The Principle of Synthetic Aperture Radar (SAR)

Radar transmits pulses and receives echoes at the rate of the pulse-repetition frequency (PRF):

PRF @ 1000 - 4000 Hz
How to Form a Radar Image

Radar transmits pulses and receives echoes at the rate of the pulse-repetition frequency (PRF):

\[ PRF = 1,000 - 4,000 \text{Hz} \]

- **Range resolution:** defined by pulse width (radar principle)
- **Azimuth resolution:** scanning in flight direction at \( V_\text{in} \)
- **Coherent imaging:** complex-valued pixels contain amplitude (brightness) and phase information

2-D Raw Image Data Matrix

- **Image Coordinates in SAR:**
  - Range (distance coordinate)
  - Azimuth (along-track coordinate)
  - Acquisition geometry (top view)
  - Emitter and point scatterer
Image Coordinate Axes in SAR:
• Range (distance coordinate)
• Azimuth (along-track coordinate)
Image Coordinate Axes in SAR:

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Image Coordinate Axes in SAR:
- Range (distance coordinate)
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2-D Raw Image Data Matrix

- echo-signal matrix
- acquisition geometry (top view)
- point scatterer
- range $R$
- azimuth $V$
- $x$
- $y$

We also refer to the range direction as: Fast time $\tau$, or Range time $\tau$.

Azimuth is also called: slow time $t$.

Simple Example of a 2-D Raw Image Data Matrix

- Imagine 4 ships on still ocean (→ ships bright, ocean dark)
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

THE CONCEPT OF SYNTHETIC APERTURE RADAR
Think – Pair – Share
The SAR Explanation Duality

- [Woodhouse, 2006] uses two major concepts to explain the main concepts of Synthetic Aperture Radar:
  - What general principles are used to explain SAR in these two concepts?
  - Which of the two approaches did you find more intuitive and why?
  - How is the SAR concept similar or dissimilar from the “range compression” method that we discussed last week?

Range Compression: Receive chirp (frequency-coded signal) and correlate with transmitted chirp to regain high-resolution ($\rho_0 \approx \frac{\omega}{2\pi}$)

The Problem: Antenna Size vs. Beam Width

- short antenna: $L = 10 \text{ km}$
- long antenna: $L = 5 \text{ km}$
- narrow beam: $R/\beta \approx 10 \text{ km}$
- wide beam: $R/\beta \approx 5 \text{ km}$

ERS-1/2 parameters

Formation of a Synthetic Aperture — SAR Principle

- Phase-corrected summation of echoes
- Factor 1/2 due to doubling of phase shifts in two-way SAR configuration
2-D Raw Image Data Matrix

Range History of a Single-Point Scatterer

Range History of a Single-Point Scatterer
Formation of the Azimuth-Chirp Signal

- Object trajectory: Range history
- Range history recorded by phase measurements

- Phase only defined between $-\pi$ (180º) and $\pi$ (+180º)
  - Only ranges (range differences) of less than the wavelength (e.g., cm) are represented unambiguously
  - Larger ranges (range differences) ambiguous
- Variation of range → variation of phase
- Rate of range change defines rate of phase change

SAR Raw-Data of a Point Scatterer (Simulation)

- Zero Doppler position of target
- Large positive
- Large negative

Azimuth SAR Processing by Correlation

- Correlate measured azimuth chirp (frequency-coded signal) with a reference function to achieve high resolution
Creation of Reference Chirp

- We need to know how range to target changes with time, which is described by:
  - Orthogonal Range to target on ground \( R_\text{og} \)
  - Relative velocity between sensor and target \( V \)

Reference chirp:
- Quadratic approximation

\[
\phi(t) = \frac{d}{dt} \left( R(t) \right) = -\frac{4}{\lambda^2} \sqrt{R(t)^3} \ \text{and} \ \phi(t) = -\frac{4}{\lambda^2} \sqrt{R(t)^3} \ \text{for} \ t \in [0, T]
\]

Chirp rate: Note the required knowledge of relative velocity \( V \) and range to target \( R_\text{og} \)

Chirp-Rate Error Effects – Matlab Example

- \( k_0 \): Chirp rate of transmitted signal
- \( k_\varphi \): Chirp rate used for focusing

Chirp rate errors:
- Insufficient focusing of scattered energy

Linear Superposition of Chirps

- Signal
- Reference chirp
- Correlation
CALCULATING THE AZIMUTH RESOLUTION OF A SAR IMAGE:
Azimuth Resolution of final SAR Image

- Physical Antenna Length: \( L \)
- Synthetic Aperture Length: \( L_s = \frac{L}{R_w} \)
- Synthetic Aperture Duration: \( T_s = \frac{L_s}{V_s} = \frac{1}{F_M} \)
- Azimuth Chirp Bandwidth: \( W_A = F_M \times T_s = \frac{1}{F_M} \times \frac{1}{V_s} = \frac{1}{V_s} \)

- How fast does frequency change with time: \( F_M = \frac{1}{T_s} \)
- Hence, bandwidth: \( W_A = F_M \times T_s \)

- Azimuth Resolution: \( \rho_A = \frac{V_s}{2W_A} = \frac{V_s}{2F_M} = \frac{L_s}{2} \)

- Independent of range!
- Only dependent on antenna length

SAR Raw-Data (After Range Compression)

Focused SAR Data
Focused SAR Data

After azimuth pixel averaging by 4 to achieve approximately square pixels

Synthetic vs. Real Apertures

Pros and Cons

- Resolution independent of range to the object
  - Explanation: "Dynamic aperture length" (increased range → increased footprint → increased synthetic aperture length → constant resolution)
- Resolution decreases with distance
- Resolution increases with decreasing real antenna length
  - Shorter antenna → increased footprint → increased synthetic aperture length → increased resolution
- Resolution decreases with decreasing real antenna length
- Image processing challenging
- Image processing straightforward

Simple Example – Range Compression
Simple Example – Range Compression
(No Range Cell Migration)
Simple Example – Range Compression
(No Range Cell Migration)

Before RC

After RC

Simple Example – Range Compression
(No Range Cell Migration)

Before AC

Focused Image

Simple Example – Range Compression
(No Range Cell Migration)
Real Data Example – Range Compression

Real Data Example – Range Compression

What’s Next?

• Next lecture (Tuesday 2/24/15) we will discuss geometric and radiometric properties of SAR images and will talk about how SAR data can be geocode for use in a GIS

• In preparation please read in Woodhouse (2006):
  – Geometric properties: 281-283
  – Radiometric properties (Speckle): 289-297
  – Geometric correction: 297-300
  – Altar: Please read alternative explanation for Synthetic Aperture Formation: 271-275