Think – Pair – Share

- While optical remote sensing has been around since about 1820, it took another about 100 years for microwave remote sensing to emerge:
  - Q1: How do you think are the development of optical and microwave remote sensing connected?
  - Q2: What scientific development was the main catalyst that gave rise to the microwave remote sensing discipline?

First photograph in history: Joseph Nicéphore Niépce
View from the Window at Le Gras, c. 1826
The Beginning – Maxwell & Co.

• James Clerk Maxwell (1831 – 79) changes the world of physics by unifying the theories on magnetism, electricity, and light

What are the symbols in these equations?

• \( \nabla \) = Nabla or gradient operator
• \( \partial \) = Partial derivative operator
• \( E = (E_x, E_y, E_z) \): Electric Field
• \( B = (B_x, B_y, B_z) \): Magnetic Field
• \( J \): Current density
• \( \rho \): Charge density (electric charge per unit volume)
• \( \varepsilon \): Permittivity of free space
• \( \mu \): Permeability of free space
• \( \nabla \times E = \text{curl } E \): Curl (rotation) of field

Some Breakthrough Implications of Maxwell’s Equations I

The Discovery of Electromagnetism

• From Eq (3): A changing magnetic field generates an electric field
• From Eq (4): A changing electric field will generate a magnetic field
• Combining Eq (3) & (4): Oscillating magnetic field \( \rightarrow \) oscillating electric field \( \rightarrow \) oscillating magnetic field ...

• This means: changing electric and magnetic fields appear together \( \rightarrow \) discovery of electromagnetism

Some Breakthrough Implications of Maxwell’s Equations II

Electromagnetic Waves and their Velocity

• Lets assume we are in a vacuum (to make things easy), then Eq (3) and (4) become:
  \[ \nabla^2 E = \frac{\mu}{\varepsilon} \frac{\partial^2 E}{\partial t^2} \]
  \[ \nabla^2 B = \frac{\mu}{\varepsilon} \frac{\partial^2 B}{\partial t^2} \]
  • This means: a self-propelling electromagnetic wave is created that propagates through space

• These partial differential equations have a solution for waves propagating with speed
  \[ \frac{1}{\sqrt{\mu\varepsilon}} \]
  with \( c \) being the speed of light
Some Breakthrough Implications of Maxwell’s Equations III

Magnetic and Electric field oscillate in orthogonal directions

- You can also prove from these equations that the electric and magnetic field are oscillating in right angles from each other.

The Electromagnetic Spectrum

- Since Maxwell: visible light, radiant heat, microwaves are all forms of electromagnetic radiation with key difference: frequency or wavelength.
- Entire range of possible waves: Electromagnetic spectrum.
HISTORY OF MICROWAVES AND THE DEVELOPMENT OF IMAGING RADARS

The Development of Radar I

- Guglielmo Marconi (1901): First transmission of radio waves over long distances shared the 1909 Nobel Prize in Physics with Karl Ferdinand Braun, "in recognition of their contributions to the development of wireless telegraphy".

  - Detection of radio waves & measuring of position and motion of distant objects
  - "Birth of radar"

- Main technological progress on radar during World War II

The Development of Radar II

- First radar experiments with continuous-wave (CV) systems by Naval Research Lab in 1920s

- 1935 Watson-Watt receives patent for RAdio Detection And Ranging (RADAR) device and builds first operational systems for detecting German aircraft approaching England (codename "Chain Home")

- First airborne radar systems were developed simultaneously in England, the U.S., and Germany in late 1930s
  - Air-to-air radar
  - First ground surveillance for navigation
Imaging the Surface with Active Radars

Side-Looking Airborne Radars (SLARs)
- Developed in 1950s driven by military
- Key element: Long antenna transmitting narrow fan-beams sideways from the aircraft
- Resolution defined by pulse length & length of antenna
- Resolution generally fair

