Synthetic Aperture Radar,

An Introduction;   Session I: SAR Imaging

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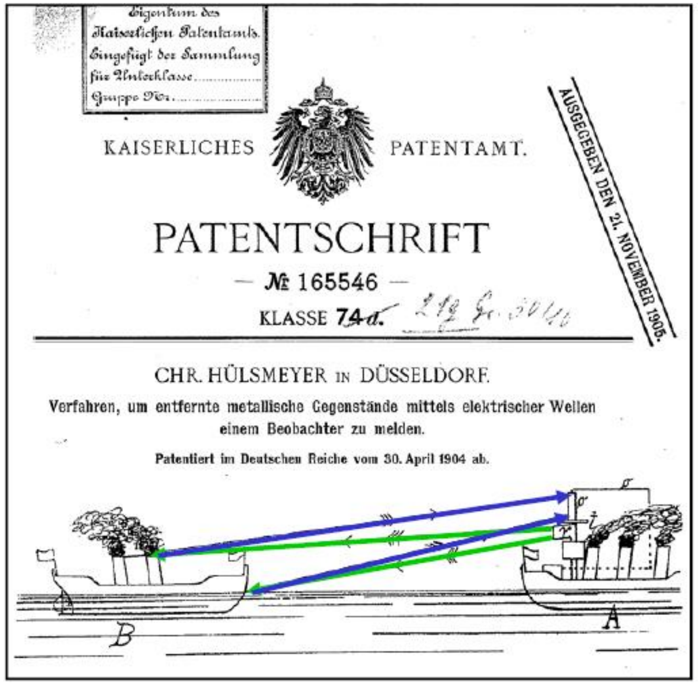
Satellite Geodesy Observation Techniques
GEOENGINE Master Program
Dec. 2019

Synthetic Aperture Radar Imaging

- Radar Remote Sensing
- Pros and Cons
- Nadir versus Side Looking Systems

Radar Remote Sensing

- Radar: Radio detection and rangin
  - Christian Hülsmeyer (1904)



KAISERLICHES PATENTAMT.

AUSGEGEBEN DEN 21. NOVEMBER 1905.

PATENTSCHRIFT

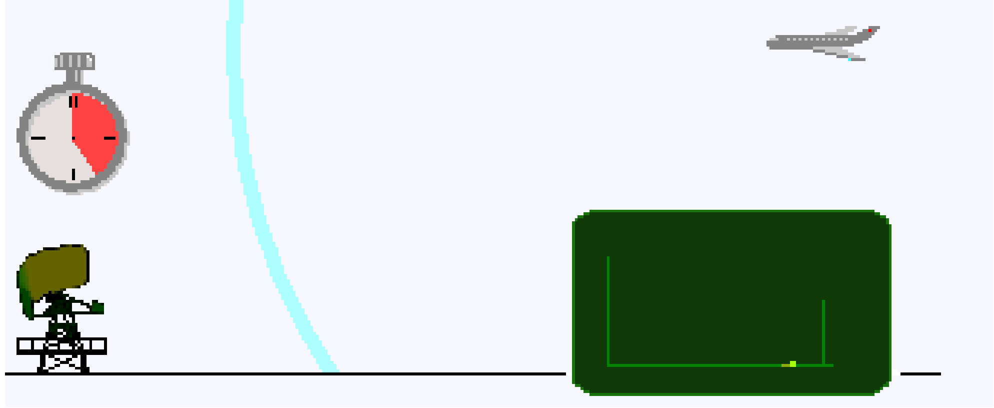
— № 165546 —

KLASSE 74d.

CHR. HÜLSMEYER in DÜSSELDORF.

Verfahren, um entfernte metallische Gegenstände mittels elektrischer Wellen einem Beobachter zu melden.

Patentiert im Deutschen Reiche vom 30. April 1904 ab.



