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

Lecture 7: Principles of Radar & Active Microwave Systems
Recent “Radar in the News”

Sentinel-1 C-band Radar monitors Dam Break in Brazil

Before dam breach: 2019-01-22
Recent “Radar in the News”

Sentinel-1 C-band Radar monitors Dam Break in Brazil

Before dam breach: 2019-01-22
After dam breach: 2019-01-28
Recent “Radar in the News”

Sentinel-1 SAR

2019-01-22

2019-01-28

VS.

Optical

2019-01-24

Planet Labs

2019-01-29

Planet Labs
Outline

- Some Basics and Three Types of Radar Systems
- Imaging Radars - Concepts:
  - The Radar Equation
  - Separating Several Range Resolution Cells within Antenna Footprint
- Imaging Radars – How it’s Really Done:
  - The Concept of Pulse Compression Systems
  - The Resolution-Bandwidth Duality
  - Range Compression – The Matched Filter Approach
- Examples of Imaging Radar Data
SOME BASICS AND THREE TYPES OF RADAR SYSTEMS
Active Microwave Systems are called RADARs

- Radars actively transmit microwave signals (usually a radar pulse)
- Radar antenna provides directivity for transmitted signal
- A radar sensor records three different parameters: Amplitude, Phase and polarization of the reflected microwave signals (here we focus on amplitude and phase)

Detected amplitude measures surface radar cross section (RCS)

Timing of transmitted signal (radar pulse) provides information about distance between satellite and ground
Three Different Types of Radar Systems

- Based on measurement type, **three** different radar systems can be discriminated:

**Non-Imaging Systems**

**Radar Altimeters**
- Measuring distance (from travel time)
- Transmitted pulses

**Scatterometers**
- Measuring radar cross section

**Imaging Systems**
- Range pixel size ~ pulse length
- Azimuth pixel size = antenna footprint (or better when doing SAR)
Radar Principle

range $R$

light velocity

scattering object

received echo:

$2 \frac{R}{c}$

transmit

$\tau$ (time)
A Short Word on Radar Altimeters

- Radar altimeter emits pulses towards the Earth's surface (nadir direction)
- Signal travel time (transmission to reception) is proportional to satellite altitude.
- Measuring Signal travel time not easy as echo signal has funny shape

Idealized altimeter echo from flat surface (e.g., smooth ocean surface)
Calculating Surface Height from Altimeter Measurements

Sensor Geometry
- Ionosphere
- Dry Troposphere
- Wet Troposphere

Dynamic Topography

Geoid Undulations

Reference Ellipsoid

Mean Sea Level = SSH_{mean}

Geoid = H_{geoid}

Orbit Height = H

Instantaneous Sea Level
- SWH
- Tides
- Barometric Effect

H_{measured}

Center of Mass
Mean Sea Level Height from Altimetry

Mean Sea Level March 2006
Microwave Scatterometers

- **Goal:** measurement of wind speed and direction over oceans

Example: Scatterometer on ERS

Wind Scatterometer geometry. The three Wind Scatterometer antennae generate radar beams 45° forward, sideways and 45° backwards across a 500 Km wide swath, 200 Km to the right of the sub-satellite track.
QuikSCAT Windfield

Wind (m/s): time=20170211: 12Z
IMAGING RADAR CONCEPTS
The Radar Equation – A Reminder

transmit power: \( P_t \)  \[W\]

antenna gain: \( G = \frac{4 \pi A}{\lambda^2} \)

power density at scatterer: \( \frac{P_t G}{4 \pi R^2} \) \[\frac{W}{m^2}\]

radar cross section: \( \sigma \)  \[m^2\]

power density at receiver: \( \frac{P_t G}{(4 \pi)^2 R^4} \sigma \) \[\frac{W}{m^2}\]

antenna area: \( A \)  \[m^2\]

reflected power: \( \frac{P_t G}{4 \pi R^2} \sigma \)  \[W\]

received power: \( P_r = A \frac{P_t G}{(4 \pi)^2 R^4} \sigma = \frac{G \lambda^2}{4 \pi} \frac{P_t G}{(4 \pi)^2 R^4} \sigma = P_t \frac{G^2 \lambda^2}{(4 \pi)^3 R^4} \sigma \)  \[W\]
targets #1 and #2 easily separable, if \( \delta_R \geq \rho_R = \tau_P c / 2 \) (range resolution)
Range Resolution Example

- Insufficient Target Separation

\[ \tau = 1 \mu s \]

- Sufficient Target Separation

\[ \tau = 1 \mu s \]
AN A BIT MORE ESOTERIC THINK – PAIR – SHARE
Think – Pair – Share
What does the Spectrum of an Image Tell Us?

