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?
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
- \( E \) = Electric Field
- \( B \) = Magnetic Field
- \( J \) = Current density
- \( \rho \) = Charge density (electric charge per unit volume)
- \( \varepsilon \) = Permittivity of free space
- \( \mu \) = Permeability of free space
- \( \nabla \cdot E = \frac{\partial \rho}{\partial t} \) = Divergence
- \( \nabla \times E = \frac{1}{c^2} \frac{\partial B}{\partial t} \) = 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 → oscillating electric field → oscillating magnetic field ...
- This means: changing electric and magnetic fields appear together → discovery of electromagnetism

Some Breakthrough Implications of Maxwell’s Equations II

Electromagnetic Waves and their Velocity
- If we assume we are in a vacuum (to make things easy), then Eq (3) and (4) become:
  - \( \nabla \cdot E = \frac{1}{c^2} \frac{\partial \rho}{\partial t} \)
  - \( \nabla \times B = \frac{1}{c^2} \frac{\partial E}{\partial t} \)
- 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
  \[ \frac{1}{c} \]
  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

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^12</td>
<td>0.3 m</td>
</tr>
<tr>
<td>10^11</td>
<td>3 m</td>
</tr>
<tr>
<td>10^10</td>
<td>30 m</td>
</tr>
<tr>
<td>10^9</td>
<td>300 m</td>
</tr>
<tr>
<td>10^8</td>
<td>3 km</td>
</tr>
<tr>
<td>10^7</td>
<td>30 km</td>
</tr>
<tr>
<td>10^6</td>
<td>300 km</td>
</tr>
</tbody>
</table>

Visible spectrum
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".

- Christian Huelsmeyer (1904): Patent for obstacle detector using radio waves
  - 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 "Radical 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

Principle of a SLAR System

![Diagram of SLAR System](image)

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

- Short antenna (10 m)
  - Low resolution
  - Footprint Size = 5 km
- Long antenna (5 km)
  - High resolution
  - Footprint Size = 1 km
Principle of Synthetic Aperture Radar (SAR)

Combination of overlapping acquisitions

Flight direction of sensor

Antenna footprint

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 Nimbus ESMR

This was the first time the Weddell Polynya was observed

In 2017, the Weddell Polynya made a surprising and mysterious return
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

Islands of the Four Mountains, Central Aleutian Chain, Alaska

Imaged by TanDEM-X, German Aerospace Center
Think – Pair – Share

The image to your right shows a panchromatic and C-band radar image of a lava flow:

- **Q1:** Which of the two images is the optical and which is the radar scene?

- **Q2:** The lava flow looks very different in the optical and radar image. What are your thoughts about how radar and optical sensors see this surface differently?
Why Radar? Well, 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 (or 'greeness')

Example: Anchorage, Alaska
### Why Microwaves? – Atmospheric Attenuation

- High-atmospheric transmittance (Radar window) \( \rightarrow \) most of the signal reaches ground
- Penetration of clouds and fog
- Penetration into the top surface layer
- Active system \( \rightarrow \) independent of external illumination

### Why Microwaves? – Atmospheric Attenuation

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GHz</td>
<td>30 cm</td>
</tr>
<tr>
<td>10 GHz</td>
<td>3 cm</td>
</tr>
<tr>
<td>100 GHz</td>
<td>3 mm</td>
</tr>
<tr>
<td>1 THz</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>10 THz</td>
<td>30 μm</td>
</tr>
<tr>
<td>100 THz</td>
<td>3 μm</td>
</tr>
<tr>
<td>1000 THz</td>
<td>0.3 μm</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
Depending 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 (GHz)</th>
<th>Wavelength (cm)</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>11 – 40</td>
<td>3.5 – 0.3</td>
<td>Rarely used for SAR (airport surveillance)</td>
</tr>
<tr>
<td>Kα</td>
<td>18 – 27</td>
<td>1.7 – 1.1</td>
<td>Rarely used for SAR (H₂O absorption)</td>
</tr>
<tr>
<td>K</td>
<td>12 – 18</td>
<td>2.4 – 1.7</td>
<td>Rarely used for SAR (satellite altimetry)</td>
</tr>
<tr>
<td>X</td>
<td>8 – 12</td>
<td>3.8 – 2.4</td>
<td>High-resolution SAR (urban monitoring; sea and snow; little penetration into vegetation cover; fast coherence decay in vegetated areas)</td>
</tr>
<tr>
<td>C</td>
<td>4 – 8</td>
<td>7.5 – 3.8</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</td>
<td>15 – 7.5</td>
<td>Little but increasing use for SAR-based Earth obs.; agriculture monitoring (e.g., forest SAR will use X-band; expands C-band applications to higher vegetation density)</td>
</tr>
<tr>
<td>L</td>
<td>1 – 2</td>
<td>30 – 15</td>
<td>Medium-resolution SAR (vegetation monitoring, biomass and vegetation mapping, high penetration; InSAR)</td>
</tr>
<tr>
<td>P</td>
<td>0.3 – 1</td>
<td>100 – 30</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 and Radians

- Degrees and radians are measurements of linear angle.

- Degrees: By definition, there are 360° in one revolution.

- Radians: Fractions of the circumference of a circle with radius 1.

Complex Numbers and Harmonic Oscillations

Complex Numbers

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

\[
\begin{align*}
z^2 + 1 &= 0 &\Rightarrow& (z - i)(z + i) &= 0 &\Rightarrow& z = i, z = -i \\
z^3 &= 0 &\Rightarrow& z = 0, z = 0, z = 0 \\
z^4 + 1 &= 0 &\Rightarrow& z = \sqrt{-1}, z = -\sqrt{-1} &
\end{align*}
\]

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

- \( z = x + jy \) complex number
- \( x = \Re(z) \) real part
- \( y = \Im(z) \) imaginary part
Complex Numbers as Vectors

\[ z = \Re(z) + j \Im(z) = |z| \exp(j \phi) \]

- \( \phi = \arg(z) \)
- \( |z| = \sqrt{\Re(z)^2 + \Im(z)^2} \)
- Check for quadrants!

Complex Conjugate

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

Different Notations of Complex Numbers

- Component Notation
  \[ z = \Re(z) + j \Im(z) \]

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

- Euler Notation (using \( \exp(j \phi) = \cos \phi + j \sin \phi \))
  \[ z = r \exp(j \phi) \]
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:

\[ z_1 + z_2 

\]

Product of Complex Numbers

- How to multiply complex numbers?

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

\[ |z_1| \cdot |z_2| \cdot e^{j(\phi_1 + \phi_2)} \]

Example:

\[ z_1 = 2 + j \\
\]

\[ z_2 = 3 + j \]

\[ z_3 = z_1 \cdot z_2 = 5 + 5j \]

Complex Numbers & Harmonic Oscillations

Phase \( \phi(t) \):

\[ A \cdot \cos(\omega t + \phi(t)) \]
Complex Numbers & Harmonic Oscillations

- 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 a sum of periodic functions, these periodic functions are often written as complex valued functions.

Complex Numbers and Signal Analysis

- To prepare for next lecture, please read:

  Woodhouse (2006), "Introduction to Microwave Remote Sensing"
  pp. 23–34 (Chapter 3 up to the Start of Section 3.3.1)