Credit: Wikipedia

Radar Remote Sensing

- Radar is an object-detection system which uses microwave region of the EM spectrum to determine the range, altitude, direction, or speed of objects

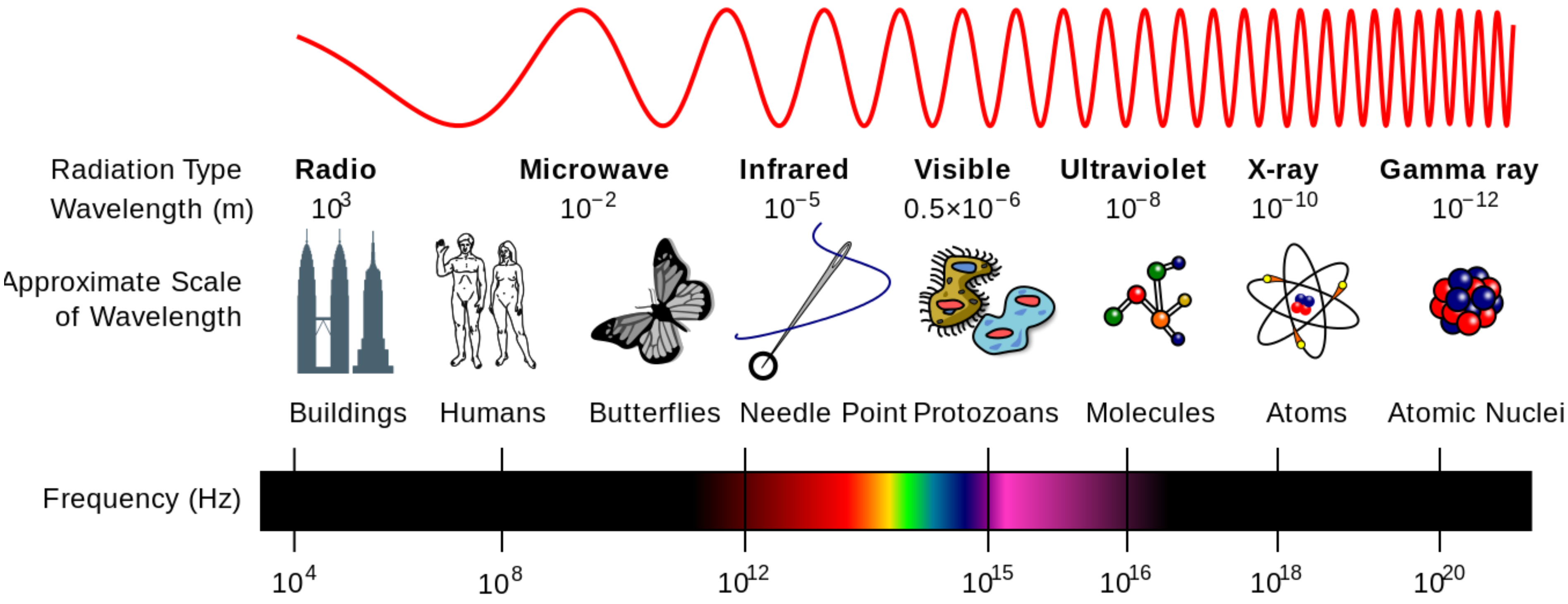


Image Credit: Wikipedia

Radar Remote Sensing

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Frequency band	Wavelength (cm)	Frequency (GHz)
Ka	0.8-1.1	40 - 26.5
K	1.1-1.7	26.5 - 18
Ku	1.7-2.4	18 - 12.5
X	2.4-3.8	12.5 -8
C	3.8-7.5	8 - 4
S	7.5-15	4 - 2
L	15 -30	2 - 1
P	30 -100	1 - 0.3

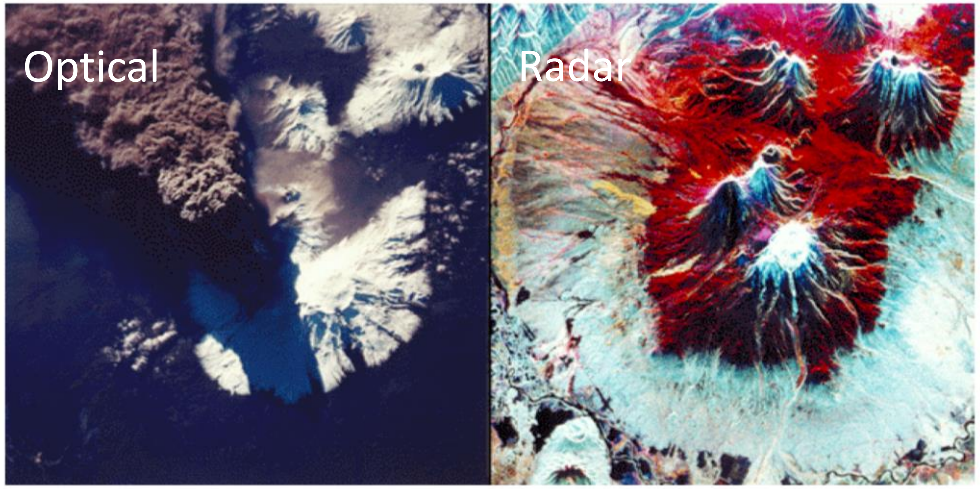
$\boxed{f \text{ (in Hertz)} = C/\lambda}$

