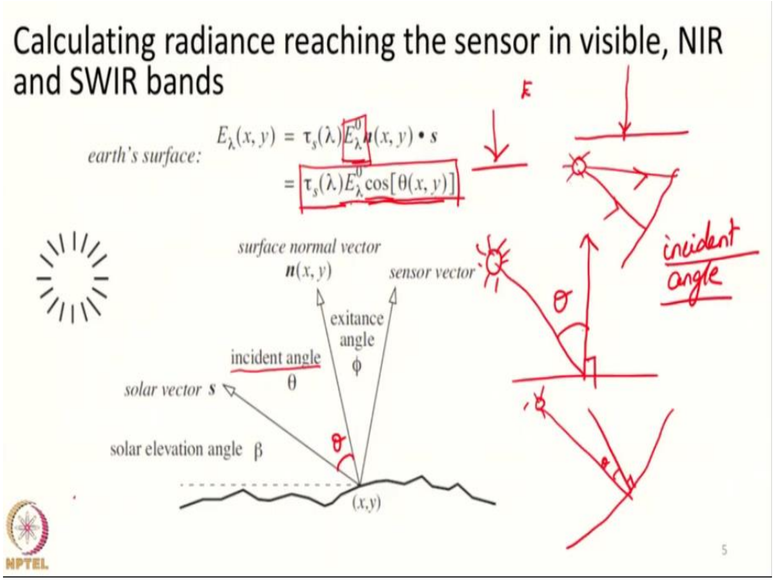

Calculating radiance reaching the sensor in visible, NIR and SWIR bands

earth's surface: $E_\lambda(x,y) = \tau_s(\lambda) \boxed{E_\lambda^0} \mathbf{n}(x,y) \bullet \mathbf{s}$

$= \boxed{\tau_s(\lambda) E_\lambda^0 \cos[\theta(x,y)]}$

We saw what fraction of energy will reach the earth surface. After it we also saw why this cos θ term is there. If the solar radiation is not normal to the surface, if it is coming in at an angle, we need to multiply with that cos θ where θ is the angle of incidence, at what angle solar radiation is coming in with respect to normal to the surface. So, that is the total energy that reaches the surface from sun.

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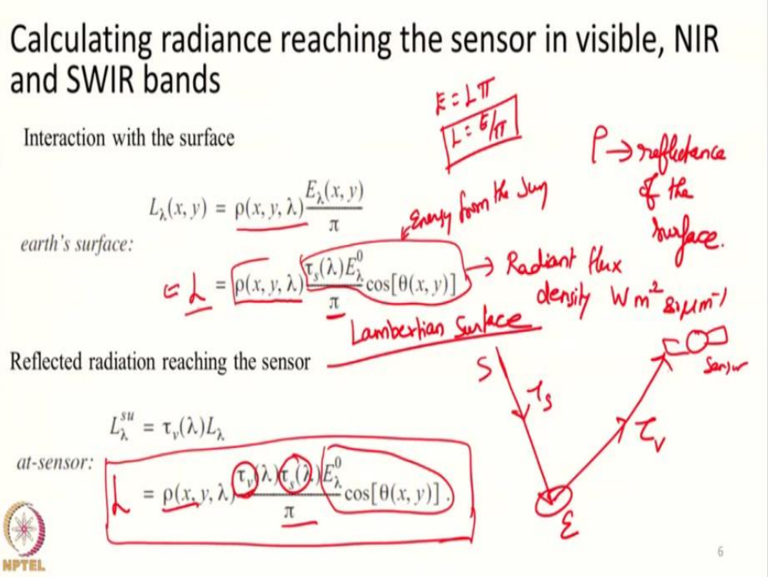

## Calculating radiance reaching the sensor in visible, NIR and SWIR bands

Interaction with the surface

earth's surface:

$$L_\lambda(x,y) = \rho(x,y,\lambda)\frac{E_\lambda(x,y)}{\pi}$$

$$= \rho(x,y,\lambda)\frac{\tau_s(\lambda)E_\lambda^0}{\pi}\cos[\theta(x,y)]$$

Reflected radiation reaching the sensor

at-sensor:

$$L_\lambda^{su} = \tau_v(\lambda)L_\lambda$$

$$= \rho(x,y,\lambda)\frac{\tau_v(\lambda)\tau_s(\lambda)E_\lambda^0}{\pi}\cos[\theta(x,y)].$$

Then we multiply that particular energy from sun with reflectance from the surface ρ and then divide it by π in order to correct it for radiance assuming a Lambertian surface, we have now converted the radiant flux density from the sun into radiance reaching the earth surface. When it reaches the sensor, it has to again go through the atmosphere there is one more transmissivity term that came in. So, this is the final equation for path 1 that reaches the sensor.

