Remote Sensing: Principles and Applications
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Lecture-42
Passive Microwave Remote Sensing-Part 3

Hello everyone, welcome to the next lecture in the course remote sensing principles and applications. We are discussing the topic of passive microwave radiometry, in the last lecture we discussed topics such as the atmospheric influence on microwave wavelengths and how antenna is use to measure the microwave signals coming from earth surface. What all the different components from the earth surface and atmosphere system that will reach the antenna. All these basic concepts we discussed, today we will continue with those topics.

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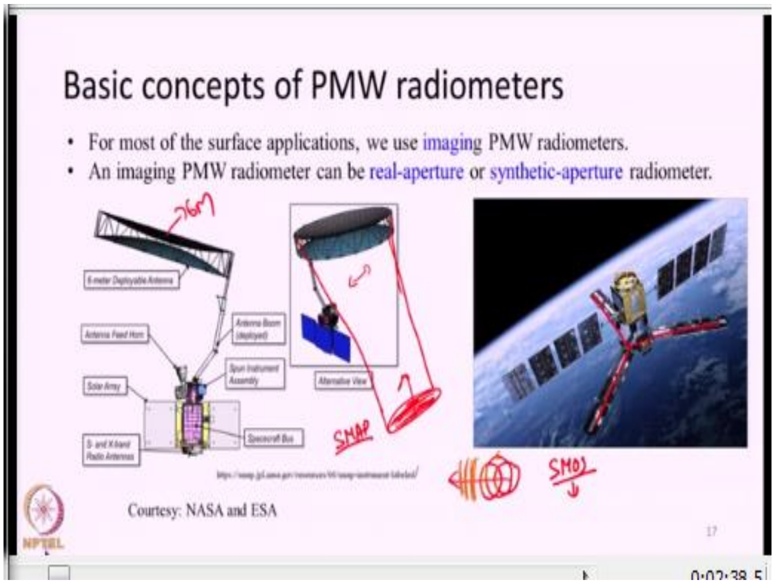

Basic concepts of PMW radiometers

- For most of the surface applications, we use imaging PMW radiometers.
- An imaging PMW radiometer can be real-aperture or synthetic-aperture radiometer.

Courtesy: NASA and ESA

So, in the last class I told you about real aperture radio meter and synthetic aperture radio meter. And also as example I have shown you how data is collected by SMAP satellite which is an example for a real aperture radiometer and SMOS satellite which is an example for synthetic aperture radiometer. So, for this particular lecture, we will not discuss in detail about how synthetic aperture radiometer works rather we will briefly take a look at the real aperture radiometer and its data collection.

So, as shown in this particular slide the SMAP satellite has a antenna and it will be rotating continuously along this particular vertical axis. It will be continuously collecting data in form of circles. So, as the satellite moves the data is going to be collected in this particular fashion, each line is going to be built like this. So, this is the basic working principle of how the real aperture radiometer works.

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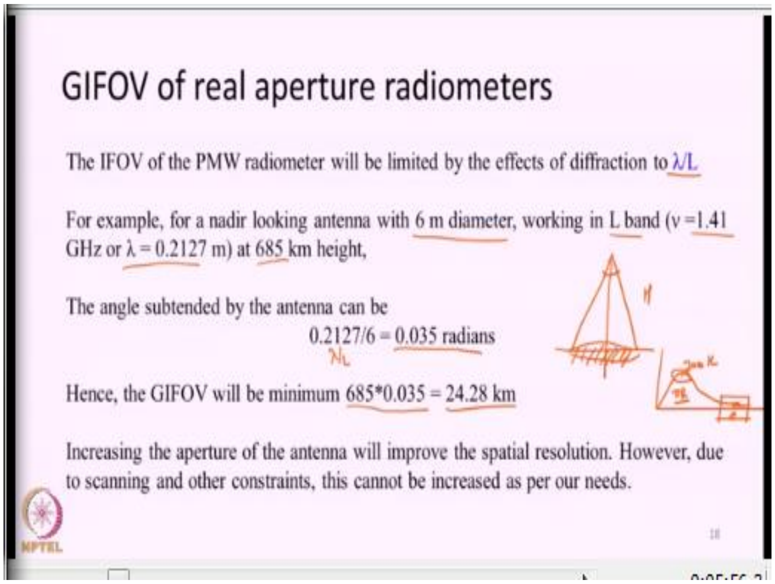