$C = 3.10^8$ m
λ =wavelength in m

Image Credit: Thuy Le Toan, Introduction to SAR Remote Sensing

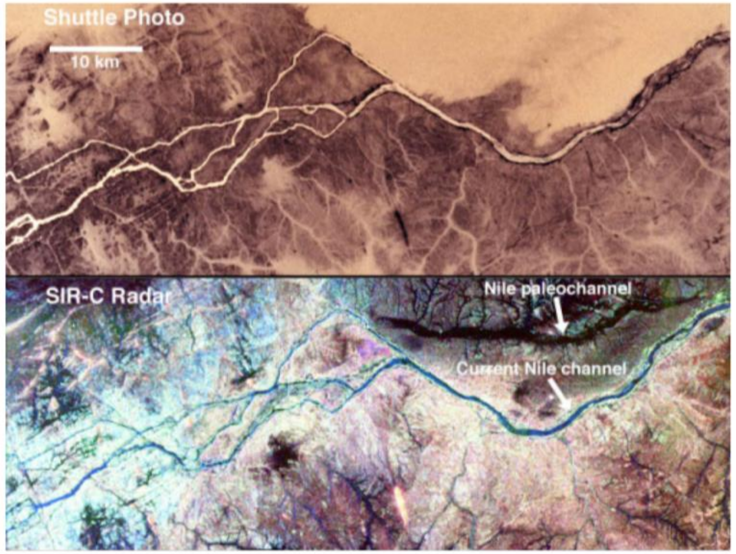
Radar Remote Sensing

- pros and cons
  - all weather capability
  - day and night operation
  - sensitivity to dielectric properties
  - sensitivity to target structure
  - subsurface penetration
  - …



Kliuchevskoi volcano in Kamchatka, Russia; Optical photo taken by shuttle astronauts during the early hours of the eruption on September 30; Radar image taken by SIR-C/X-SAR aboard the Space Shuttle Endeavour Oct 5, 1994. Red (L-band HH), Green (L-band HV), Blue (C-band HV) ; Credit: NASA JPL

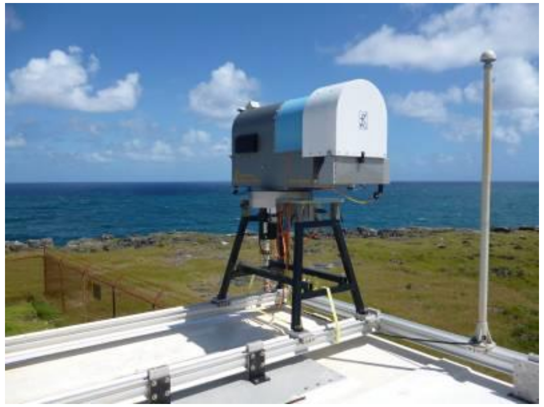
  - complex processing
  - complex interpretation
  - …



Color infrared photograph (top) and SIR-C radar image (bottom) recorded in 1995 over the Sahara Desert in Sudan. In the top right hand quadrant of the radar image a previous, ancient channel of the Nile is evident, now buried under sand; the color composite radar image was created by displaying the C band VH cross-polar channel as red, the L band VH cross-polar channel as green and the L band co-polar HH channel as blue; since the paleo channel appears white there is good penetration at each of those wavelength/polarization combinations (Credit: NASA JPL)