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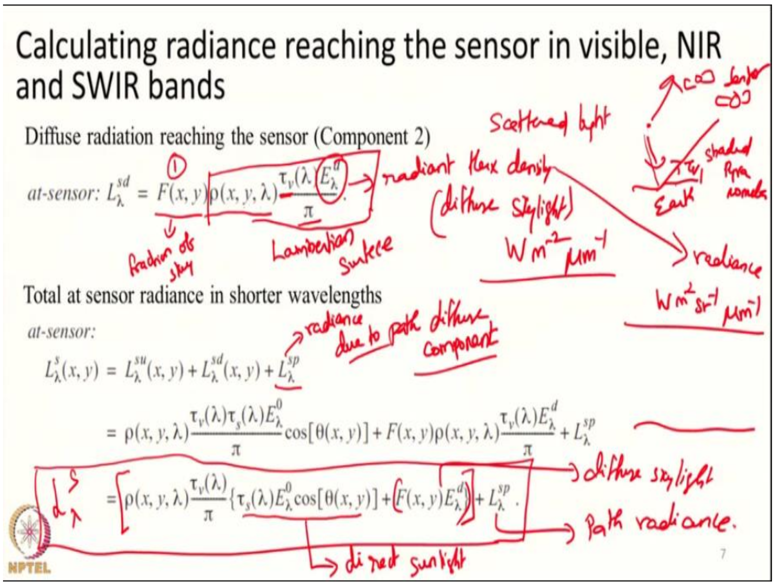

## Calculating radiance reaching the sensor in visible, NIR and SWIR bands

Diffuse radiation reaching the sensor (Component 2)

$$\text{at-sensor: } L_\lambda^{sd} = F(x,y)\rho(x,y,\lambda)\frac{\tau_v(\lambda)E_\lambda^d}{\pi}.$$

Total at sensor radiance in shorter wavelengths

at-sensor:

$$L_\lambda^s(x,y) = L_\lambda^{su}(x,y) + L_\lambda^{sd}(x,y) + L_\lambda^{sp}$$

$$= \rho(x,y,\lambda)\frac{\tau_v(\lambda)\tau_s(\lambda)E_\lambda^0}{\pi}\cos[\theta(x,y)] + F(x,y)\rho(x,y,\lambda)\frac{\tau_v(\lambda)E_\lambda^d}{\pi} + L_\lambda^{sp}$$

$$= \rho(x,y,\lambda)\frac{\tau_v(\lambda)}{\pi}\{\tau_s(\lambda)E_\lambda^0\cos[\theta(x,y)] + F(x,y)E_\lambda^d\} + L_\lambda^{sp}.$$

Now, we are going to proceed and look at path 2 and path 3. Let us first talk about reflectance of the surface from diffuse skylight component. So, diffuse skylight is just the scattered light that remains in the atmosphere which travels towards the sensor and also towards the earth surface. We can measure diffuse radiance using an instrument called shaded pyranometer or we can also model it using various atmospheric and radiative transfer models. So, here we are not going to derive it because there are not actual derivations to account for how to do it. But we are just going to assume we have some measurement or some model output of how much diffuse radiation is present.

When we talk about direct solar radiation, it is easy for us to calculate. Everything is fixed. But when we talk about diffuse radiation, it is not fixed. It will vary with time, with cloudiness where sun is located, etc,. So, assume we have a instrument called shaded pyranometer here and we are measuring it. We are not going to go in detail and derive what factors are using and we are just going to assume we have that measurement. So, again we are using the reflectance term here. So, this is the radiant flux density multiplied by reflectance of the surface. Again we are dividing it by π assuming a Lambertian surface in order to convert radiant flux density to radiance with the unit of watt/meter$^2$/steradian/micrometer. This π is to account for that. Let us multiply it with reflectance of surface divided by π, which will give us the radiance leaving the surface due to diffuse skylight component. Now, this radiance leaving the surface has to travel entire atmosphere again. So, when it reach the surface that is fine because the radiance can start from any point in the atmosphere. So, we have not taken into account atmospheric transmissivity as atmospheric components only is what is creating this diffuse skylight. But once it reflects with the object it has to travel back toward the sensor. So, this energy will be again absorbed or scattered by atmospheric components. There we have to use this transmissivity term between earth and sensor. So, here we are using $\tau_v$. $\tau_v$ is the transmissivity towards earth and sensor.

