GEOS 657 – MICROWAVE REMOTE SENSING

GRADUATE-LEVEL COURSE AT THE UNIVERSITY OF ALASKA FAIRBANKS

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Lecture 2: History of Microwave RS & Mathematical Background

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

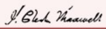
THE MAXWELL EQUATIONS

THE BIRTH OF MICROWAVE REMOTE SENSING

The Beginning – Maxwell & Co.

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

$$\nabla \cdot E = \frac{\rho}{\varepsilon}$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\frac{\partial}{\partial t} B$$
$$\nabla \times B = \mu J + \mu\varepsilon \frac{\partial}{\partial t} E$$



What are the symbols in these equations?

- ∇ = Nabla or gradient operator
- ∂ = Partial derivative operator
- $E = (E_x, E_y, E_z)$: Electric Field
- $B = (B_x, B_y, B_z)$: Magnetic Field
- J: Current density
- ρ: Charge density (electric charge per unit volume)
- ε: Permittivity of free space
- μ: Permeability of free space
- $\nabla \cdot E = div\, E = \frac{\partial E}{\partial x} + \frac{\partial E}{\partial y} + \frac{\partial E}{\partial z}$: Divergence
- $\nabla \times E = curl\, E$: 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 → 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

- Lets assume we are in a vacuum (to make things easy), then Eq (3) and (4) become:

$$\nabla^2 E = \varepsilon\mu \frac{\partial^2}{\partial t^2} E$$

$$\nabla^2 B = \varepsilon\mu \frac{\partial^2}{\partial t^2} B$$

- **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

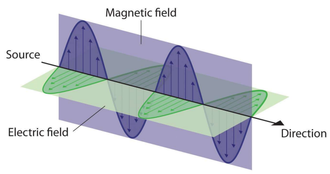
$$\frac{1}{\sqrt{\mu\varepsilon}}$$

with *c* being the speed of light

Some Breakthrough Implications of Maxwell's Equations III

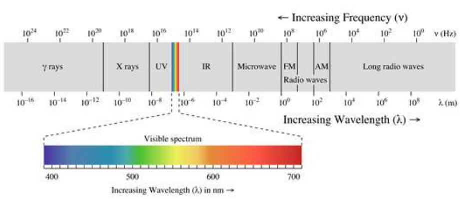
Magnetic and Electric field oscillate in orthogonal directions

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

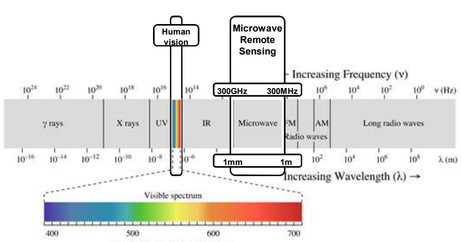


The Electromagnetic Spectrum

- **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**



The Electromagnetic Spectrum



HISTORY OF MICROWAVES AND THE DEVELOPMENT OF IMAGING RADARS

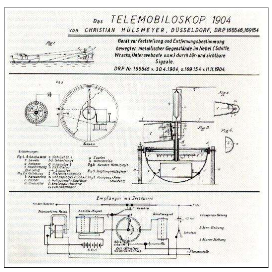
The Development of Radar I

- 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*"

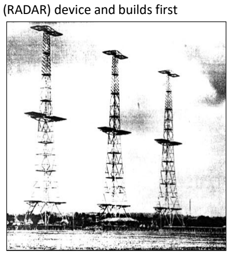
- Christian Huelsmeyer (1904): Patent for obstacle detector using radio waves
  - Detection of radio waves & measuring of position and motion of distant objects
  - "Birth or radar"

- Main technological progress on radar during World War II



The Development of Radar II

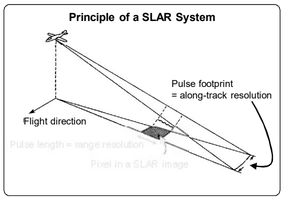
- First radar experiments with continuous-wave (CV) systems by Naval Research Lab in 1920s
- 1935 Watson-Watt receives patent for RAdio Detection And Ranging (RADAR) device and builds first operational systems for detecting German aircraft approaching England (codename "Chain Home")
- First airborne 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*