GIFOV of real aperture radiometers

The IFOV of the PMW radiometer will be limited by the effects of diffraction to λ/L

For example, for a nadir looking antenna with 6 m diameter, working in L band (ν =1.41 GHz or λ = 0.2127 m) at 685 km height,

The angle subtended by the antenna can be
0.2127/6 = 0.035 radians

Hence, the GIFOV will be minimum 685*0.035 = 24.28 km

Increasing the aperture of the antenna will improve the spatial resolution. However, due to scanning and other constraints, this cannot be increased as per our needs.

So, now we will get a brief look at the spatial resolution or the GIFOV, the footprint of real aperture radiometers. So, in general each sensor will have a detector element that will subtend a small solid angle on the ground, we have seen it, it is the case for optical sensors too. So, based on that particular solid angle or based on IFOV and the orbital height the sensor will define a footprint, what we call as GIFOV. So, the angle that is subtended by the sensor element on the ground, the IFOV is basically limited by λ/L what we call as antenna beam width where λ is the wavelength in which the microwave radiometer is working and L is the length of the antenna.

So, if we take satellite SMAP, it has a antenna of 6 meter diameter works in L band, so 1.4 gigahertz, λ is roughly 21 centimeters at 685 kilometer height. From these data we can calculate, λ by L, we can calculate the angle subtended by the antenna on the ground as 0.035 radians. So, this is like a circular footprint so you take the orbital height and multiply this angle in order to get the ground coverage. So, we can see that, so the orbital height multiplied by the angle subtended by the antenna will give us a footprint of roughly 24.2 kilometers. So, this suggests a minimum value beyond which the GIFOV cannot become finer. So, actually the SMAP acquires data with a resolution of around 40 kilometers which is much coarser.

So, the minimum limit itself is in the order of 24 kilometers, one footprint of the satellite covers tens of kilometers on the ground. So, this is the general nature of passive microwave radiometers. So, passive microwave radiometers they normally tend to have a very coarse spatial resolution because of this λ/L constraint. And also if you look in a physical sense the energy coming out from the earth surface in a microwave region is very small. If you recall the Planck's curve for earth surface at 300 Kelvin blackbody curve, microwave portion falls in the tail region and the energy emitted by the earth surface is pretty low when compared with this TIR bands. So, the energy is very low and we know that for a sensor to get some meaningful output you should collect some good amount of signal, then only the signal to noise ratio will be high.

And then only it will be able to differentiate between, this is the true signal and this is the noise. So, in order to collect some meaningful amount of signal, the sensor should actually look at a very large area. So, this is a major limitation of passive microwave radiometers though they are all weather capability. The coarse spatial resolution actually limits the application of passive microwave radiometry to different fields.

