# GEOS 657 – MICROWAVE REMOTE SENSING

GRADUATE-LEVEL COURSE AT THE UNIVERSITY OF ALASKA FAIRBANKS

**Lecturer:**
Franz J Meyer, Geophysical Institute, University of Alaska Fairbanks, Fairbanks; fjmeyer@alaska.edu

**Lecture 3: Properties and Propagation of Electromagnetic Waves**

UAF Course GEOS 657

## Think – Pair – Share

Today we will talk about the main quantitative parameters of EM waves, including frequency $f$, amplitude $A$, phase $\varphi$, and polarization.

Radar remote sensing is one of very few techniques that can exploit **all** of these parameters for earth observation

- The ability of radar system to exploit signal polarization particularly unique! *Why do you think radar's can exploit polarization why most optical systems cannot?*
- Radars also are good at exploiting interference and phase difference measurements for analyzing the ground. Other systems that are good at that are, e.g., Lidars and GPS. *What system property do you think allows them to use interference and phase as a source of information?*

## PHYSICAL PROPERTIES OF EM WAVES

## Importance of Understanding EM Wave Properties

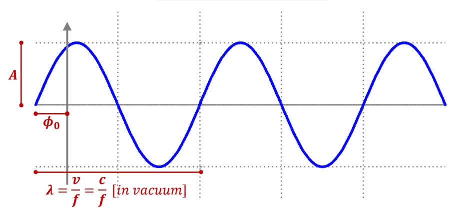
- **Allow qualitative and quantitative description of EM waves**
- **Qualitative:**
  - Understand how microwaves are created
  - How the are measured
  - How the interact with other media or discrete objects
- **Quantitative:**
  - Quantify physical processes (e.g., scattering) in terms of measurable parameters (e.g., frequency, polarization, directions, …)



## Wave Description of EM Signals

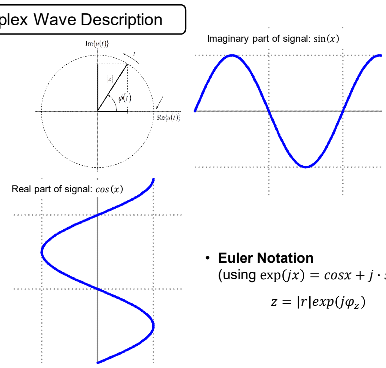
- Simplest way of describing a wave: Harmonic waves (= sine wave)
- Typically we use three parameters to describe harmonic waves:

$$\Psi(t) = A \cdot sin(2\pi f t + \phi_0)$$






## Complex Wave Description



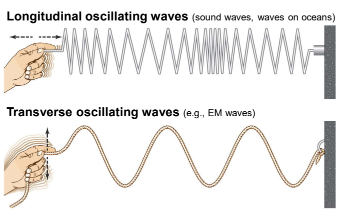

- **Euler Notation**
  (using $\exp(jx) = cosx + j \cdot sinx$)

$$z = |r| exp(j\varphi_z)$$

## SIGNAL POLARIZATION



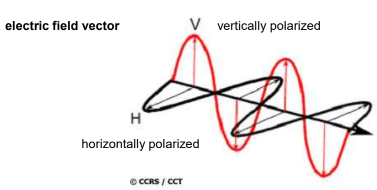
## Transverse vs. Longitudinal Oscillation




Traverse oscillating waves (like EM waves) have one additional degree of freedom: Direction in which oscillation takes place, **called Polarization**



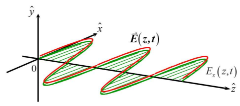
## Polarization States of a Coherent Plane Wave

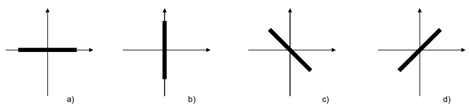



- Polarization planes are perpendicular – orientation technically arbitrary
- Usually, horizontal and vertical planes are chosen
- The terms horizontal and vertical then refer to either the earth or the antenna surface

