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

UAF Course GEOS 657

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

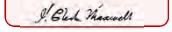
THE MAXWELL EQUATIONS

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

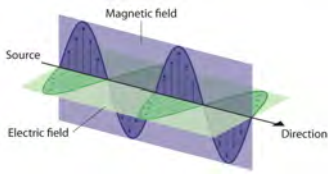
$$\frac{1}{\sqrt{\mu\varepsilon}} =$$

with c being the speed of light

Some Breakthrough Implications of Maxwell's Equations III

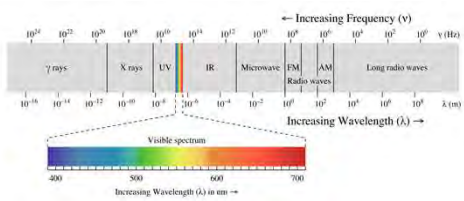
Magnetic and Electric field oscillate in orthogonal directions

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

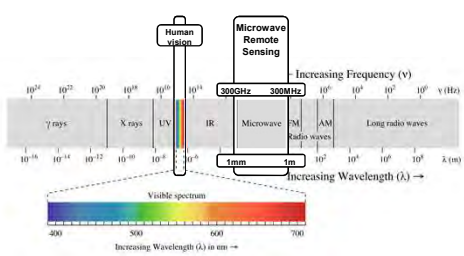


The Electromagnetic Spectrum

- **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

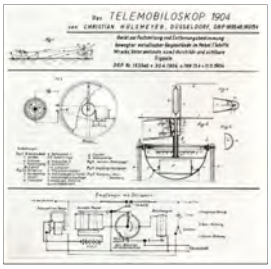
The Development of Radar I

- 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*"

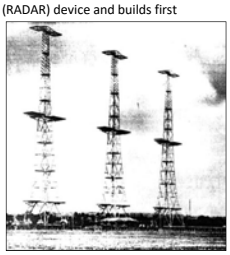
- Christian Huelsmeyer (1904): Patent for obstacle detector using radio waves
  - Detection of radio waves & measuring of position and motion of distant objects
  - "Birth or radar"

- Main technological progress on radar during World War II



The Development of Radar II

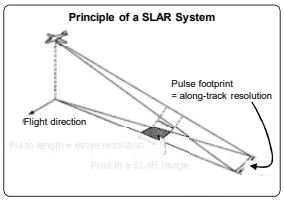
- First radar experiments with continuous-wave (CV) systems by Naval Research Lab in 1920s
- 1935 Watson-Watt receives patent for RAdio Detection And Ranging (RADAR) device and builds first operational systems for detecting German aircraft approaching England (codename "Chain Home")
- First airborne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



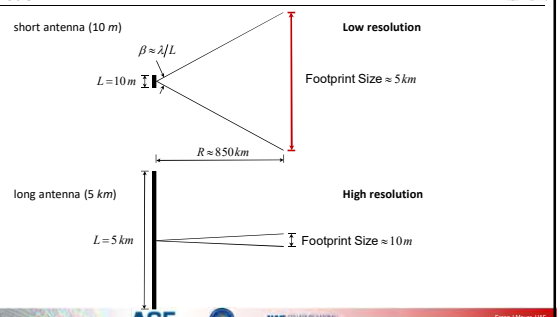
Imaging Radars II

Synthetic Aperture Radars (SARs)

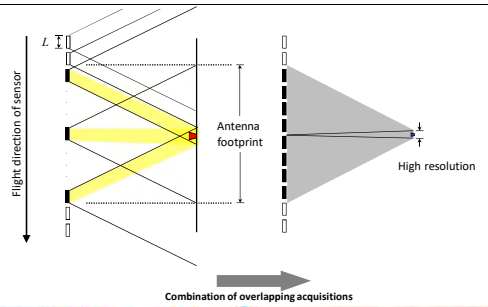
- Carl Wiley 1952 "Doppler beam sharpening" for improving spatial resolution of imaging radars
- Advantage: Technique allows small antennas to achieve the effective resolution of a much larger antenna (or aperture)
- Drawback: Complicated algorithm of high computational load necessary for processing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



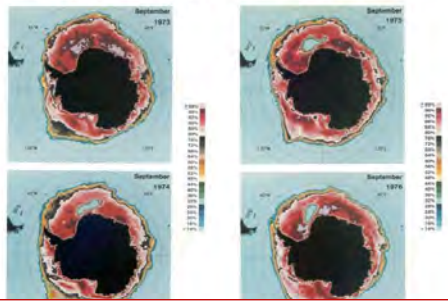
Principle of Synthetic Aperture Radar (SAR)



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 ESMR



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

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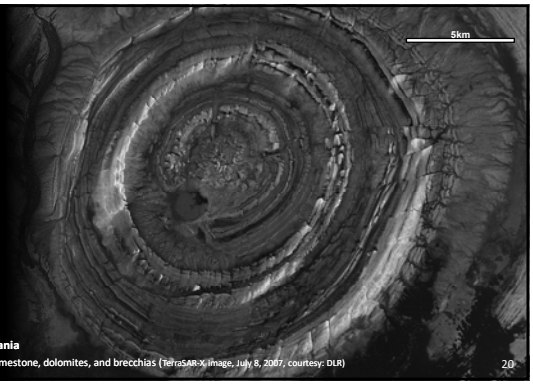
Spaceborne Imaging Radars

