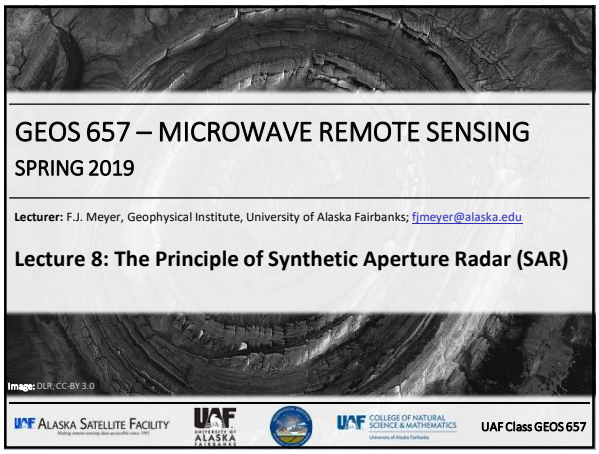
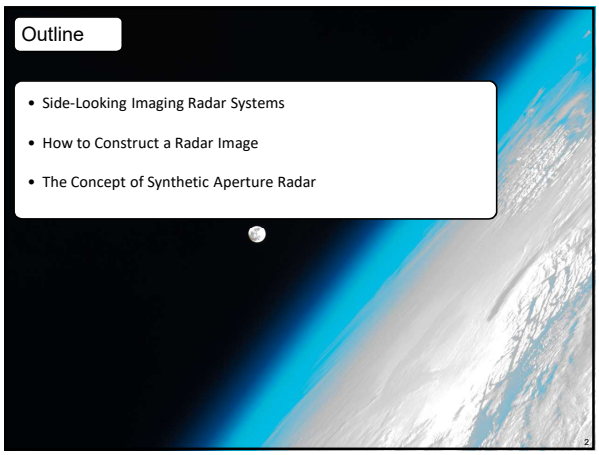
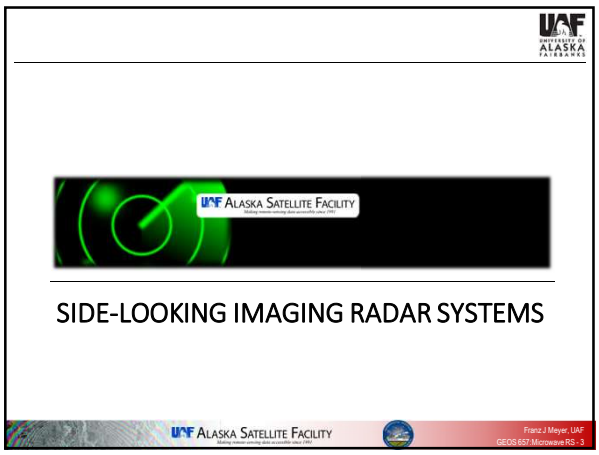
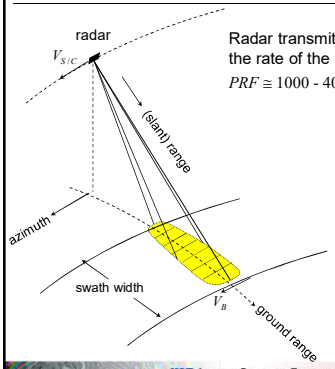

GEOS 657 – MICROWAVE REMOTE SENSING
SPRING 2019
Lecturer: F.J. Meyer, Geophysical Institute, University of Alaska Fairbanks; fjmeyer@alaska.edu
Lecture 8: The Principle of Synthetic Aperture Radar (SAR)
Image: DLR, CC-BY 3.0
ALASKA SATELLITE FACILITY
UAF Class GEOS 657


Outline
• Side-Looking Imaging Radar Systems
• How to Construct a Radar Image
• The Concept of Synthetic Aperture Radar
2


ALASKA SATELLITE FACILITY
SIDE-LOOKING IMAGING RADAR SYSTEMS
ALASKA SATELLITE FACILITY
Franz J Meyer, UAF
GEOS 657: Microwave RS - 3

The Radar Imaging Geometry

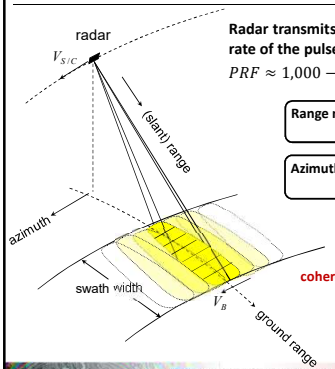


Radar transmits pulses and receives echoes at the rate of the pulse-repetition frequency (PRF):