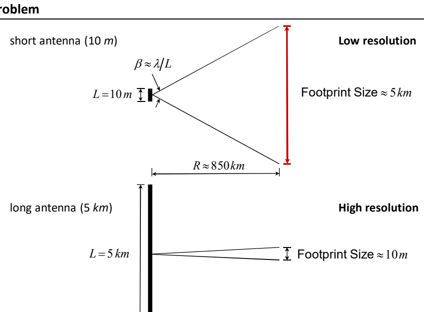
Imaging Radars II

Synthetic Aperture Radars (SARs)

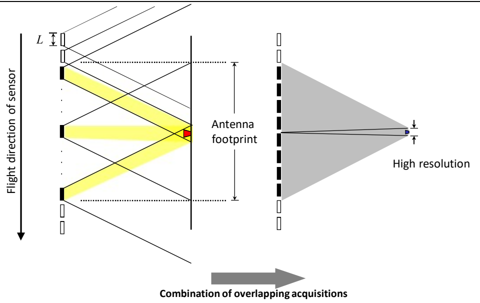
- Carl Wiley 1952 "Doppler beam sharpening" for improving spatial resolution of imaging radars
- Advantage: Technique allows small antennas to achieve the effective resolution of a much larger antenna (or aperture)
- Drawback: Complicated algorithm of high computational load necessary for processing
  - 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

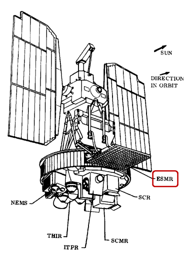


Principle of Synthetic Aperture Radar (SAR)

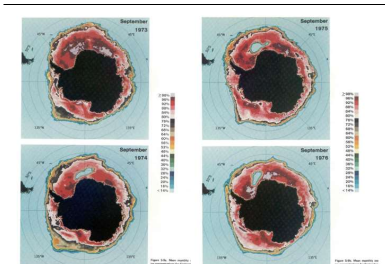


Microwave Remote Sensing from Space

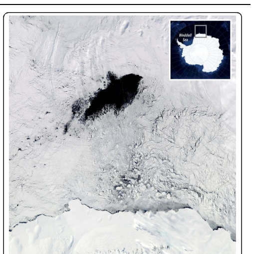
- First spaceborne microwave sensors were radiometers
- **December 1972:** Nimbus 5 launched with the Electrically Scanned Microwave Radiometer (ESMR) on board.
  - The first successful microwave imager in space.
- **Original mission:** Mapping global rainfall rates
- **Mission evolved after launch:**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



The Weddell Polynya as seen with Nimbus ESMR



This was the first ~~and only~~ time the Weddell Polynya was observed

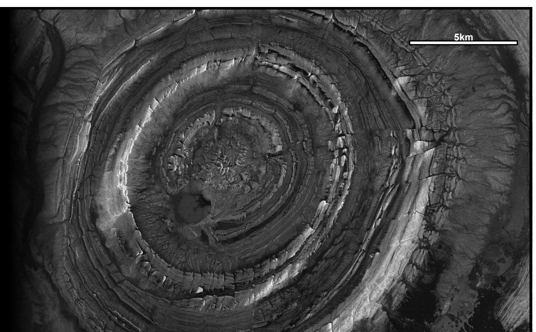


In 2017, the Weddell Polynya made a surprising and mysterious return

Spaceborne Imaging Radars

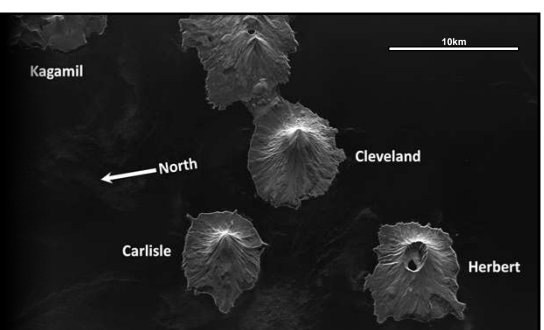
- First spaceborne imaging radar: **Seasat in 1978**
  - Imaging from space allowed covering the whole globe in short time
  - Using SAR guaranteed constant imaging quality