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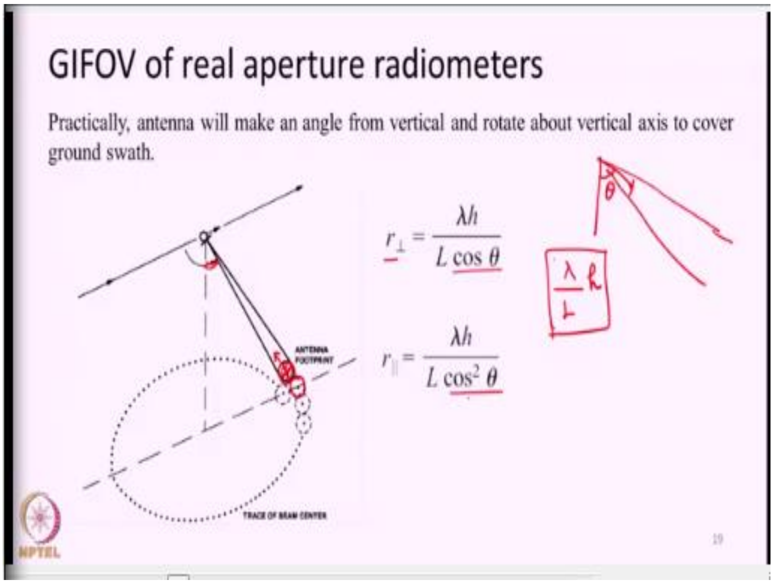

GIFOV of real aperture radiometers

Practically, antenna will make an angle from vertical and rotate about vertical axis to cover ground swath.

$$r_{\perp} = \frac{\lambda h}{L \cos \theta}$$

$$r_{||} = \frac{\lambda h}{L \cos^2 \theta}$$

$$\boxed{\frac{\lambda}{L} h}$$

So, the calculation that we made for the radiometer, λ/L accounting for the 24 kilometers is actually for a nadir looking antenna. But most of the cases real aperture radiometers the antenna may not be nadir looking, it may be tilted away from the nadir. Say for example in SMAP, it is tilted roughly about 40 degrees away from the nadir. So, essentially the spatial resolution what we calculated that is $(\lambda/L)\times h$ where h is the orbital height, this was the formula we use to roughly calculate the spatial resolution. But since the antenna is looking away from the nadir, we also have to account for that particular thing. So, the antenna footprint may not be even like having that resolution of 24 kilometers. It has to be adjusted for the cos θ terms and cos square θ terms, like in which direction it is basically looking. So, if the dimension of this particular footprint is in a direction perpendicular to the scan angle, then the dimension will be $\lambda h/L\cos\theta$ and parallel to the cross section the dimension will be $\lambda h/L\cos^2\theta$.

So, this suggests the spatial resolution what we calculated, the 24 kilometers itself is a very small number. The actual resolution by this limitation of antenna beam width itself is pretty high, will be in order of say 27, 28 kilometers and hence the passive microwave radiometry especially the real aperture radiometers are coarse spatial resolution in nature. So, as the frequency increases, say these 2 SMAP and SMOS satellites or L band, C band or X band, the spatial resolution will improve to some extent because we have this λ/L term.

But again as we all know, as the wavelength decreases, say it becomes to X band or C band then the atmospheric attenuation may become high. And the satellite may not provide us the all weather capability that we normally require from a passive microwave system.

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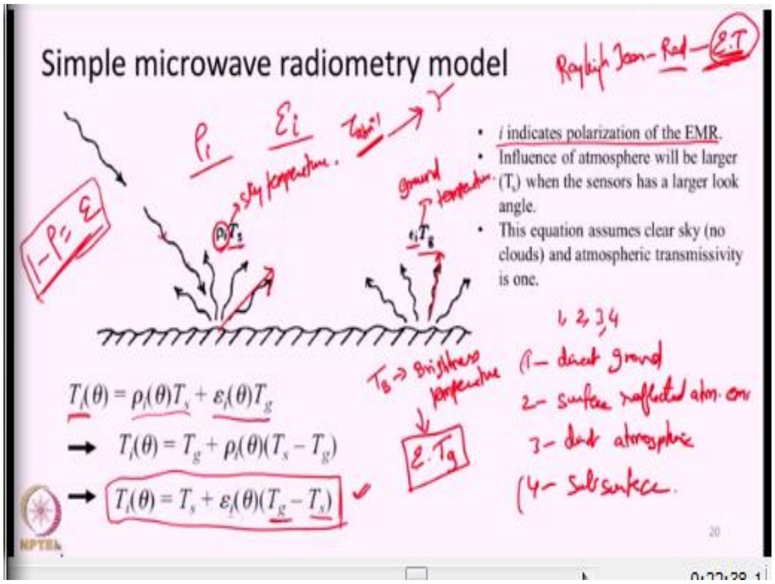
So, now let us take a look at a very simple microwave radiometry model in which the different components of the signals from the earth surface gets mixed with each other. So, initially when I told the different components of the signal that is reaching the microwave antenna, I told you that there can be direct signal from the ground, there can be surface reflected atmospheric emitted component, there can be atmospheric emitted component and so on.



