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 (travel time)
  - **Scatterometers**: Measuring radar cross section

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

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Radar Principle

TX

RX

Time

Range $R$

Light velocity

Scattering object

Received echo: $2A_F$

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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

- Center of Mass
- Orbit Height = H
- Instantaneous Sea Level
- Dynamic Topography
- Geoid Undulations
- Mean Sea Level = SSH\textsubscript{mean}
- Geoid = H\textsubscript{geoid}

Mean Sea Level from Altimetry

Microwave Scatterometers

- Goal: measurement of wind speed and direction over oceans

Example: Scatterometer on ERS
The Radar Equation – A Reminder

- Transmit power: $P_t [W]$
- Antenna gain: $G = \frac{4\pi d^2}{\lambda^2}$
- Power density at scatterer: $P_s \left[ \frac{W}{m^2} \right]$  
  $= \frac{P_t G}{4\pi R^2}$  
- Radar cross section: $\sigma \left[ m^2 \right]$
- Reflected power: $P_r \left[ W \right]$  
  $= \frac{P_s \sigma}{4\pi}$  
- Received power: $P_r \left[ W \right]$  
  $= \frac{P_s \sigma}{4\pi R^2}$  
- Antenna area: $A = \frac{\lambda^2}{4\pi}$
- Power density at receiver: $P_r \left[ \frac{W}{m^2} \right]$  
  $= \frac{P_r}{A}$
Pulse Waveform and Range Resolution

targets #1 and #2 easily separable, if \( d_t > d_r = c \tau / 2 \) (range resolution)

Range Resolution Example

- Insufficient Target Separation
- Sufficient Target Separation

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:

<table>
<thead>
<tr>
<th>Image</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image #1</td>
<td>Spectrum #A</td>
</tr>
<tr>
<td>Image #2</td>
<td>Spectrum #B</td>
</tr>
<tr>
<td>Image #3</td>
<td>Spectrum #C</td>
</tr>
</tbody>
</table>

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

- For satellite applications:
  
  $$ P_r \approx \frac{1}{R^4} P_i $$

- 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 $\tau_0$
  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 $W_0$ of transmitted chirp signal
  - The higher the bandwidth, the narrower the compressed pulse
    \[ \tau_0 = \frac{1}{W_0} \]

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**Achieving Good Range Resolution**

**The Airborne Case**

- Send a longer "chirped" signal to increase $P_f$
- Use a focusing process to recover the smeared targets

**Achieving Good Range Resolution**

**The Spaceborne Case**

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

- Chirp signal: \( s(t) = \exp(j\pi k \tau^2) = \cos(\pi k \tau^2) + j \sin(\pi k \tau^2) \)

**Frequency**

**Radar center frequency** \( f_0 \)

**Chirp rate** \( k \)

**Pulse duration** \( \tau_p \)

**Bandwidth** \( W_0 \)

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: \( \rho_0 \approx \frac{\lambda}{2 \tau_p} \)

Shape of compressed pulse

- Linear (magnitude)
- Logarithmic
- Resolution
- Side lobes

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

<table>
<thead>
<tr>
<th>Chirp Bandwidth</th>
<th>Chirp in Time Domain</th>
<th>Correlation Result</th>
</tr>
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<tbody>
<tr>
<td>$k = 100$ Hz/s</td>
<td><img src="image1" alt="Chirp in Time Domain" /></td>
<td><img src="image2" alt="Correlation Result" /></td>
</tr>
<tr>
<td>$k = 50$ Hz/s</td>
<td><img src="image3" alt="Chirp in Time Domain" /></td>
<td><img src="image4" alt="Correlation Result" /></td>
</tr>
</tbody>
</table>

Range Compression: Matlab Example (I)

Range Compression: Matlab Example (II)
Range Compression: Matlab Example (III)

Chirp-Rate Error Effects – Matlab Example

Where Do Side-Lobes Come From?
Effect of Windowing – Matlab Example (I)
Where Do Side-Lobes Come From?
Effect of Windowing – Matlab Example (II)

Examples of Imaging Radar Data

Side-Looking Radars Use Pulse Compression to Increase Range Resolution
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

Side-Looking Radars Use Pulse Compression to Increase Range Resolution

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

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 these in class)
Coherently Received Echo of a Point Target

Every pixel of a complex radar image contains amplitude and phase information.

\[ r^2 = \rho^2 + \tau^2 \]

transmit

coherent demodulation

range resolution, \( \Delta \rho \)

phase:

\[ \phi = \frac{4\pi}{\lambda} R_{\text{scatt}} - \nu - 2\pi \]

Phasor Representation of a Wave Signal

After demodulation:

\[ a = A \exp(j\phi) \]

amplitude:

\[ A = |a| \]

intensity, power:

\[ A^2 = |a|^2 \]

phase:

\[ \phi \]

Every sample of a radar raw-data set and every pixel of a complex SAR image consists of a real and an imaginary part, i.e., it is a phasor and contains amplitude and phase information.