## Linearly Polarized Signals

- **Several stages of linear polarization possible**
  - Horizontal polarization (a)
  - Vertical polarization (b)
  - Linear -45º polarization (c)
  - Linear +45º polarization (d)

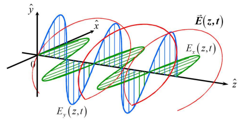


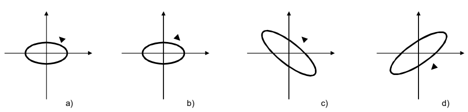






## Circular and Elliptical Polarization

- **Combination of vertically and horizontally polarized signals**
  - Right circular polarization (a)
  - Left circular polarization (b)
  - Right elliptical polarization (c)
  - Left elliptical polarization (d)



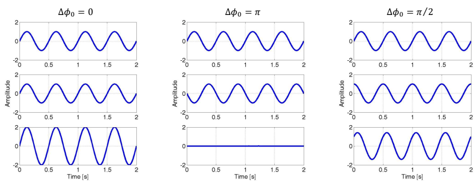






## Interference and Coherence

## Combination of Waves

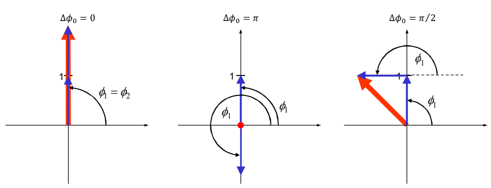
- Superposition of waves called *interference* (e.g., two waves: $\psi = \psi_1 + \psi_2$)
- As $\psi_1$ and $\psi_2$ can have different amplitude, frequency, and phase, the shape of $\psi$ is not straightforward
  - **Examples:** $A$ and $f$ of waves kept the same; $\phi_0$ can vary






## Combination of Waves

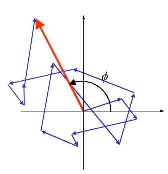
- **The result of interference can be easier calculated in the complex plane**
- In the complex plane, the addition of two waves $\psi_1$ and $\psi_2$ is simply their vector sum






## Interference and Coherence

- Waves with phase differences that remain constant over time are said to be ***coherent***
- Coherent waves → combined wave vector is stationary
- If coherence is low, interference effects are less predictable
- Coherence can be seen as measure of predictability



## How to Quantify Coherence

**Measure similarity of two waves over finite interval of time or space**

- correlation coefficient between the two complex SAR images $u_1$ and $u_2$:

$$\gamma = \frac{E\{u_1 \cdot u_2^*\}}{\sqrt{E\{|u_1|^2\} \cdot E\{|u_2|^2\}}}$$

**Practical way to calculate coherence**

$$|\hat{\gamma}[i,k]| = \frac{|\sum_W u_1[i,k] \cdot u_2^*[i,k]|}{\sqrt{\sum_W |u_1[i,k]|^2 \cdot \sum_W |u_2[i,k]|^2}}$$

$W$: small window centered around pixel $[i,k]$



Add boardwork below

## SOME BASICS ABOUT PROPAGATION OF MICROWAVES



## Propagation through Media other than Vacuum

- To quantify interaction of EM waves with materials or a medium, electromagnetic properties of these materials need to be known
- EM properties of materials are frequency dependent

- **Three terms used**:
  - Electric permittivity $\varepsilon$
  - Magnetic permeability $\mu$
  - Electric conductivity $g$
- For non-conductive, so called *dielectric* materials (most solid materials), only *electric permittivity* $\varepsilon$ is usually considered



## Electric Permittivity – Most Important Material Parameter for Remote Sensing

- Describes how electric field affects and is affected by a dielectric medium
- Relates to a material's ability to transmit an electric field