Simple microwave radiometry model

- *i* indicates polarization of the EMR.
- Influence of atmosphere will be larger (T_s) when the sensors has a larger look angle.
- This equation assumes clear sky (no clouds) and atmospheric transmissivity is one.

$$T_i(\theta) = \rho_i(\theta)T_s + \varepsilon_i(\theta)T_g$$

$$\rightarrow \quad T_i(\theta) = T_g + \rho_i(\theta)(T_s - T_g)$$

$$\rightarrow \quad \boxed{T_i(\theta) = T_s + \varepsilon_i(\theta)(T_g - T_s)}$$

So, initially we discussed 4 different paths were first path is direct emission from ground, second path this surface reflected atmospheric emission, third path is direct atmospheric emission and fourth is subsurface emission. So, these four paths I told you, so if we combine, path 1 and 4 the direct ground and subsurface has one with each other. Because both of them anyway indicates the signal from ground. If that is the case, then we will discuss the total signal that is going to reach the antenna or going to move towards the antenna from the ground surface. So, here we have a land surface with a temperature T_g ground temperature. We have the surface has an emissivity of ε_i, where i indicates the polarization of EMR.

As I told you the signals emitted by the earth surface will vary with the polarization and the polarization effect is highly noticed in microwave domain. So, the emissivity varies with polarization and hence the signal or the radiation emitted by earth surface will vary with polarization. We will not care about this polarization effect in optical remote sensing or thermal infrared remote sensing but in microwave the effect of polarization has to be taken care of, because earth surface objects have different, different characteristics in different, different polarizations. So, here we have to take into account the variation of emissivity with respect to polarization also.

In microwave radiometry, brightness temperature is a product of surface emissivity and the temperature of that particular surface. So, we will think in terms of brightness temperature because as per Rayleigh-Jean approximation, the radiance emitted by the surface is directly proportional to the product of emissivity and temperature. So, rest of the terms will be a constant, so this will be the only term that will be vary. So, rather than talking in terms of radiance, it is easy to talk in terms of brightness temperature in passive microwave radiometry. So, we will just look at how objects interact or how objects emit in terms of their brightness temperature.

We have an atmosphere, so the atmosphere has a temperature of T_s where people call it as sky temperature and the signals or the radiance emitted by the atmosphere will move towards the earth surface and a portion of it will get reflected towards the antenna. So, here the surface has a reflectance of ρ_i and it has an emissivity of ε_i.

So, Kirchhoff's law suggest that $1 - \rho$ = emissivity. So, in a given polarization and a given wavelength, the surface has an emissivity of ε_i and it also has a reflectance of ρ_i where i indicates the polarization, and this is the relationship between emissivity and reflectance. So, the total brightness temperature from this particular land surface that moves towards the atmosphere, basically depends on two components one is the T_g multiplied by emissivity of the surface, that is ground temperature multiplied by emissivity of surface and the other component is T_s multiplied by reflectance of surface. So, you can just replace emissivity with reflectance in order to get this particular equation.

So, essentially what this suggests is the total net temperature of this particular surface that comprises of both the surface emission or atmospheric emission is almost a linear combination of the ground temperature and the atmospheric temperature. So, there holds a direct relationship between the brightness temperatures that is going out and the brightness temperature of individual components whereas, in thermal infrared remote sensing, we discussed all these in terms of radiance. If you just recall the earlier lectures, I was explaining all these components in terms of radiance.