---

Imaging Radars II

Synthetic Aperture Radars (SARs)
- Carl Wiley 1952 "Doppler beam sharpening" for improving spatial resolution of imaging radars
- Advantage: Technique allows small antennas to achieve the effective resolution of a much larger antenna (or aperture)
- Drawback: Complicated algorithm of high computational load necessary for processing
  - In fact, until the 80s, SAR images were focused on optical systems based on a set of focusing lenses

---

Doing Real Aperture Radar from Space:
The Resolution Problem
Principle of Synthetic Aperture Radar (SAR)

- Combination of overlapping acquisitions
- High resolution

Microwave Remote Sensing from Space

- First spaceborne microwave sensors were radiometers
- December 1972: Nimbus 5 launched with the Electrically Scanned Microwave Radiometer (ESMR) on board.
  - The first successful microwave imager in space.
- Original mission: Mapping global rainfall rates
- Mission evolved after launch: Mapping global sea ice coverage.

The Weddell Polynya as Seen with ESMR

This was the first and only time the Weddell Polynya was ever observed.
Spaceborne Imaging Radars

- First spaceborne imaging radar: Seasat in 1978
  - Imaging from space allowed covering the whole globe in short time
  - Using SAR guaranteed constant imaging quality

Modern Radars (so called SAR’s) Enable
Meter Resolution Imaging from Space

Another Example of a 1-m Resolution Spaceborne Radar Image
Radar Sensors for Change and Activity Monitoring

Change Detection: Port of Baltimore TerraSAR-X Spotlight Imagery

Why Radar? Well, we see different things
Why Microwaves? – We See Different Things

- Microwave interactions are governed by different physical parameters
  - e.g.: Reflection of leaves:
    - Microwave: proportional to leaf size, shape, surface roughness, and water content
    - Optical: proportional to amount of chlorophyll (i.e. 'greeness')

Example: Anchorage, Alaska

- High atmospheric transmittance (Radar window) → most of the signal reaches ground
- Penetration of clouds and fog
- Penetration into the top surface layer
- Active system → independent of external illumination
Why Microwaves? – Atmospheric Attenuation

- Water vapor (H₂O)
- Carbon dioxide (CO₂)
- Ozone (O₃)
- Fog (0.1 g/m³)
  - Visibility: 50 m
- Heavy rain
  - (25 mm/h)
- Drizzle
  - (0.25 mm/h)

Attenuation (dB/km) from Woodhouse (2006)

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Wavelength (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1000</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The Importance of Radar Remote Sensing

Radar observations of current activity at Mount Cleveland
- Optical sensors yield little information due to cloud cover
- Radar data can see through clouds, ash, and smoke
- Active radars can operate day and night

Depend on Signal Wavelength, SAR can Penetrate Into Vegetation and Soils

- Example: X-band vs P-band penetration into forest canopies
The Microwave Spectrum

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency</th>
<th>Wavelength</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>27 – 40 GHz</td>
<td>1.1 – 0.8 cm</td>
<td>Rarely used for SAR (airport surveillance)</td>
</tr>
<tr>
<td>K</td>
<td>18 – 27 GHz</td>
<td>1.7 – 1.1 cm</td>
<td>Rarely used for SAR (H2O absorption)</td>
</tr>
<tr>
<td>Kα</td>
<td>13 – 18 GHz</td>
<td>2.4 – 1.7 cm</td>
<td>Rarely used for SAR (satellite altimetry)</td>
</tr>
<tr>
<td>X</td>
<td>8 – 12 GHz</td>
<td>3.8 – 2.4 cm</td>
<td>High-resolution SAR (urban monitoring; ice and snow; little penetration into vegetation cover; fast coherence decay in vegetated areas)</td>
</tr>
<tr>
<td>C</td>
<td>4 – 8 GHz</td>
<td>7.5 – 3.8 cm</td>
<td>SAR workhorse (global mapping, change detection, monitoring areas with low to moderate vegetation, improved penetration, higher coherence)</td>
</tr>
<tr>
<td>S</td>
<td>2 – 4 GHz</td>
<td>15 – 7.5 cm</td>
<td>Little but increasing use for SAR-based Earth obs., agriculture monitoring (NISAR will carry S-band) expands C-band applications to higher vegetation density</td>
</tr>
<tr>
<td>L</td>
<td>1 – 2 GHz</td>
<td>30 – 15 cm</td>
<td>Medium-resolution SAR (biophysical monitoring, biomass and vegetation mapping, high penetration, InSAR)</td>
</tr>
<tr>
<td>P</td>
<td>0.3 – 1 GHz</td>
<td>100 – 30 cm</td>
<td>Biomass estimation. First P-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.</td>
</tr>
</tbody>
</table>