1. Explain what the “Spectrum (Fourier Representation)” of an Image represents.

2. Assign the right spectrum to the right image:

3. Based on these image relationships above, which image parameter dictates how “wide” the spectrum of the image is?
IMAGING RADAR – HOW IT’S REALLY DONE
Some Problems with the Radar Imaging Concept

• Power $P_r$ of returned signal reduces rapidly the distance $R$ to the target

$$P_r \propto \frac{1}{R^4} P_t \quad \text{with} \quad P_t = \text{transmit power}$$

• For satellite applications:

$$P_r \approx \frac{1}{40000000000000000000000000000} \cdot P_t ^{!!!!!!!}$$

→ For Satellite applications:

Difficult to transmit a pulse that (1) has enough power to be able to detect backscattered response AND (2) is short enough to yield sufficient range resolution
Most Radars Replace Pulse with Linear Frequency Modulated (Chirped) Signal

- **Reason:** Sending sufficient power in a single short pulse is near impossible.
- Radars that send chirped signal are called “**Pulse Compression Systems**”

**Procedure:**
1. Transmit frequency coded signal of length $\tau_P$
2. Receive frequency coded echo
3. Compress frequency coded signal using a decoding operation called matched filtering

**What is the resolution of the compressed pulse?**
- Ability to compress the pulse depends on the bandwidth $W_P$ of transmitted chirp signal.
- The higher the bandwidth, the narrower the compressed pulse.

$$\tau_P = \frac{1}{W_P}$$
Achieving Good Range Resolution
The Airborne Case

\[ R \quad \Delta R \]

Antenna

Point targets

Transmitted signal

Echoes of pulse

\[ \frac{2R}{c} \quad \frac{2\Delta R}{c} \]
Achieving Good Range Resolution
The **Spaceborne** Case

- **transmitted signal**
  - Send a longer “chirped” signal to increase $P_t$

- **echo of pulses**

\[
\frac{2R}{c} \quad \text{and} \quad \frac{2\Delta R}{c}
\]

- Use a focusing process to recover the smeared targets
Properties of the Frequency Coded (Chirped) Signal

- Chirp signal: \( u(\tau) = \exp(j\pi k\tau^2) = \cos(\pi k\tau^2) + j \cdot \sin(\pi k\tau^2) \)
Range Compression by Matched Filtering (I)

1. **Data Acquisition:**
   1. Transmit chirp instead of short pulse
   2. Every point target will return chirp echo

2. **Range Compression:**
   Correlate received signal with replica of transmitted chirp

3. **Final range resolution after Range Compression:**
   \[ \rho_R \approx \frac{c}{2W_P} \]

---

**Shape of compressed pulse**

- Linear (magnitude): \( |\text{sinc}(\cdot)| \)
- Logarithmic
- Resolution
- Side lobes

-10 dB
-20 dB
Range Compression by Matched Filtering (II)

signal

reference chirp

correlation

Focused pulse
Range Compression: Resolution-Bandwidth Duality

- You see two different chirps of identical duration but different chirp rates ($k = 50$ & $k = 100$ Hz/s)
- Higher chirp rate $\rightarrow$ twice the bandwidth $\rightarrow$ two times better resolution after correlation

![Chirp in time domain](image1)

![Chirp Bandwidth](image2)

![Correlation Result](image3)
Range Compression: Matlab Example (I)
Range Compression: Matlab Example (II)

Three Overlapping Chirp Signals

Three Overlapping Chirps in Noise
Range Compression: Matlab Example (III)
Chirp-Rate Error Effects – Matlab Example

\( k_s \): Chirp rate of transmitted signal

\( k_f \): Chirp rate used for focusing

Chirp rate errors → insufficient focusing of scattered energy

Effects of Chirp Rate Errors

- \( k_s = 100 \)
- \( k_f = 100 \)
- \( k_f = 101 \)
- \( k_f = 102 \)
- \( k_f = 103 \)
Where Do Side-Lobes Come From?
Effect of Windowing – Matlab Example (I)
Where Do Side-Lobes Come From?

Effect of Windowing – Matlab Example (II)

Effects of Windowing of Spectrum

No Windowing

Kaiser Window

Hamming Window
EXAMPLES OF IMAGING RADAR DATA
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 the Surface with SLARs

Scanning Ground-based Radar System as a SLAR Example

- Resolution defined by pulse length & length of antenna
Example of Scanning Ground-Based Radar Acquisition

- 180 degrees scan angle – location: Fairbanks, Alaska

Decreasing resolution (in scan direction) with range

Sensor Location
What’s Next?

• After improving resolution in range we also want to enhance the azimuth resolution of imaging radars

• Hence, next lecture (Tuesday 20-Feb-17) we will chat about something called “Aperture Synthesis” (the basis of Synthetic Aperture Radar)

• In preparation please read in Woodhouse (2006):
  – Pages 271 – 280
  – Specifically think about the two different interpretations of the aperture synthesis process (we will discuss those in class)