Because there the relationship between radiance, temperature and emissivity are highly nonlinear, the original form of Planck's function is what we were using. Here in microwave wavelengths, since we can apply Rayleigh Jean approximation, which tells us the radiance is directly proportional to the product of emissivity and surface temperature which is the brightness temperature. So, it is easy for us to think in terms of temperature itself rather than thinking in terms of radiance and finally converting in terms of temperature. So, this is a very simple explanation or a very simple model of telling what will be the different components from the ground that will move towards the sensor.

But here we have not spoken anything about the atmosphere, we just spoke about the ground components. And we also assumed atmospheric transmissivity is equal to 1. So, just to show how emissivity or the brightness temperature varies with the incidental angle or the polarization, we have given 2 simple plots, we will just have a brief look at it.

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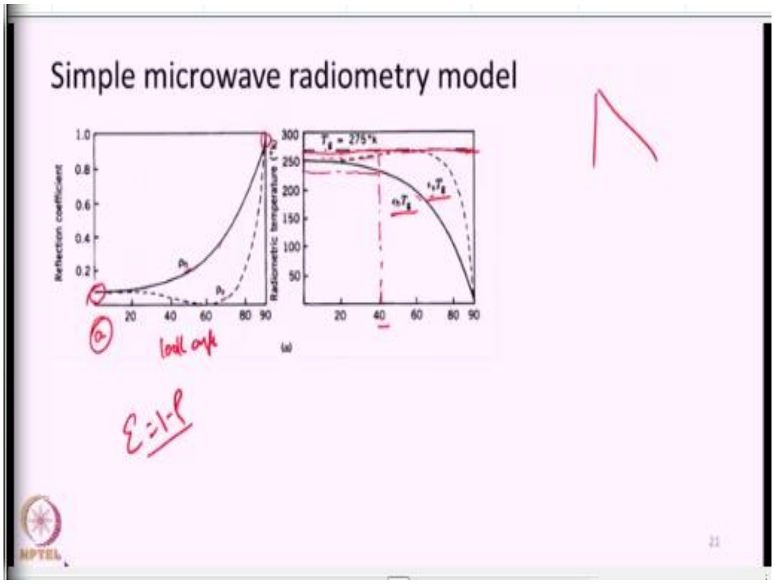

Simple microwave radiometry model

So, the plot on the left side, we will label it as figure a, figure a tells us how the surface reflectance varies with respect to the incidence angle or we can call it as look angle. And the polarization, h represents horizontal polarization, v represents the vertical polarization. So, here we can observe that with respect to polarization or with respect to the angle, the reflectance of the surface varies a lot. So, at very low angle of incidence we can say that the reflectance is pretty low, and it suddenly increases all the way to 1 at very high incidence angle. So, the reflectance is highly varying. Similarly, emissivity which is equal to 1 - reflectance that will also vary in the same way, because these 2 share a common relationship with each other.

So, just for this particular ground pixel, which we assumed had a ground temperature T_g, if we assume it has 275 Kelvin, just as an example. So, this top horizontal line indicates the ground temperature T_g the true temperature and the brightness temperature recorded you can see how it varies, say the black dotted line here indicates the vertical polarization and this black solid line indicates the horizontal polarization. So we can observe how the brightness temperature changes with respect to the look angle and the polarization. Say for example, we will take at a 40 degree angle, at horizontal polarization the brightness temperature is roughly about 240 to 245 Kelvin. Whereas, in vertical polarization the temperature is about in the order of 250 or 255 Kelvin.

So, this suggest that the same surface at a given temperature will produce a completely different brightness temperature when the surface is looked at different angles or at different polarizations. And the effect of polarization on look angle on emissivity is pretty strong, so it will vary a lot with respect to the angle in which we look and the polarization in which we observed. So, this thing has to be taken care of, when we try to observe a surface and use that particular brightness temperature for different applications.