- 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)

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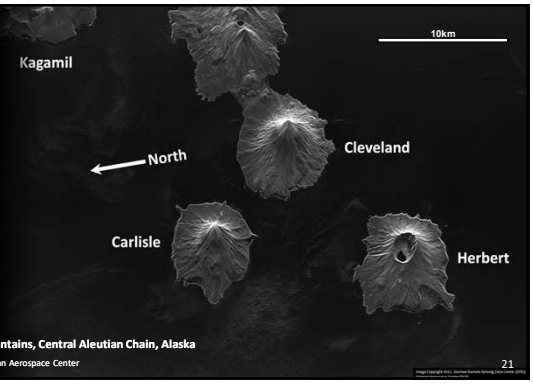
Another Example of a 1-m Resolution Spaceborne Radar Image



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

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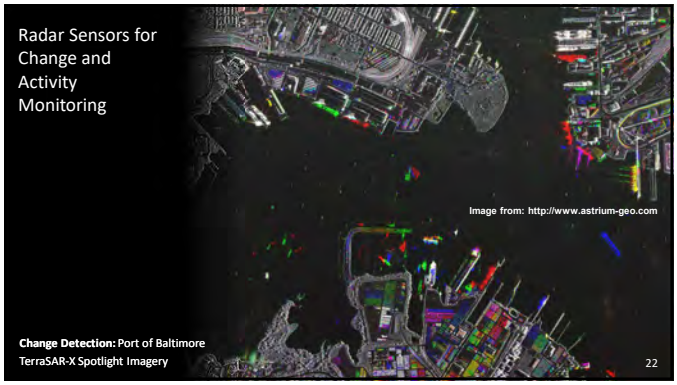
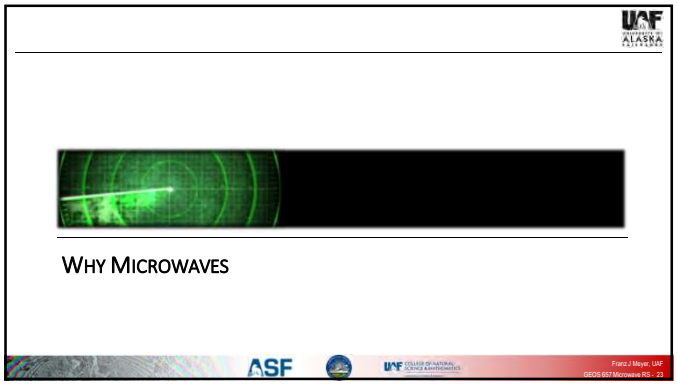

Radar Sensors for Change and Activity Monitoring
Image from: http://www.astrium-geo.com
Change Detection: Port of Baltimore
TerraSAR-X Spotlight Imagery
22


WHY MICROWAVES
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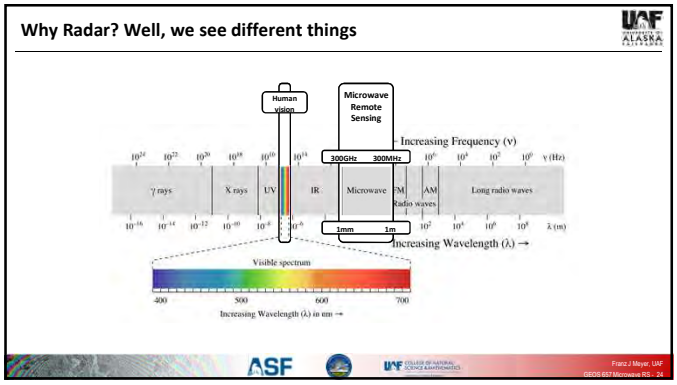
Why Radar? Well, we see different things
Human vision
Microwave Remote Sensing
Increasing Frequency (ν)
300GHz
300MHz
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
1mm
1m
Increasing Wavelength (λ) →
Visible spectrum
400
500
600
700
Increasing Wavelength (λ) in nm →
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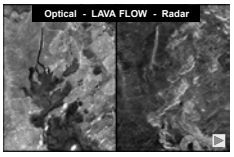
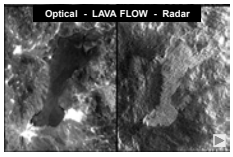
Why Microwaves? – We See Different Things

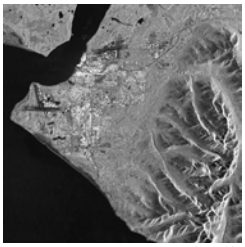
- **Microwave interactions are governed by different physical parameters**
- e.g.: Reflection of leafs:
  - Microwave: proportional to leaf size, shape, surface roughness, and water content
  - Optical: proportional to amount of chlorophyll (or 'greeness')