$PRF \cong 1000 - 4000$ Hz

HOW TO CONSTRUCT A RADAR IMAGE

How to Form a Radar Image



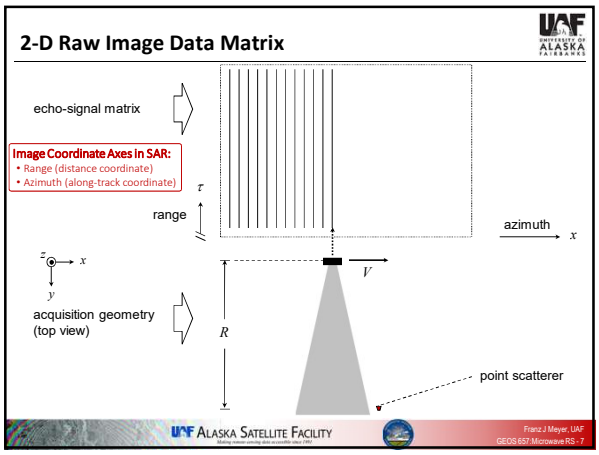
Radar transmits pulses and receives echoes at the rate of the pulse-repetition frequency (PRF):

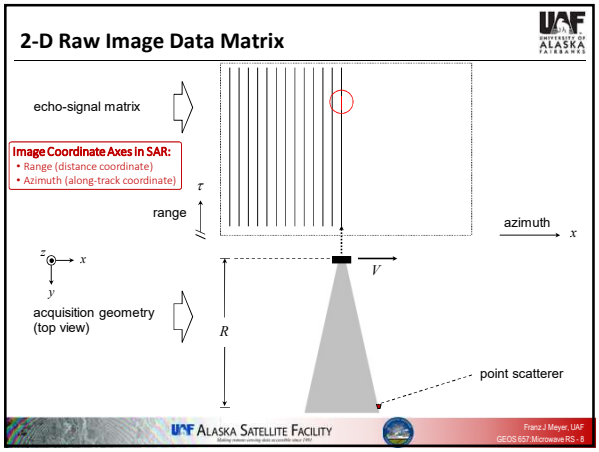
$PRF \approx 1{,}000 - 4{,}000Hz$

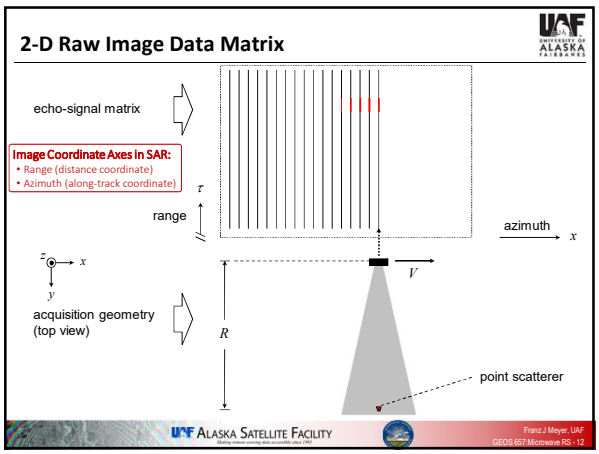
Range resolution: defined by pulse width (radar principle)

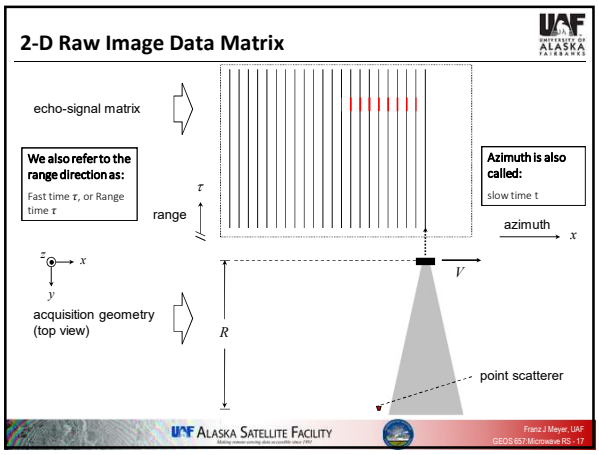
Azimuth resolution: scanning in flight direction at $V_{S/C}$