So, this is effectively the radiance reaching the sensor due to diffuse skylight component. What is this F part. F part is to account for the fraction of sky. Let us assume the surface is completely free from any obstacles. Whatever the surface we are talking about is not covered by any feature surrounding it. So, F will be 1. For the sake of simplicity I am just going to neglect this. Assume F as 1. So, $E_\lambda^d$ is the radiant flux density due to diffuse skylight component multiplied with $\rho/\tau$ to calculate the radiance leaving the surface multiplied with $\tau_v$ to get radiance reaching the sensor. So, now, we have calculated 2 paths. One is reflectance from the surface due to direct sunlight component, path 2 reflectance from the surface due to diffuse skylight component.

Third component is the path radiance, what scattered energy that directly reaches the sensor. Again we have to model the path radiance somehow. We have to use what is known as radiative transfer models to calculate it, how much is the path radiance at a given time with a given atmospheric conditions, temperature, pressure, cloud fraction and everything.

The diffuse radiation that is going towards the sensor is path radiance. We cannot measure it actually and so we have to model it. Let us assume we also have that model and there is no defined equations for us to derive here. If we assume that values available to us, so, we get what is known as $L_\lambda^{sp}$. So, this is the radiance due to path or diffuse component. So, this is the total radiance that will reach the sensor from earth surface.

If you look at this, the signal about the earth surface is present in 2 components. One is the direct sunlight component. This is the direct sunlight component. This is the diffuse skylight component, this term. And this is the path radiance component. So, this will effectively tell us what is the radiance that reaches the sensor in visible, NIR and SWIR wavelengths?

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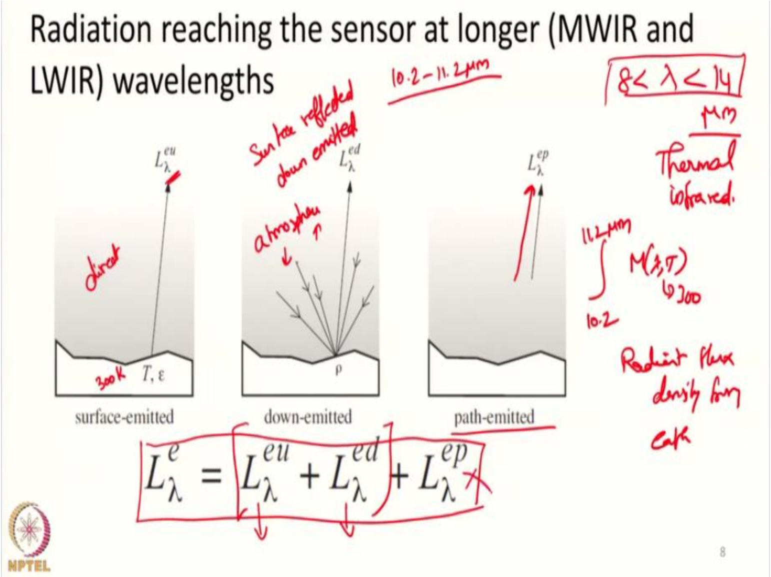

Radiation reaching the sensor at longer (MWIR and LWIR) wavelengths

$$\boxed{L_\lambda^{e} = \boxed{L_\lambda^{eu} + L_\lambda^{ed}} + \cancel{L_\lambda^{ep}}}$$

Next, we are going to see what is the radiance that reaches the sensor in thermal infrared wavelengths or mid wave infrared wavelengths? First we will talk about thermal infrared wavelength. What will happen in thermal infrared wavelength? That is λ between 8 to 14 micrometers, we call it as thermal infrared region. Already we discussed that, in this particular wavelengths, solar incoming radiation is almost 0.

