Slide 1 – Title Slide

Hello and welcome to Week 3, Part 2 of EGM703: Surface and Atmospheric Interaction. In this lesson, we'll cover how microwaves interact with the Earth's surface and atmosphere.

Slide 2 – EMR and Earth Surface

We've seen this slide before, but I'm including it here as a reminder of the different ways that electromagnetic radiation interacts with the Earth's surface. We'll be expanding on this as we go, but this is a good place to start from.

Slide 3 – Kirchoff's radiation law

This is another slide that we've seen before, but I'm going to make one addition for this lesson. For microwave radiation, this fact means that we can derive emissivity (which we need for applications of passive remote sensing), using measurements of reflectance (which we can get from active remote sensing) – we have a nice synthesis of the two different approaches.

Slide 4 – Propagation of waves

We've mentioned quite a few times already how electromagnetic radiation is a self-propagating wave. Most of what we've considered, though, is based on electromagnetic radiation propagating in a vacuum – we need to also consider how it propagates through different media. We've mostly been focused on the atmosphere, but microwaves can actually penetrate into different media, so we need to also think about what it is that we're observing. It turns out that this depends on the material's electromagnetic properties: the electric permittivity, ε. Yes, it annoys me that this is the same variable as we've used for emissivity, but we'll press on. The electric permittivity describes how susceptible a material is to becoming polarized by an electric field – that is, how well it can store or transmit electric charge. The next property is the magnetic permeability, denoted μ. This describes how a material responds to a magnetic field – a higher magnetic permeability means that the material is more likely to become magnetized. Finally, we have the electric conductivity, denoted as g. This depends on how mobile electrons in a material are – in metals, for instance, electrons can move freely throughout the material, meaning they have a high electric conductivity. From Maxwell's equations and the theory of electromagnetism, it turns out that electromagnetic waves cannot propagate in a conducting material: the electric field component induces a current in the material that dissipates the energy of the wave. As a result, electromagnetic waves are (almost) totally reflected by conductive materials. For non-conductive materials, also known as dielectric materials, the electric permittivity is the most relevant, and the one we'll cover in more detail.

Slide 5 – Electric permittivity

The electric permittivity describes how an electric field interacts with a dielectric material, or medium. It describes how well an electric field polarizes the molecules in a material, or how well the material transmits the electric field. We normally describe the permittivity of a material relative to the permittivity of a vacuum, ε_0: here, ε_r is given as a dimensionless value. Because the interaction of an electromagnetic wave with a material causes a change of phase of the electromagnetic wave, we often consider permittivity as a complex number, with ε' corresponding to the real part of the permittivity, and ε'' corresponding to the imaginary part. You may also hear or see the term "dielectric constant" – most of the time, this is only referring to the real part of the complex electric permittivity.

Slide 6 – Electric permittivity

As an electromagnetic wave travels through a dielectric medium, it interacts with the molecules or atoms of that medium, causing it to lose, or attenuate, energy. If we look again at the different components of the electric permittivity, the real part, ε', or the dielectric constant, is lossless. It … The imaginary part, ε'', tells us about how the material absorbs electromagnetic radiation – it relates to the energy loss as a result of propagation through the dielectric medium. One thing to keep in mind is that the attenuation happens exponentially – that is, the amplitude of the electromagnetic wave decays exponentially as a function of depth in the material. We can estimate the depth, or distance, at which the amplitude is reduced by a factor of e (Euler's constant), using this equation. This depth is known as the penetration depth – we can see here how it depends on the different components of the electric permittivity. As long as the real part is larger than about 10% of the imaginary part, and as long as we can ignore scattering effects inside of the material, this approximation holds. For microwave remote sensing, most materials have at least some penetration depth, with the exception of liquid water and materials such as very wet snow. At the risk of spoiling things for you, it turns out that liquid water, which plays a massive role in the dielectric properties of a material, is extremely important in microwave remote sensing. A small amount of liquid water on a surface can completely change how the surface appears using radar, for example.