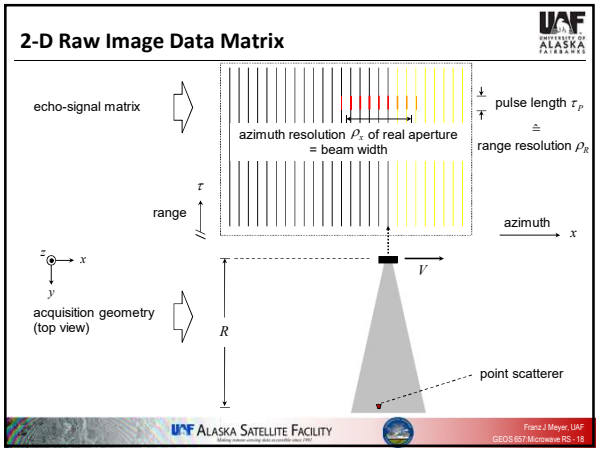
coherent imaging: complex-valued pixels contain amplitude (brightness) and phase information

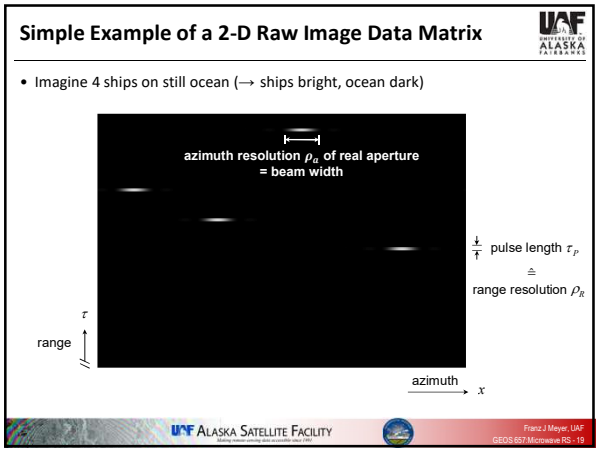

2-D Raw Image Data Matrix
echo-signal matrix
Image Coordinate Axes in SAR:
• Range (distance coordinate)
• Azimuth (along-track coordinate)
τ
range
azimuth
x
z
x
y
V
acquisition geometry
(top view)
R
point scatterer
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657: Microwave RS - 7


2-D Raw Image Data Matrix
echo-signal matrix
Image Coordinate Axes in SAR:
• Range (distance coordinate)
• Azimuth (along-track coordinate)
τ
range
azimuth
x
z
x
y
V
acquisition geometry
(top view)
R
point scatterer
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657: Microwave RS - 8


2-D Raw Image Data Matrix
echo-signal matrix
Image Coordinate Axes in SAR:
• Range (distance coordinate)
• Azimuth (along-track coordinate)
τ
range
azimuth
x
z
x
y
V
acquisition geometry
(top view)
R
point scatterer
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657: Microwave RS - 12


2-D Raw Image Data Matrix
echo-signal matrix
We also refer to the range direction as:
Fast time τ, or Range time τ
Azimuth is also called:
slow time t
range
τ
azimuth
x
z
x
y
V
acquisition geometry (top view)
R
point scatterer
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657:Microwave RS - 17

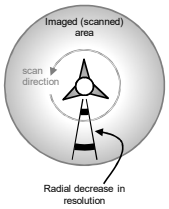

2-D Raw Image Data Matrix
echo-signal matrix
azimuth resolution ρ_a of real aperture
= beam width
pulse length τ_p
≙
range resolution ρ_R
range
τ
azimuth
x
z
x
y
V
acquisition geometry (top view)
R
point scatterer
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657:Microwave RS - 18


Simple Example of a 2-D Raw Image Data Matrix
• Imagine 4 ships on still ocean (→ ships bright, ocean dark)
azimuth resolution ρ_a of real aperture
= beam width
pulse length τ_p
≙
range resolution ρ_R
range
τ
azimuth
x
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657:Microwave RS - 19