And whatever the energy that reaches the sensor is purely because of energy emitted by features on the earth surface and atmosphere. So, it is effectively due to earth's own temperature. That is what is going to reach the sensor. So, again here we have 3 paths. Path 1 is direct surface emitted component that is earth has certain temperature. Let us say this is like 300 Kelvin. Due to this temperature, earth will emit a radiation. Again using Planck's law we can calculate. So, these sensors will essentially operate at this wavelength not at shorter wavelength. Most likely let us say 10.2 to 11.2 micrometer and so on. This will be like the wavelength range at which thermal infrared sensors will operate. So, similar to calculating the energy from sun apply the same principle here.

Use Planck's law, substitute earth's temperature of 300 Kelvin. If it is so, most likely substitute the wavelengths range 10.2 to 11.2. For example say if you integrate Planck's law, we will be calculating what is the radiant flux density from earth. So, this is that direct emitted component. Second thing atmosphere also has certain temperature that will also emit some energy. And when it emits it will emit in upward direction and also in downward direction. So, whatever is coming towards the ground a fraction of it will be reflected by the surface that will reach the sensor. So, this is the surface reflected down emitted radiance. Atmosphere also has certain temperature. Air will have certain temperature it will emit energy in these wavelengths. So, that particular energy will come down towards the surface and a fraction of it will be reflected back.

That is it. And third thing is the direct atmospheric emission reaching the sensor. We call it as path emitted component. So, in thermal infrared wavelengths, the energy reaching the sensor will have again 3 paths. First path is the direct emitted component, second thing is surface reflected atmospheric emitted energy and third thing is path emitted energy. These 2 paths carry some signals about the surface. And this is entirely unwanted energy which reaches the sensor.
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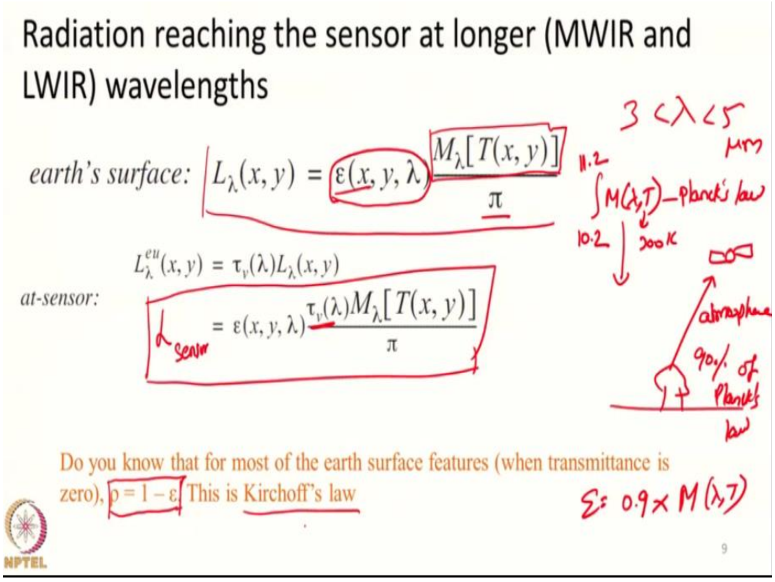

## Radiation reaching the sensor at longer (MWIR and LWIR) wavelengths

earth's surface: $L_\lambda(x,y) = \varepsilon(x,y,\lambda)\dfrac{M_\lambda[T(x,y)]}{\pi}$

at-sensor: $L_\lambda^{eu}(x,y) = \tau_v(\lambda)L_\lambda(x,y)$

$L_{sensor} = \varepsilon(x,y,\lambda)\dfrac{\tau_v(\lambda)M_\lambda[T(x,y)]}{\pi}$

Do you know that for most of the earth surface features (when transmittance is zero), $\rho = 1 - \varepsilon$. This is Kirchoff's law

If it is thermal infrared wavelength, only emitted components will be there. If it is not thermal infrared, if it is MWIR that is between 3 micrometers to 5 micrometers wavelength or up to 5 micrometers wavelength especially during daytime, the energy containing or energy reaching the sensor will have both reflection components and also emission components. Because at 3 to 5 micrometer wavelength, the energy coming from the sun cannot be neglected.