Some (Annoying But) Useful Mathematics

Degrees andRadians

- Degrees and radians are measurements of linear angle

![Degrees and Radians](image)

- Degrees: By definition, there are 360° in one revolution
- Radians: Fractions of the circumference of a circle with radius 1
Complex Numbers

Motivation: Polynomials of order \( n \) should have \( n \) roots.

\[
\begin{align*}
2^2 - 4 & = 0 & \Rightarrow & & (2-1)(2+1) & = 0 & \Rightarrow & & \{2/2\} \cup \{-1/0\} & = \{1, -1\}
\end{align*}
\]

Def.: \( j = \sqrt{-1} \) imaginary unit (in mathematics mostly \( i \))

Check for quadrants!

Complex Numbers as Vectors

\[
\begin{align*}
|z| & = \sqrt{\text{Re}(z)^2 + \text{Im}(z)^2} \\
\arg(z) & = \text{angle} \left( \frac{\text{Im}(z)}{\text{Re}(z)} \right)
\end{align*}
\]

Check for quadrants!
### Complex Conjugate

If \( z = x + yi \)
then the complex conjugate of \( z \) is defined to be \( z^* = x - yi \).

### Different Notations of Complex Numbers

- **Component Notation**
  \[ z = \text{Re}(z) + j \text{Im}(z) \]

- **Polar Notation**
  \[ z = r \cos \phi + j \sin \phi \]

- **Euler Notation**
  (using \( e^{j\phi} = \cos \phi + j \sin \phi \))
  \[ z = r e^{j\phi} \]

### Summation of Complex Numbers

\[ z_1 + z_2 = \text{Re}(z_1) + \text{Re}(z_2) + j(\text{Im}(z_1) + \text{Im}(z_2)) \]

Corresponds to vector sum:
Product of Complex Numbers

- How to multiply complex numbers?

\[ z_1 \cdot z_2 = (\text{Re}(z_1) \text{Re}(z_2) - \text{Im}(z_1) \text{Im}(z_2)) + (\text{Re}(z_1) \text{Im}(z_2) + \text{Im}(z_1) \text{Re}(z_2))j \]

Example:

- \( z_1 = 2 + j \)
- \( z_2 = 3 + j \)
- \( z_3 = z_1 \cdot z_2 = 5 + 5j \)

Complex Numbers & Harmonic Oscillations

\[ f(t) = A \sin(\Omega t + \phi) \]

Phase \( \phi \):

\( \phi = 0 \), \( \phi = \pi \), \( \phi = 2\pi \), \( \phi = 3\pi \), \( \phi = 4\pi \)

- \( A = |z| \)
Complex Numbers and Signal Analysis

- Complex numbers are used for convenient description of periodically varying signals.
- For given real functions representing actual physical quantities, often in terms of sines and cosines, corresponding complex functions are considered of which the real parts are the original quantities.
- In Fourier analysis, where a given real-valued signal is written as sum of periodic functions, these periodic functions are often written as complex valued functions.

Reading Assignment

- To prepare for next lecture, please read:
  
  Woodhouse (2006), "Introduction to Microwave Remote Sensing"

  pp. 23 – 34