- The permittivity properties of a material $\varepsilon$ are usually described relative to the permittivity of vacuum $\varepsilon_0$ using a relative permittivity parameter $\varepsilon_r$

$$\varepsilon = \varepsilon_r \varepsilon_0$$

$\varepsilon_r$ is variable of interest

- As interaction with material causes a phase change in addition to an amplitude change, permittivity is given as a complex number

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

- Electric permittivity is often referred to as **complex dielectric constant**
- **$\varepsilon_r$ can vary dramatically for different materials**

## Meaning of the Dielectric Constant

- **Parameterize microwave interactions (surface scattering, volume scattering, absorption, penetration) with a material**

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$$

Real Part — Imaginary Part

- Real part $\varepsilon_r'$ defines if signal penetrates or gets reflected at surface
- Imaginary part $\varepsilon_r''$ defines energy losses (absorption) on both surface and volume → defines how deep signals penetrate and now much of the incoming energy will be re-emitted
- The dielectric properties define the propagation speed of EM waves:

$$v = \frac{1}{\sqrt{\varepsilon_r}}\frac{1}{\sqrt{\varepsilon_0\mu_0}} = \frac{c}{\sqrt{\varepsilon_r}}$$

$\sqrt{\varepsilon_r}$ is often referred to as the "refractivity index"



## Dielectric Properties Describe Signal Attenuation in Lossy Media

- In homogeneous lossy media (e.g. atmosphere, dry snow, sand, ...) $\varepsilon_r''$ describes energy losses
- Attenuation acts exponentially → exponential decay of wave amplitude with propagation depth
- Propagation depth $\delta_p$ is distance at which power is reduced by factor $e$ (drop to about 37% of original power)

$$\delta_p \approx \frac{\lambda\sqrt{\varepsilon_r'}}{2\pi\varepsilon_r''}$$

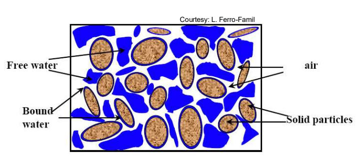
- For most microwave applications, some penetration occurs except for liquid water or very wet snow.



## Dielectric Properties and Surface Moisture Content

- Dielectric properties of soil is a function of the soil composition of solid particles, **soil moisture (free and bound water)**, and air pockets

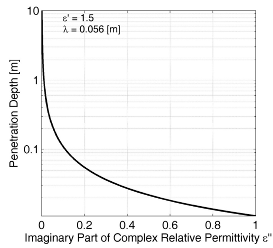
Soil composition




- **Water content of soil is important parameter in defining $\varepsilon_r$**

## Penetration Depth as a Function of $\varepsilon_r$

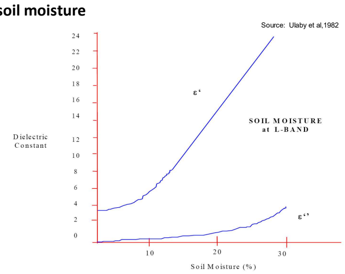
- **Example:** $\varepsilon_r$ parameters similar to **dry snow** with varying moisture level
- C-band radar ($\lambda = 0.056\ [m]$)
- Penetration depth up to 10 m for low moisture content






## Dielectric Properties and Surface Moisture Content

- **Dielectric constant proportional to soil moisture**
  - High moisture
    → high dielectric constant
    → low penetration
    (surface scattering)






## Types of Interactions with Media

- Depending on dielectric properties of medium, signals can be **reflected**, **absorbed**, or **transmitted** through medium:
- **Reflectivity $\rho$:**
  - Ratio of reflected power to incident power in a given direction
  - Complete reflection: $\rho = 1$
- **Transmissivity $\Upsilon$:**
  - Ratio of power transmitted through a medium to the power incident on the surface of the medium
  - Transparent medium: $\Upsilon = 1$; opaque medium: $\Upsilon = 0$
- **Absorptivity $\kappa$:**
  - Ratio of power absorbed by a medium to the incident power
  - $\kappa = 0$ for lossless media