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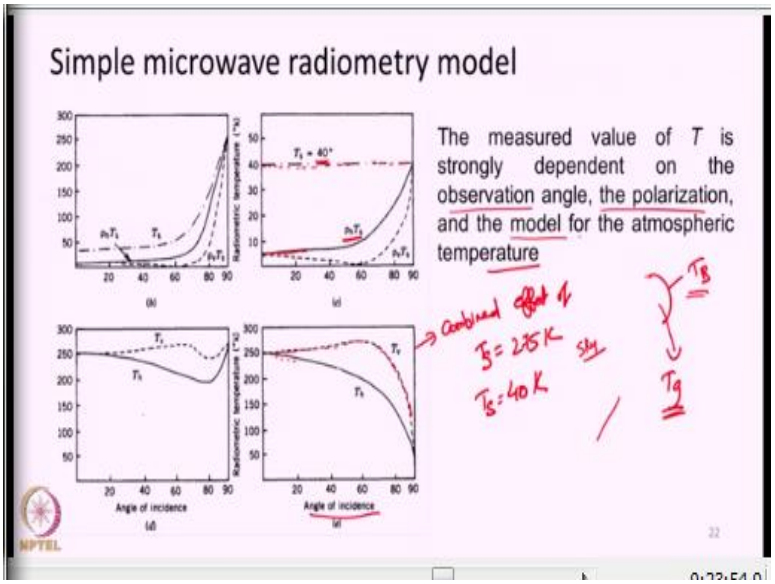

Simple microwave radiometry model

The measured value of T is strongly dependent on the observation angle, the polarization, and the model for the atmospheric temperature

In the last slide, we just looked at how the surface temperature will vary with emissivity of the surface with different look angles. Here if we take into account the atmospheric emission also then, it has two components, direct emission from the surface and atmospheric emitted component.

So, if we assume the sky has a temperature of 40 Kelvin and if we take the reflectance and multiply with that sky temperature we can get the effect of the sky component that is going to move towards the antenna. So, here also we can see based on the polarization and based on the observation angle, the effect of atmosphere or the temperature of the atmosphere that is going to get added up will vary. So, this is like the total effect or the combined effect of ground temperature T_g = 275 Kelvin and the sky temperature T = 40 Kelvin. So, if we combine both of them, this is how the net signal will look like. The net brightness temperature = (sky temperature + emissivity) × (T_g – T_s). So, this equation is the net relationship and the net value for that angle of incidence and the polarization.

So, this suggests that the brightness temperature T is strongly dependent on the observation angle, the polarization and also the model for atmospheric temperature. Because normally when we want to disentangle or remove the effect of atmosphere the brightness temperature will have a combined effect of surface and atmosphere. So, we need to use some sort of models or radiated transfer equations to calculate the sky temperature or atmospheric temperature to remove the effects and separate only the effect of this T_g. So, all these factors have to be taken care of when we work with the passive microwave radiometry signals. So, just compare this in analogy with the optical remote sensing. In optical remote sensing the objects will look completely different when we change the look angle and same thing will happen here also.

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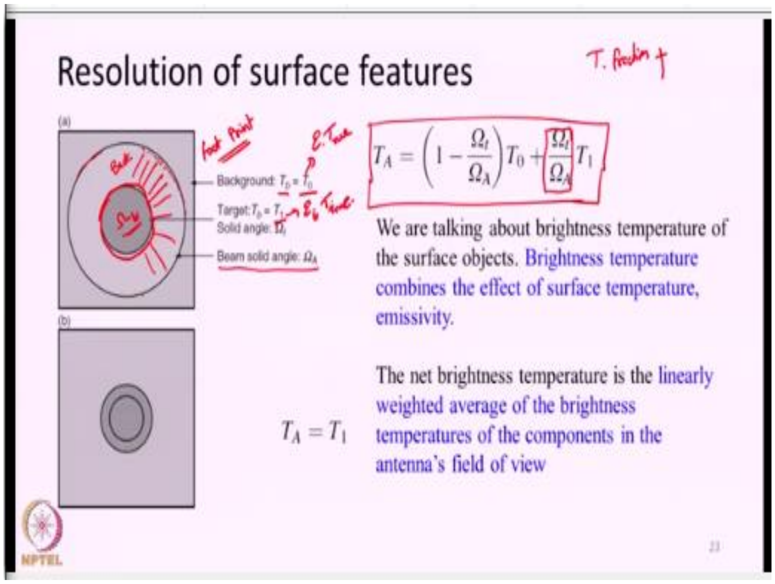