Imaging the Surface with SLARs

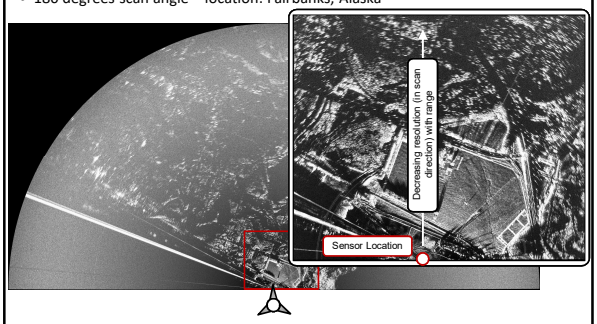
Scanning Ground-based Radar System as a SLAR Example

- Resolution defined by pulse length & length of antenna



Example of Scanning Ground-Based Radar Acquisition

- 180 degrees scan angle – location: Fairbanks, Alaska



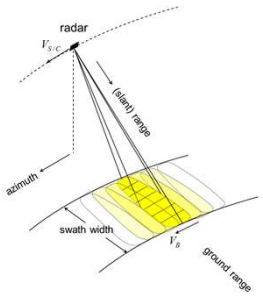
THE CONCEPT OF SYNTHETIC APERTURE RADAR

Think – Pair – Share

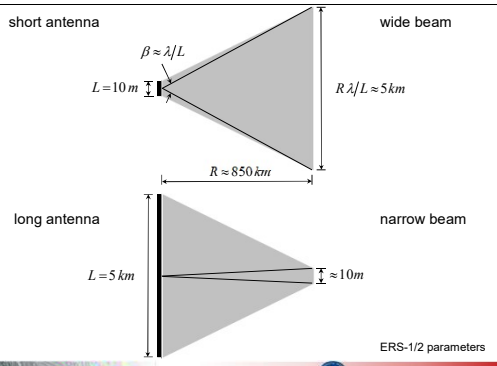
The SAR Explanation Duality

- **(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?

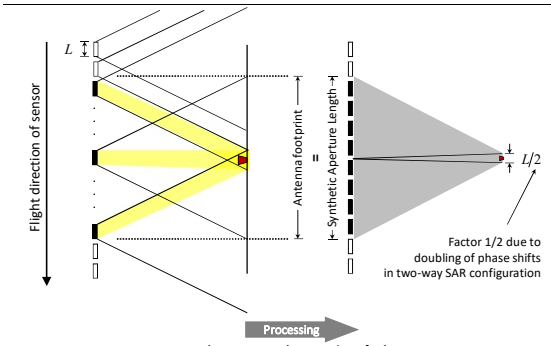
Range Compression: Receive chirp (frequency-coded signal) and correlate with transmitted chirp to regain high-resolution ($\rho_R \cong \frac{c}{2W_P}$)



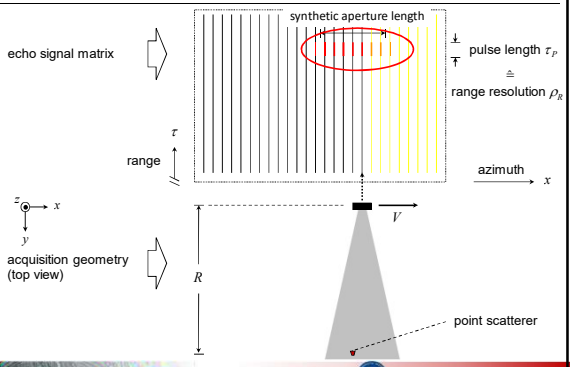
The Problem: Antenna Size vs. Beam Width



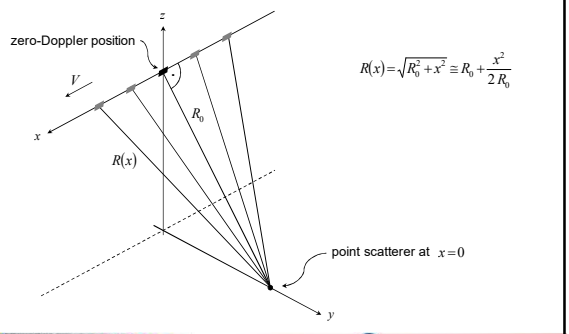
Formation of a Synthetic Aperture — SAR Principle