Modern Radars (so called **SAR**'s) Enable Meter-Resolution Imaging from Space

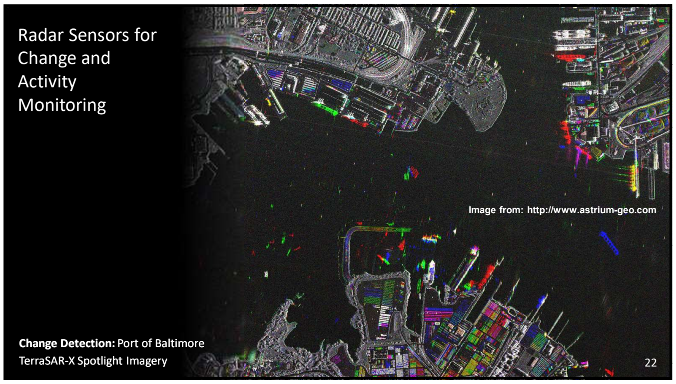


Guelb er Richat, Mauritania
Shallow ring structures of limestone, dolomites, and brecchias (TerraSAR-X image, July 8, 2007, courtesy: DLR)

Another Example of a 1-m Resolution Spaceborne Radar Image



Islands of the Four Mountains, Central Aleutian Chain, Alaska
Imaged by TerraSAR-X, German Aerospace Center



WHY MICROWAVES

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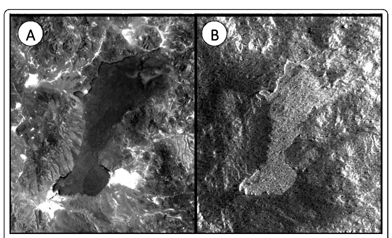
Think – Pair – Share

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?



This image shows side by side a SAR image and a panchromatic optical image. The feature in the center of the scene is a lava flow.

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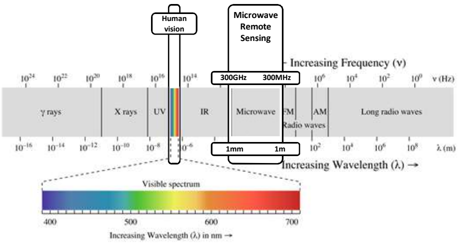
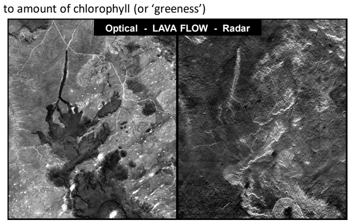
Why Radar? Well, we see different things

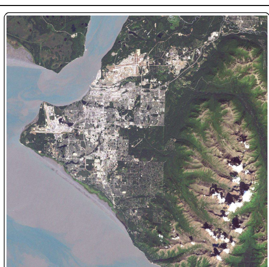


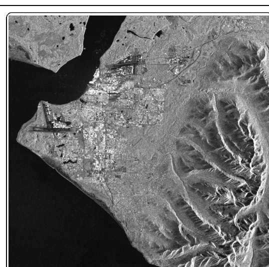
Why Microwaves? – We See Different Things

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



Example: Anchorage, Alaska

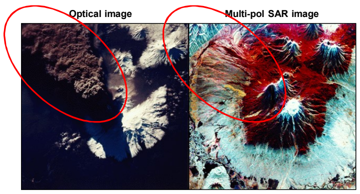

Landsat Image


RADARSAT-1 Image

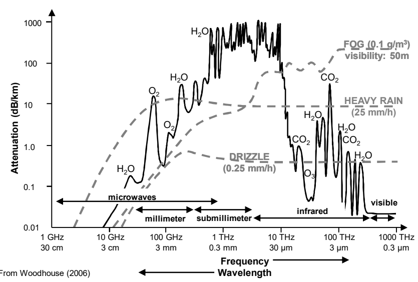
Credits: CSA

Why Microwaves? – Atmospheric Attenuation

- 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

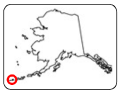


From Woodhouse (2006)