Example: Anchorage, Alaska

Landsat image

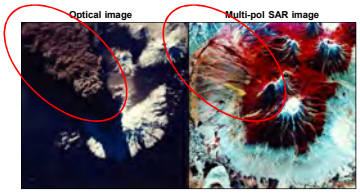


RADARSAT-1 image

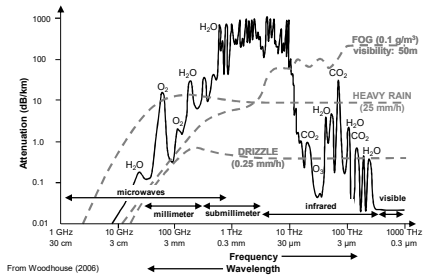
Credits: CSA

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



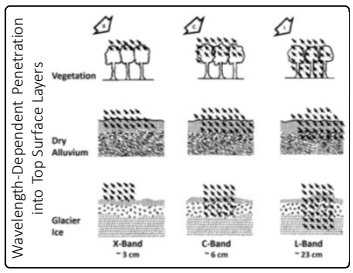
From Woodhouse (2006)

The Importance of Radar Remote Sensing

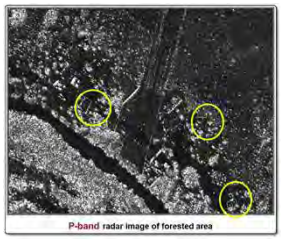
Radar observations of current activity at Mount Cleveland

- 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

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

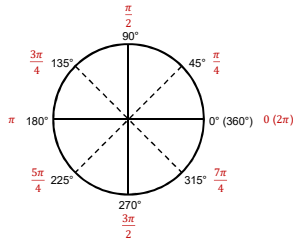
(approximate)

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

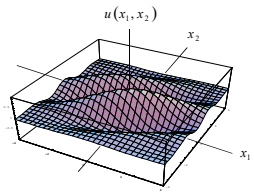
Degrees and Radians

- **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

Complex Numbers and Harmonic Oscillations



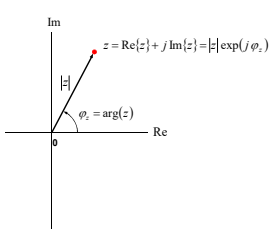
Complex Numbers

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* “)**
$z = x + j\,y$	$x, y \in \Re$	**complex number**
$x = \mathrm{Re}\{z\}$		**real part**
$y = \mathrm{Im}\{z\}$		**imaginary part**

Complex Numbers as Vectors

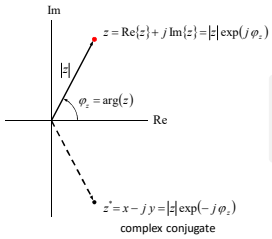


$$|z| = \sqrt{\mathrm{Re}\{z\}^2 + \mathrm{Im}\{z\}^2}$$

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

Check for quadrants!

Complex Conjugate



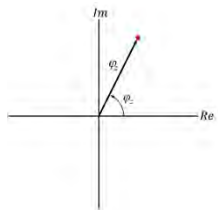
If $z = x + yi$

then the *complex conjugate* of z

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

Different Notations of Complex Numbers

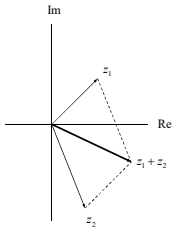
- **Component Notation**
  $z = Re\{z\} + j \cdot Im\{z\}$
- **Polar Notation**
  $z = |r|(cos\varphi_z + j \cdot sin\varphi_z)$
- **Euler Notation**
  (using $\exp(jx) = cosx + j \cdot sinx$)
  $z = |r|exp(j\varphi_z)$



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?

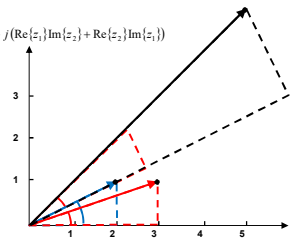
$$z_1 \cdot z_2 = \mathrm{Re}\{z_1\}\mathrm{Re}\{z_2\} - \mathrm{Im}\{z_1\}\mathrm{Im}\{z_2\} + j(\mathrm{Re}\{z_1\}\mathrm{Im}\{z_2\} + \mathrm{Re}\{z_2\}\mathrm{Im}\{z_1\})$$

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

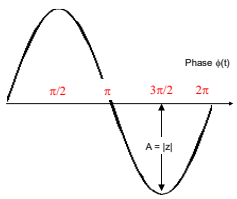
Example:

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

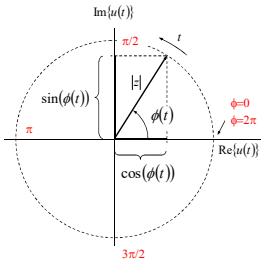
$z_3 = z_1 \cdot z_2 = 5 + 5j$

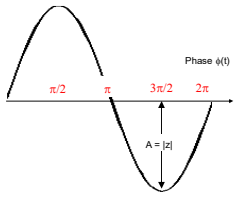


Complex Numbers & Harmonic Oscillations



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