## More Rules about Interactions with Media and What they Mean for Remote Sensing

- Conservation of energy implies:

$$\rho + \Upsilon + \kappa = 1$$

- **Kirchoff's radiation law**: "good absorbers are good emitters" →

$$\kappa = \epsilon$$

(spectral absorptance equals spectral emissivity)

- **For remote sensing of the earth's surface**:
  - Objects of interested can often be assumed as opaque ($\Upsilon = 0$) resulting in:

$$\rho + \epsilon = 1$$

**Important Consequence:**
**This brings passive and active microwave remote sensing together** as we can derive surface emissivity (passive sensing) from measurements of reflectivity (active sensing) (and vice versa)



## Natural and Artificial Microwave Radiation



## Microwaves Produced in Nature

- Every body with physical temperature $T$ is emitting thermal radiation across a wide range of frequencies
- Max Planck (1857 – 1947) derived law for radiation intensity emitted at different frequencies by a sufficiently opaque body

- **This so called *Planck function* is often called *Blackbody Curve***

$$B_f(T) = \frac{2hf^3}{c^2} \frac{1}{exp\left(\frac{hf}{kT}\right) - 1} \; [Wm^{-2}sr^{-1}Hz^{-1}]$$

where $h$ is Planck constant, $c$ speed of light, $k$ is Boltzmann's constant, $T$ is the objects temperature in Kelvin, and $f$ is the frequency

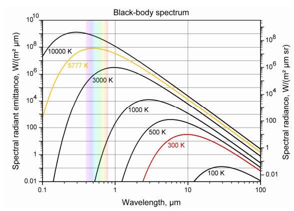
- $B_f(T)$ is given in units of Kelvin $K$

## The Blackbody Curve and Deviations from it

- **Examples of Blackbody curves for various $T$**
- **Note:** Real bodies are not perfect black bodies
- **Emissivity $\epsilon$** describes how effectively a body radiates energy as specific frequency

$$\epsilon = \frac{brightness\ of\ object}{brightness\ of\ blackbody}$$

- $\epsilon$ varies with frequency





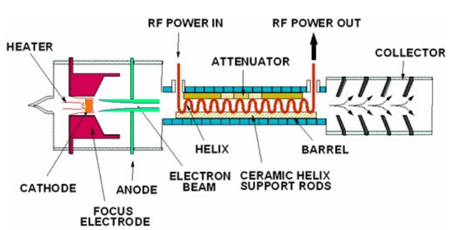

## How to Generate Microwaves Artificially?

- **From Maxwell we know that we need to create either an changing electric or magnetic field to generate EM waves!**
- **Practical approach:** Use electron tubes that use motion of high speed electrons to generate a variable EM field
- After EM wave was created it is guided through hollow tubes (waveguides) to a radiating structure (e.g., antenna)
- **Examples microwave generating devices:**
  - The Magnetron
  - The Klystron
  - Traveling Wave Tubes (TWTs)



## Traveling Wave Tube (TWT) Amplifier

- Sketch of a TWT amplifier:



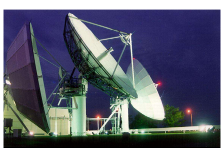
## Key Notes about TWTA

- Heater and Cathode act as electron gun (located at side of RF Input)
- Collectors sits on RF output
- Electrons are fired by cathode and received by collectors
- Microwave signal is amplified through bunching effect after traveling along the path of Helix coil
- Higher cathode voltage causes higher microwave signal power
- Ranges of Frequency for TWTA: 1GHz – 40 GHz



## Application of TWTA

- Point-to-point communication
- Satellite communication and Radar systems
- Missile tracking applications
- Television live broadcasting
  - LIVE news vans with satellite dishes on the roof carry TWTA inside





## Reading Assignment

- **To prepare for next lecture, please read:**

**Woodhouse (2006), "Introduction to Microwave Remote Sensing"**

**pp. 112 – 149**

**"Interaction of Microwaves with Real Life Objects"**