2-D Raw Image Data Matrix

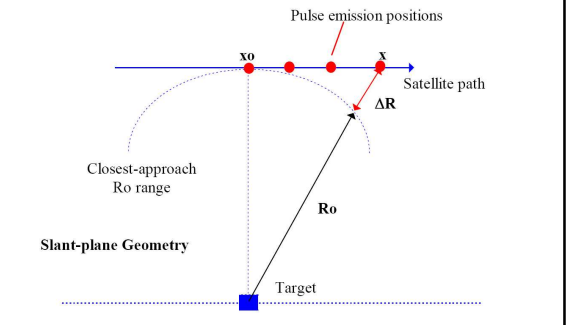


Range History of a Single-Point Scatterer



$$R(x)=\sqrt{R_0^2+x^2}\cong R_0+\frac{x^2}{2R_0}$$

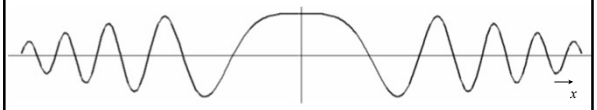
Range History of a Single-Point Scatterer



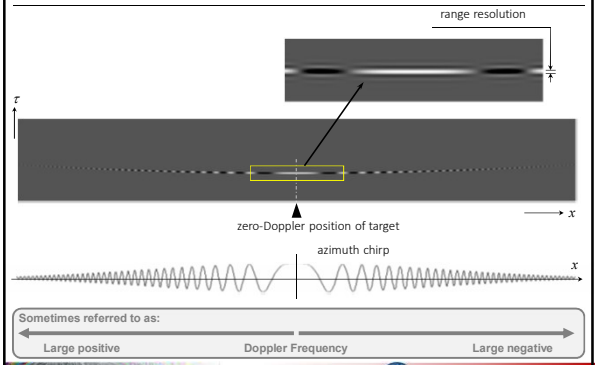
Formation of the Azimuth-Chirp Signal

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

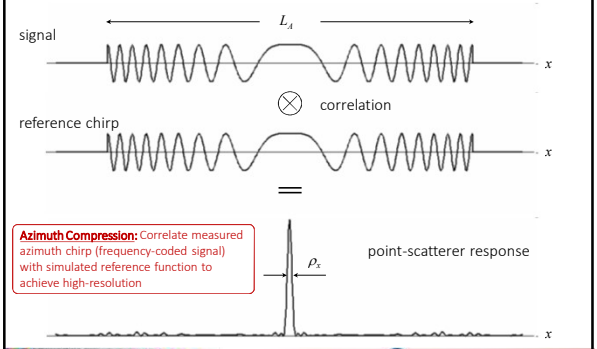
- Phase only defined between $-\pi$ (-180º) and $+\pi$ (+180º) →
  - Only ranges (range differences) of less than the wavelength (several cm) are represented unambiguously
  - larger ranges (range differences) ambiguous
- Variation of range → variation of phase
- Rate of range change defines rate of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



SAR Raw-Data of a Point Scatterer (Simulation)



Azimuth SAR Processing by Correlation



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_0
  - Relative velocity between sensor and target V

- **Reference chirp:**

quadratic approximation

$$\phi(t;R_0) = -\frac{4\pi}{\lambda} R(t;R_0) = -\frac{4\pi}{\lambda}\sqrt{R_0^2 + V^2(R_0)\cdot t^2} \cong -\frac{4\pi}{\lambda}\left(R_0 + \frac{V^2(R_0)}{2R_0} t^2\right)$$

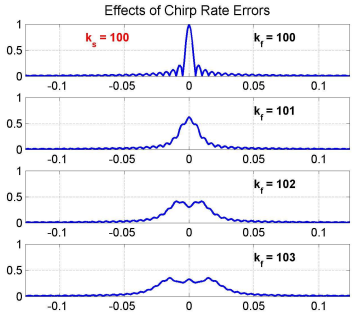
Chirp rate: Note the **required** knowledge of relative velocity V and range to target R_0

Chirp-Rate Error Effects – Matlab Example

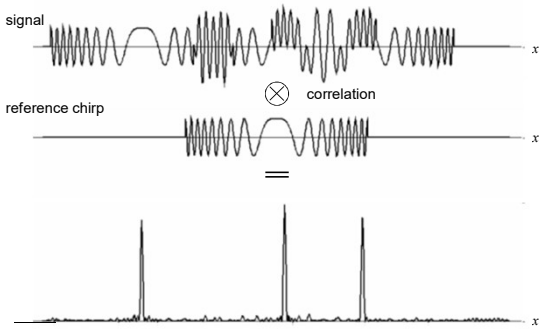
k_s: Chirp rate of transmitted signal

k_f: Chirp rate used for focusing

Chirp rate errors → insufficient focusing of scattered energy



Linear Superposition of Chirps



CALCULATING THE AZIMUTH RESOLUTION OF A SAR IMAGE:

Azimuth Resolution of final SAR Image

- **Physical Antenna Length**: L
- **Synthetic Aperture Length**: $L_A = \frac{\lambda}{L} R_0$
- **Synthetic Aperture Duration**: $T_A = \frac{L_A}{V} = \frac{\lambda}{L} \frac{R_0}{V}$
- **Azimuth Chirp Bandwidth**: $W_A = FM \cdot T_A = \frac{2}{\lambda} \frac{V^2}{R_0} \cdot \frac{\lambda}{L} \frac{R_0}{V} = \frac{2V}{L}$
  - How fast does frequency change with time: $\mathrm{FM} = \frac{1}{2\pi} \cdot \frac{\partial}{\partial t} \phi(t; R_0) = \frac{2}{\lambda} \frac{V^2}{R_0}$
  - Hence, bandwidth: $W_A = FM \cdot T_A$
- **Azimuth Resolution**: $\rho_a = \frac{V}{W_A} = \frac{V \cdot L}{2V} = \frac{L}{2}$
  - **independent of range !**
  - **Only dependent on antenna length**

SAR Raw-Data (After Range Compression)

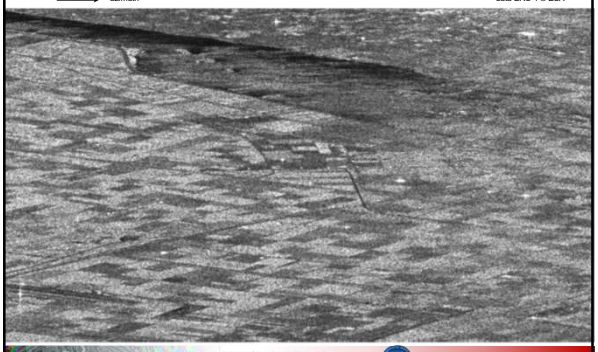
azimuth

data ERS-1 © ESA

Focused SAR Data

azimuth

data ERS-1 © ESA



Focused SAR Data

azimuth

data ERS-1 © ESA

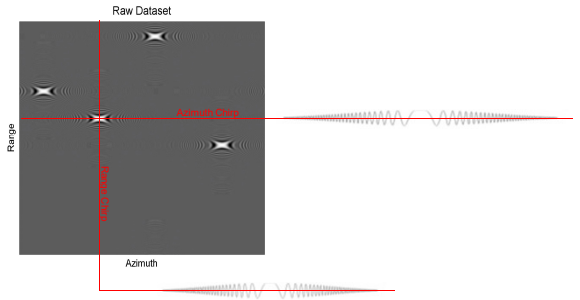
after
azimuth pixel averaging by 4
to achieve approximately
square pixels