Similarly, energy emitted by the earth also cannot be neglected. Both will be there during daytime. So, that is why remote sensing in mid wave infrared band between 3 to 5 micrometers especially during daytime is a bit complex process. It has 6 different paths now. 3 paths for surface reflected component, 3 paths for surface emitted component. But if it is purely thermal like between 8 to 14 micrometers, only emitted path will be there.

If it is less than 3 micrometers only solar reflected path will be there. In this portion 3 to 5, both will be there, especially during daytime. At night time reflected path will not be there because sun is absent so only emitted path is there. This, please make it clear. And based on time availability we will see mid wave infrared portion also. How remote sensing can be done in mid wave infrared portion later in the course.

Right now, we will focus on calculating the emitted components. So, how to calculate the emitted energy? I already said in the last slide that calculating energy from earth is very similar to how we did it for sun. Let us say our sensor is sensing between 10.2 to 11.2 micrometers. So, let us assume the earth is at 300 Kelvin temperature. So, if you substitute this 300 Kelvin integrate Planck's law between whatever wavelength the sensor is observing, we will get the energy emitted by earth, this part. Here there is a new term called ε. What is this? This is called surface emissivity. What surface emissivity is? Whenever we discussed about Planck's law, Stefan Boltzmann law and everything, not all objects will obey those laws.

That is, those laws are defined for objects what are known as black bodies. What black bodies are? Black bodies can radiate energy or can emit energy with its full efficiency that is, so, Planck's law, Stefan Boltzmann law are kind of like the peak energy that can be emitted maximum limit that is the maximum energy an object can emit at a given wavelength at a given temperature.

But not all objects will obey that law or will emit radiation with that maximum efficiency I will say. Like, if I say maximum that can be 100 units of energy emission. That is the limit, but certain objects cannot emit at that particular efficiency. Let us assume like I am having 100 rupees, if I have the capacity to spend all the 100 rupees that is fine. I am having 100 spending 100.

But I have 100 rupees. There is some limitation on me that I can spend only 90 rupees. I cannot spend the 10 rupees. Somehow something is stopping me from doing it. So, my efficiency of spending there is 0.9. Same thing here, there is some energy contained within an object. It can radiate energy as prescribed by Planck's law. But there is something that is stopping.

It cannot radiate with its maximum efficiency something that is stopping it from radiating with maximum efficiency. And hence, it is emitting energy only a fraction of what is described by Planck's law. Say Planck's law tells this object at a given temperature can emit 100 units of energy. But if the object has an efficiency of let us say only 0.9, it can emit only 90% of what is described by Planck's law.

This term what I am calling it as efficiency is actually known as emissivity. We will describe in detail about emissivity when we discuss about thermal infrared remote sensing. But here you just know that emissivity is with what efficiency objects can emit radiation. Certain objects like water bodies, deep water bodies have an emissivity of 0.98, 0.99 and so on.

For vegetation, emissivity will be 0.9 to 0.99. For some manmade objects, concrete and all, efficiency is somewhat lower. Highly polished metallic surfaces, steel, highly polished steel surfaces or highly polished mirrors which can reflect a lot for them emissivity will be much lower say 0.8, 0.85 and so on. So, we have to account for it how much with what efficiency and object can emit. That fraction is known as emissivity.

That is what we are using here. So, here it is to account for say the earth surface features cannot radiate energy as prescribed by Planck’s law. It can radiate only a fraction of energy and that fraction is emissivity. See, this is the object. Some vegetation is there, let us say it can emit only 90% of what Planck’s law says. So, its emissivity is 0.9 multiplied with what is given by Planck’s law. That will give you the energy emitted by it.

So, again, this is in radiant flux density. You are dividing it by π in order to convert it into radiance. So, this is the energy emitted by the surface or radiance emitted by the surface. Now, this radiance from the surface that is emitted by this feature has to travel through sensor. And hence there is an atmosphere in between. We have an atmospheric transmissivity term τ.

So, if you multiply the energy emitted by the object with atmospheric transmissivity, we will get the radiance reaching the sensor from the object of interest. So, this how we have to calculate it. And one more information, reflectance will be is equal to 1 minus emissivity for most of the objects. This is known as Kirchoff’s law. Just for your information I am posting it here. I will explain this in detail in later classes, when we discuss thermal remote sensing.