Resolution of surface features

$$\boxed{T_A = \left(1 - \frac{\Omega_t}{\Omega_A}\right) T_0 + \boxed{\frac{\Omega_t}{\Omega_A}} T_1}$$

We are talking about brightness temperature of the surface objects. Brightness temperature combines the effect of surface temperature, emissivity.

$$T_A = T_1$$

The net brightness temperature is the linearly weighted average of the brightness temperatures of the components in the antenna's field of view

So there is no separate external sources involved, but by changing the geometry of the instrument, by changing the look angle or by changing the polarization we are going to get a different picture of the same object that is there on the ground surface. The resultant brightness temperature what we are going to get will be highly influenced by these directional effects and polarization effects.

So, this slide again tells us the net effect of the resolution of two different objects within a given GIFOV. So, this is like a one single footprint of the satellite. So, here what we are discussing is, there is one particular target object with the brightness temperature T_1. It is surrounded by a background, let us say this is ocean and this is a small block of ice on the ocean. So, the ocean water will be at a different temperature, the ice block will be at a different temperature.

So, T_0 and T_1 are two brightness temperatures, so that is the product of emissivity of that particular object multiplied by it is true temperature. Similarly, for the target also, this is the product of emissivity of that particular object say emissivity of T target determined by it is true temperature, so these are brightness temperatures.

So, the total solid angle subtended by the sensor in one go is this, among which the solid angle subtended by the target is a small fraction, say ω_A and ω_T. So, the net resultant brightness temperature can be simply given by the fraction of the solid angle occupied by the target $(\omega_T/\omega_A) \times T_1$ where T_1 is the brightness temperature of target. So, 1 minus of this fraction will give us the remaining portion of the solid angle occupied by the background multiplied by background temperature.

So, this will be the net brightness temperature that will be reaching or that will be reflected in the sensor. So, just take an analogy with the thermal infrared remote sensing. In thermal infrared remote sensing, I told you that if a pixel has more than one feature that does a mixed pixel then the net resultant radiometric temperature depend on the weighted average of radiance coming out from each object and the net resultant emissivity we have to take into account.

So, it is a complex nonlinear relationship we discussed in detail, the definition of radiometric temperature for a mixed pixel. Here in this case, in passive microwave radiometry it is a very straightforward thing. If a pixel has more than one feature, we need to know the individual brightness temperature not the true temperature because that is what the sensor will basically sense. So, each individual object's brightness temperature weighted by their fraction occupied within that particular GIFOV will give us the net resultant brightness temperature for that particular pixel. So, it is easy for us to resolve the total brightness temperature of the pixel. so concept wise it is easy to understand. So, the net resultant temperature brightness temperature of a pixel is given by the weighted average of brightness temperature of each and every feature present within this pixel where the weights are given by the fraction of the area occupied by each feature within that particular footprint.

So, as a summary, in this particular lecture we discussed about the spatial resolution of real aperture radiometers and discussed a very simple model to describe how the brightness temperature from a pixel containing more than one feature will be reflected. And also the effect of atmosphere which means how the brightness temperature of the ground and the brightness temperature of the atmosphere will add up in reaching the sensor. So, with this we end this particular lecture.

Thank you very much.