Slide 7 – Scattering

At boundaries between media that have different dielectric properties, electromagnetic radiation is somehow redirected, or scattered. For example, the ordered redirection of electromagnetic radiation from a "smooth" surface is something that we've seen quite a lot – we've just called it reflection. Most of the time when we talk about scattering, we mean a random redirection of electromagnetic radiation – for example, this could be absorption and re-emission of radiation for small-diameter particles, or it can mean physical scattering of radiation for larger particles – think pool balls, or bowling pins. We have two main cases of scattering that we'll consider in microwave remote sensing: the first is scattering from surfaces, which happens when the area of the scatterer is much larger than the wavelength; the second is scattering from objects, which happens when the area of the scatterer is about the same size as the wavelength.

Depending on the size of the particle, there are three main mechanisms, or types, of scattering.

Rayleigh scattering is caused by particles with a diameter d that's around 1/10th of the wavelength – usually atmospheric molecules such as oxygen or nitrogen. The amount of Rayleigh scattering also strongly depends on the wavelength of the light – it's proportional to 1 over the wavelength to the fourth power – this means that blue light at about 400 nm scatters about 5 times more than red light at about 700 nm. This is why the sky appears blue to us during the day – blue light is scattered from all portions of the sky. Rayleigh scattering is also partly why the sky appears red or orange during a sunset. Near the horizon, the sun's light travels through more of the atmosphere – as a result, shorter wavelengths are more preferentially scattered away from the observer, and so the light that we see has longer wavelengths.

Mie scattering is caused by particles that are between 1/10th and 10 times the wavelength – this is usually things like dust or smoke particles, or even smaller water droplets. The amount of scattering depends less on wavelength – rather than 1 over lambda to the fourth, it's only 1 over lambda. If you've seen any of the apocalyptic images from areas affected by wildfires over the past year – for example, Australia in 2019/2020, the dark, orange or red skies that you see in those photos is a result of Mie scattering. Dust storms can have a similar effect, caused by the same mechanism.

Non-selective scattering occurs with particles that are bigger than about 10 times the wavelength of the electromagnetic radiation – it's called non-selective because it scatters all wavelengths equally. This is caused by large water droplets or ice crystals, usually in the form of clouds. From the ground, clouds normally appear white to gray, owing to the relatively even scattering across wavelengths. Another classic example of non-selective scattering is fog – the dull gray color of fog is caused by even scattering of relatively low levels of light.

Slide 8 – Scattering cross-section

We can measure how effective a scatterer is using something called the scattering cross-section, or σ. The scattering cross section, as a function of direction θ, is the ratio of the scattered power per unit solid angle into the direction we're measuring from to the intensity of the original plane wave, divided by 4π (to make sure that it's also in units of power per solid angle). For radar systems, we call this the radar cross section, and it's the ratio of the received power to the power sent by the transmitter, multiplied by 4π, multiplied by the distance between the transmitter and the target, R, squared. From this, you can see that this will have units of area (m^2). Because this depends on the resolution of our radar sensor, we normally divide this by the area of the object to get the normalized radar cross section, σ^0, also called "sigma nought" or the diffferential radar cross section. This is one of the fundamental properties that we measure with radar remote sensing. Because it is normalized by area, it is unitless – it is a property of the thing that we're observing (the "target"), not the measurement geometry of our system.

Slide 9 – Types of scattering

We can categorize scattering into four main categories:

The first is scattering from a smooth, or "specular," surface. For microwave remote sensing, a common example of this is calm water bodies – the water surface reflects almost all of the signal away from the sensor.

The second is scattering from a rough surface. We can break these into two different categories: the first, randomly rough surfaces, include agricultural fields or low vegetation (think grasses). Scattering from periodically rough surfaces is called Bragg scattering – common examples of this might be wind-driven ocean surfaces, crops types that are planted in regular rows, or agricultural fields that are plowed in a regular pattern.