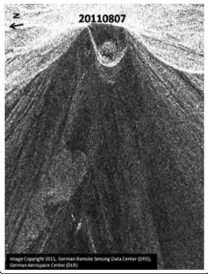
The Importance of Radar Remote Sensing

Radar observations of current activity at Mount Cleveland

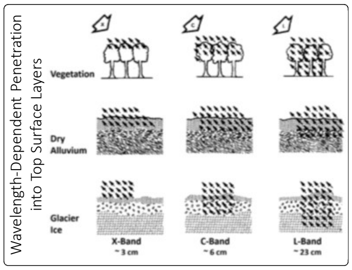
- Optical sensors yield little information due to cloud cover
- Radar data can see through clouds, ash, and smoke
- Active radars can operate day and night



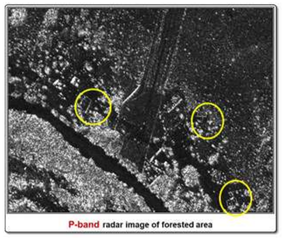
2011 Dome Growth of Mount Cleveland from SAR



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



- **Example**: X-band vs P-band penetration into Forest Canopies



P-band radar image of forested area

The Microwave Spectrum

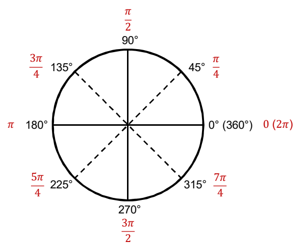
(approximate)

Band	Frequency f_0		Wavelength $\lambda = c/f_0$		Typical Application
Ka	27 – 40	GHz	1.1 – 0.8	cm	Rarely used for SAR (airport surveillance)
K	18 – 27	GHz	1.7 – 1.1	cm	Rarely used for SAR (H_2O absorption)
Ku	12 – 18	GHz	2.4 – 1.7	cm	Rarely used for SAR (satellite altimetry)
X	8 – 12	GHz	3.8 – 2.4	cm	**High-resolution SAR** (urban monitoring; ice and snow; little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4 – 8	GHz	7.5 – 3.8	cm	**SAR workhorse** (global mapping; change detection; monitoring areas with low to moderate vegetation; improved penetration; higher coherence)
S	2 – 4	GHz	15 – 7.5	cm	**Little but increasing use for SAR-based Earth obs.**; agriculture monitoring (NISAR will carry S-band; expands C-band applications to higher vegetation density)
L	1 – 2	GHz	30 – 15	cm	**Medium resolution SAR** (Geophysical monitoring; biomass and vegetation mapping; high penetration; InSAR)
P	0.3 – 1	GHz	100 – 30	cm	**Biomass estimation**. First P-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

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

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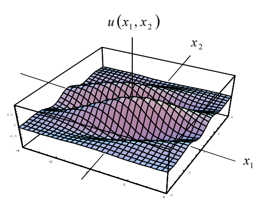
Complex Numbers and Harmonic Oscillations



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Complex Numbers

Motivation: Polynomials of order *n* should have *n* roots.

$$z^2 - 1 = 0 \Rightarrow (z-1)(z+1) = 0 \Rightarrow z_1 = 1; \quad z_2 = -1$$
$$z^2 = 0 \Rightarrow z_1 = 0; \quad z_2 = 0$$
$$z^2 + 1 = 0 \Rightarrow z_1 = \sqrt{-1}; \quad z_2 = -\sqrt{-1}$$