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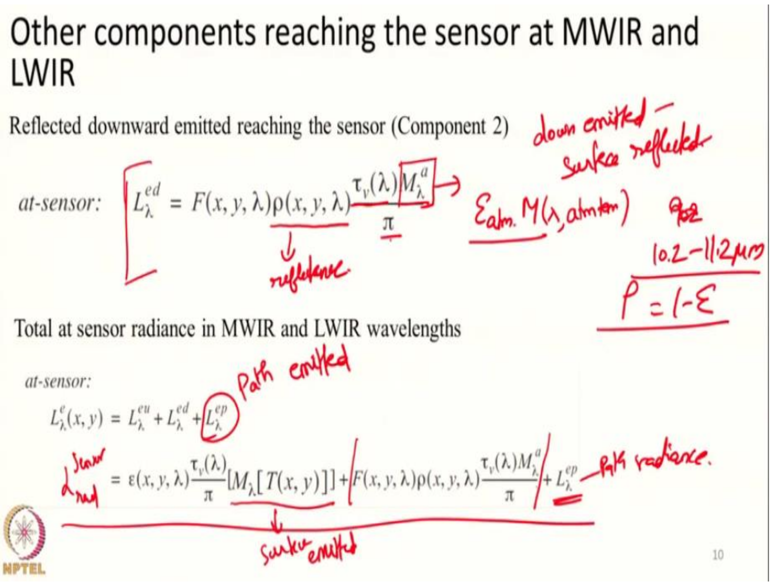

Other components reaching the sensor at MWIR and LWIR

Reflected downward emitted reaching the sensor (Component 2)

down emitted - surface reflected

at-sensor: $L_\lambda^{ed} = \underbrace{F(x,y,\lambda)\rho(x,y,\lambda)}_{\text{reflectance}}\frac{\tau_v(\lambda)\boxed{M_\lambda^a}}{\pi} \rightarrow \varepsilon_{atm.} M(\lambda, \text{atm tem})$

10.2-11.2μm

$\rho = 1-\varepsilon$

Total at sensor radiance in MWIR and LWIR wavelengths

at-sensor:

$L_\lambda^e(x,y) = L_\lambda^{eu} + L_\lambda^{ed} + L_\lambda^{ep}$ Path emitted

Sensor rad $= \underbrace{\varepsilon(x,y,\lambda)\frac{\tau_v(\lambda)}{\pi}[M_\lambda[T(x,y)]]}_{\text{surface emitted}} + F(x,y,\lambda)\rho(x,y,\lambda)\frac{\tau_v(\lambda)M_\lambda^a}{\pi} + L_\lambda^{ep}$ — Path radiance.

Now, the second term down emitted surface reflected component. So, atmosphere has some temperature that is also emitting some energy. So, this is essentially emissivity of atmosphere multiplied by Planck’s law at whatever wavelengths we need at atmospheric temperature. So, again we are applying Planck’s law multiplying with emissivity of atmosphere and getting this. That will reach the earth surface.

Here we are using reflectance of surface okay. That is at this particular wavelengths let us say like 10.2 to 11.2. This is the example we are seeing. At this particular wavelength, what is the reflectance for surface? Reflectance is equal to 1 minus emissivity that also I told you. If you do this that is the fraction of energy that will be reflected back to the space multiplied with $\tau_v$ transmissivity divided by $\pi$. You will get radiance reaching the sensor due to down emitted surface reflected component.

The third component is path emitted component that is what fraction of energy that is emitted by atmosphere reaching the sensor. But again we have to model it using radiative transfer models. We cannot have a measure for it or measure it from the ground. We have to model it from the sensor.

So, the final equation of the radiance reaching the sensor in thermal infrared band comprises again 3 components where this first component is essentially the surface emitted. This is of real interest to us, what is the energy emitted by surface. The second component is surface reflected atmosphere emitted component. This is kind of like noise we do not need this basically. We have to correct for this effect. And third thing is path radiance. Again, we have to correct for it. So, why we discussed all these things in detail? The major reason is the signal received by remote sensing sensor is not simple or direct. Lot of energy components come in and a mixed energy only will be reaching the sensor. What we need? What we do not need? For what things we need to correct? All these things we should be very clear when we do remote sensing.