The third is scattering from corner or edge reflectors – these are surfaces that very effectively reflect electromagnetic waves back to the sensor, and so appear very bright. These can include buildings or other human-built structures; some natural surfaces can also serve as corner reflectors. Scientists often deploy large corner reflectors – because they're easily detected in an image, and because we can measure their precise location, it helps to both calibrate and geolocate radar systems.

Finally, we have volume scattering. A volume scatterer is composed of randomly-distributed scatterers – the signal returned is due to elements inside of the media, rather than the surface – in part because microwaves tend to have some penetration depth into most media. How much volume scattering occurs from a given media depends on the wavelength, but some common examples include dry snow, deep, dry sand, or dry soil; forests, and ice.

And, just to be clear here: when we say a surface is "smooth", what we mean is that the irregularities of the surface are much smaller than the wavelength of the electromagnetic radiation – surfaces such as asphalt and tarmac can appear smooth at microwave wavelengths, even if the surface would appear rough to us, because it's the scale that's important here. Conversely, we say that a surface is "rough" if the irregularities are of a similar size as the wavelength, or if they are larger than the wavelength.

In addition to the properties of the surface, the amount of scattering that we measure will also depend on the incidence angle – similar to what you have seen in previous modules for visible and infrared remote sensing.

Slide 10 – The atmosphere

At microwave wavelengths, Earth's atmosphere is almost completely transparent – we can see here that after around 5-6 mm or so, the atmospheric transmittance is very high. This includes clouds: one of the major advantages that microwave remote sensing has over visible or infrared remote sensing is that it is very often independent of weather: we can make observations day or night, even with heavy cloud cover. As you can imagine, if we're studying polar regions, this is an especially useful property. The one big exception here is the ionosphere, which is the ionized portion of Earth's atmosphere, which ranges from around 50 km above Earth's surface to around 950 km above Earth's surface. By "ionized", we mean that there are lots of electrons and charged atoms and molecules floating around. This is part of what gives us the aurorae, or northern/southern lights; it can also make microwave remote sensing more of a challenge. This happens in particular through process known as Faraday rotation, which is the rotation of the polarization vector of an electromagnetic wave as a result of traveling through a charged medium in the presence of an external magnetic field. Depending on the wavelength or frequency of our sensor, this changes what we measure. This example here, from a paper by Wegmüller and others, shows the effects of this on estimates of surface displacement derived from L-band (wavelength ~24 cm) radar. On the left, we have the estimated offset in the range direction (more on this later). In the center panel, we see the estimated offset in the azimuth direction – notice the clear bands of blue and green here. On the right, we have the estimated ionospheric azimuth offsets due to Faraday rotation of the received signals. Depending on our application, these kinds of processes might be critical to understand and correct.

Slide 11 – Summary

In this lesson, we've discussed how microwave interaction with a material depends heavily on the electromagnetic properties of that material.

We've also recapped how scattering, or redirection, of electromagnetic radiation takes place at the boundary between different media – for example, the Earth's surface. For microwaves, because of the long wavelengths involved, we see primarily non-selective scattering; the exact mechanism involved depends on the "smoothness" of the surface or boundary, relative to the wavelength.

Finally, we've seen how the atmosphere is mostly transparent to microwaves, although the ionosphere can pose a significant problem (depending on the application).

Slide 12 – Additional resources

You can read more about the topics we've discussed here in the textbooks – Lillesand, Kiefer & Chipman, Chapter 1.3, or Cambpell & Wynne, Chapters 2.5-2.6, and 7.4-7.6. I've also included a link to this paper from Wegmüller and others, showing the ionospheric effects on estimates of surface displacement. Finally, I've included a couple of links to some videos here – one that covers scattering (and why the sky appears blue to us), the other covering specular and diffuse reflection. That's all for this lesson – I hope you found it interesting, and you have any questions, please don't hesitate to e-mail me or post in the discussion forum on blackboard. Bye!