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

$z = x + j\,y \quad x, y \in \Re$ **complex number**

$x = \mathrm{Re}\{z\}$ **real part**

$y = \mathrm{Im}\{z\}$ **imaginary part**

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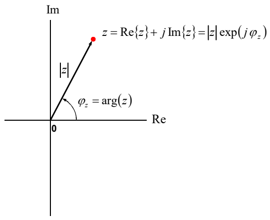
Complex Numbers as Vectors

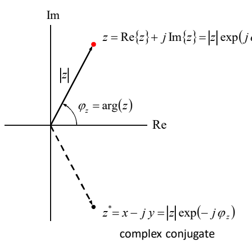


$$|z| = \sqrt{\mathrm{Re}\{z\}^2 + \mathrm{Im}\{z\}^2}$$

$$\varphi_z = \arg(z) = \arctan\left(\frac{\mathrm{Im}\{z\}}{\mathrm{Re}\{z\}}\right)$$

Check for quadrants!

Complex Conjugate



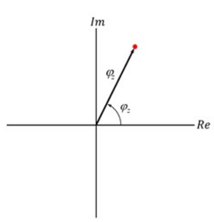
If $z = x + yi$

then the *complex conjugate* of z

is defined to be $z^* = x - yi$.

Different Notations of Complex Numbers

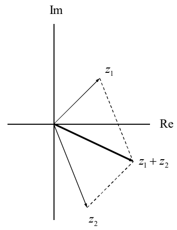
- **Component Notation**
  $z = Re\{z\} + j \cdot Im\{z\}$
- **Polar Notation**
  $z = |r|(cos\varphi_z + j \cdot sin\varphi_z)$
- **Euler Notation**
  (using $\exp(jx) = cosx + j \cdot sinx$)
  $z = |r|exp(j\varphi_z)$



Summation of Complex Numbers

$$z_1+z_2=\mathrm{Re}\{z_1\}+\mathrm{Re}\{z_2\}+j\left(\mathrm{Im}\{z_1\}+\mathrm{Im}\{z_2\}\right)$$

Corresponds to vector sum:



Product of Complex Numbers

- How to multiply complex numbers?

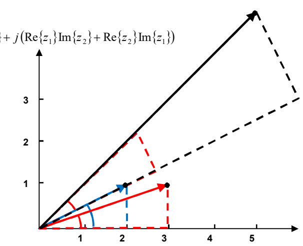
$$z_1 \cdot z_2=\mathrm{Re}\{z_1\}\mathrm{Re}\{z_2\}-\mathrm{Im}\{z_1\}\mathrm{Im}\{z_2\}+j\left(\mathrm{Re}\{z_1\}\mathrm{Im}\{z_2\}+\mathrm{Re}\{z_2\}\mathrm{Im}\{z_1\}\right)$$

$$=|z_1||z_2|\exp\left(j\left(\varphi_{z_1}+\varphi_{z_2}\right)\right)$$

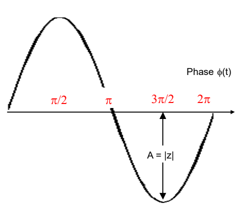
Example:

$z_1 = 2 + j$
$z_2 = 3 + j$

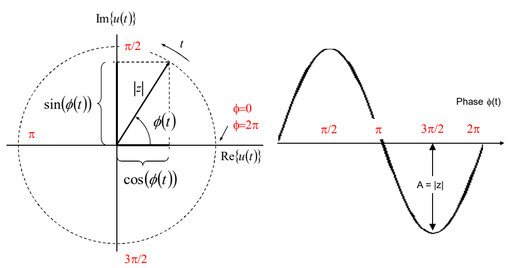
$z_3 = z_1 \cdot z_2 = 5 + 5j$



Complex Numbers & Harmonic Oscillations



Complex Numbers & Harmonic Oscillations



Complex Numbers and Signal Analysis

- Complex numbers are used for conventient description of periodically varying signals
- For given real functions representing actual physical quantities, often in terms of sinues 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 (Chapter 3 up to the Start of Section 3.3.1)