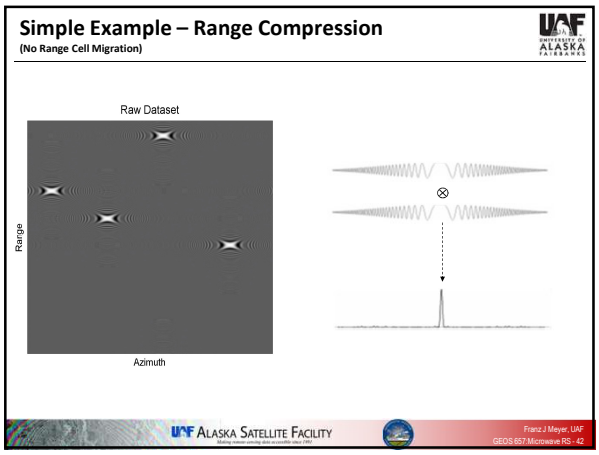
Synthetic vs. Real Apertures

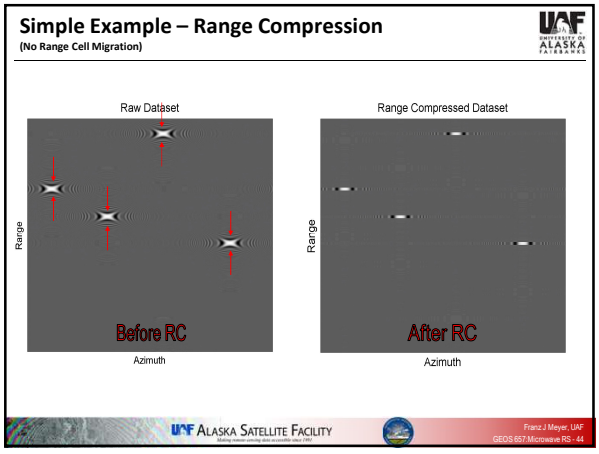
Pros and Cons

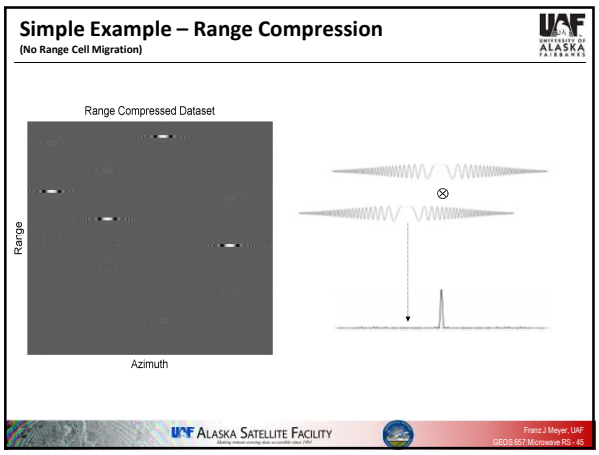
- ⊕ **Resolution independent of range to the object**
  - Explanation: "dynamic aperture length" (increased range → increased footprint → increased synthetic aperture length → constant resolution)
- ⊖ **Resolution decreases with distance**
- ⊕ **Resolution *increases* with *decreasing* real antenna length**
  - 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

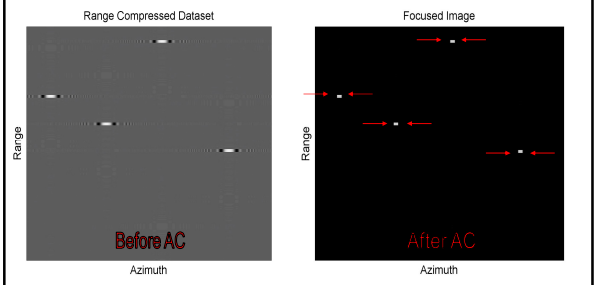



Simple Example – Range Compression
(No Range Cell Migration)
Raw Dataset
Range
Azimuth
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657:Microwave RS - 42

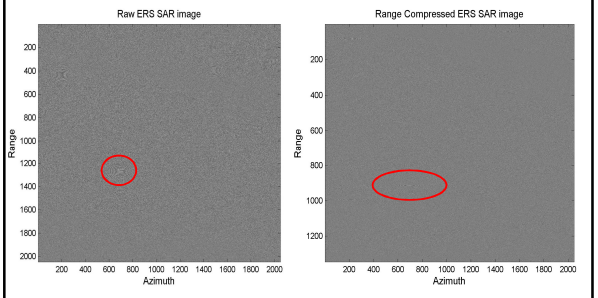

Simple Example – Range Compression
(No Range Cell Migration)
Raw Dataset
Range Compressed Dataset
Range
Range
Before RC
After RC
Azimuth
Azimuth
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657:Microwave RS - 44


Simple Example – Range Compression
(No Range Cell Migration)
Range Compressed Dataset
Range
Azimuth
UAF Alaska Satellite Facility
Franz J Meyer, UAF
GEOS 657:Microwave RS - 45

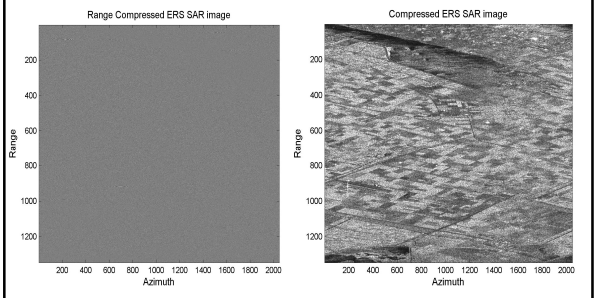
Simple Example – Range Compression
(No Range Cell Migration)



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
  - **Also:** Please read alternative explanation for Synthetic Aperture Formation: **271-275**