Say for example, when we do remote sensing either in wavelength less than 3 micrometers or in 8 to 14 micrometers path radiance is unwanted term. It is kind of like a noise that is getting added into the system. We have to remove it. Similarly, if you look at thermal infrared band, there is a small surface reflected component which we do not need. Because whatever emitted by the surface is of real interest to us. We do not need this surface reflection in those wavelengths. We have to remove that effect. So, all these things we should know okay. Why this energy component is coming in? Due to which it is there, whether we should remove it or not, we have to clearly understand it and work according to it.

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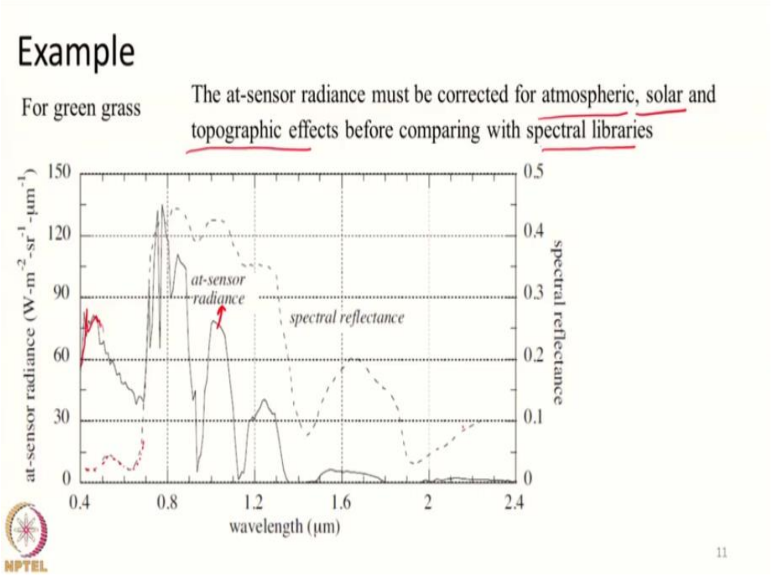

Example

For green grass

The at-sensor radiance must be corrected for atmospheric, solar and topographic effects before comparing with spectral libraries

And I will give a very good example for what will happen in especially in shorter wavelengths in this particular slide. This is the spectral reflectance curve of vegetation, this dotted line. So, I described what is meant by spectral reflectance curve in the last class. So, that is at different wavelengths objects will have different reflectance values. If we plot them together that is known as a spectral reflectance curve. And this spectral reflectance curve, this actually will be helpful for us to identifying the object. If the curve is having a certain pattern we call it okay this is vegetation. If the curve has a certain pattern we call okay this is a water body. Like this, the spectral reflectance curve will help us to identify features. That is why sometimes we call the spectral reflectance curve as spectral signatures.

But this is true only when the signal we have is pure without any contamination, we are taking all the measurements in controlled lab environment in a ground means it is fine. Directly we can measure spectral reflectance. Use it for object identification in remote sensing images. But as I just described in these 2 lectures, the remote sensing signals that reaches the sensor not only has signals about the target of our interest. It also has signals from various other objects like atmosphere, neighbouring pixels, lot of those things. So, finally, if you look at the signals you got from the sensor and try to calculate reflectance from it, we may have something like this what is given the slide, what we need is these dotted lines, what we may get is this dark black line actually. So, this black line is the at sensor radiance.

This is how the shape will look whereas the shape essentially should look like how this reflectance features is. Unless we get this proper reflectance curve, we will not be able to classify this. So, what this at-sensor radiance has? This at-sensor radiance has atmospheric effect, effect from neighbouring pixels and effect due to angle of solar radiation.

If the solar radiation is not perpendicular to the surface we need to multiply with some cos θ terms. If the surface is not flat, if it is slope, there may be other errors and all those things. So, the at-sensor radiance, whatever energy that reached the sensor must be corrected for atmospheric, solar and topographic effects before we compare them with spectral libraries. That is before we compare them with spectral reflectance curve.

Say, unless we correct this dark black radiance curve for all these effects, we will not get this proper spectral reflectance curve for us to do object matching. So, in the next set of lectures, we will be discussing some simple strategies to correct these effects and calculating surface reflectance especially in the wavelengths less than 3 micrometers.

Thank you very much.