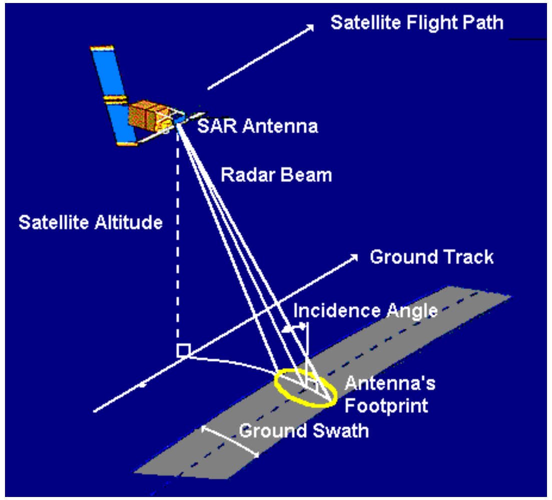
Radar Remote Sensing

- passive
  - microwave radiometers
- active
  - scatterometers
  - radar imaging systems
  - altimeters

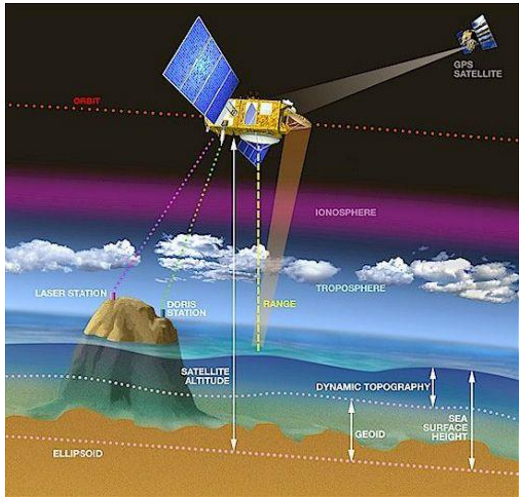


Humidity and Temperature Profiler

airport scatterometer



radar imaging

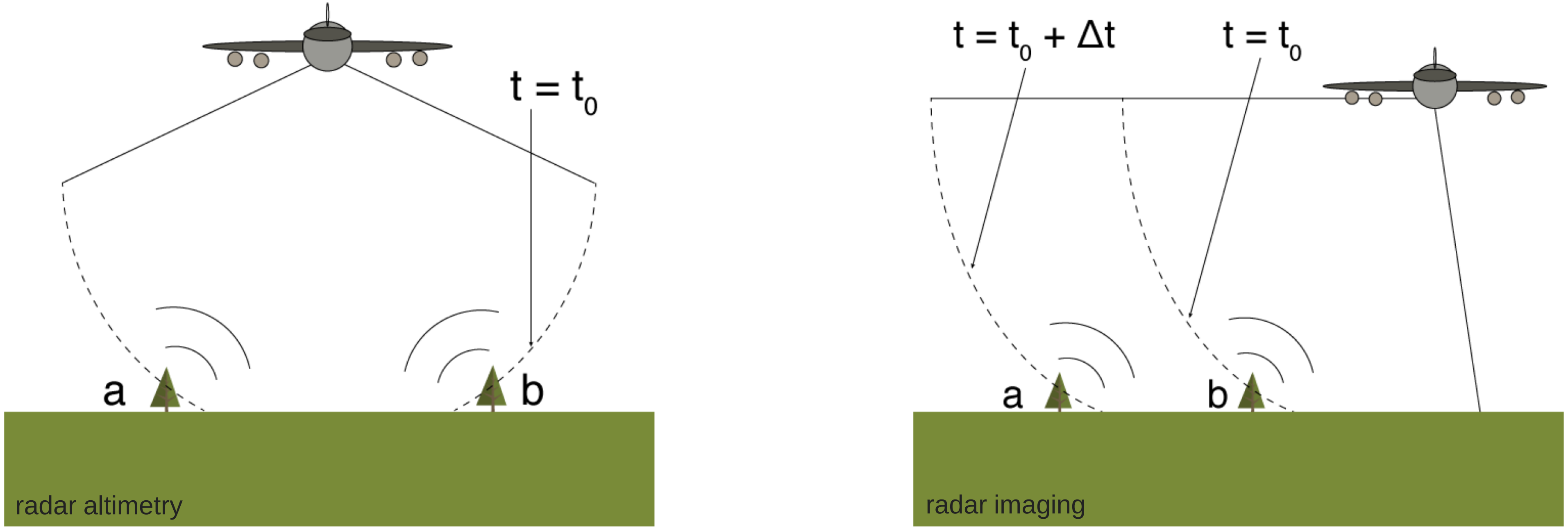


radar altimetry

Image Credits: (top left) Wikipedia, (top right) Wikipedia, (bottom left) CRISP, and (bottom right) CNES

Radar

- nadir versus side looking systems



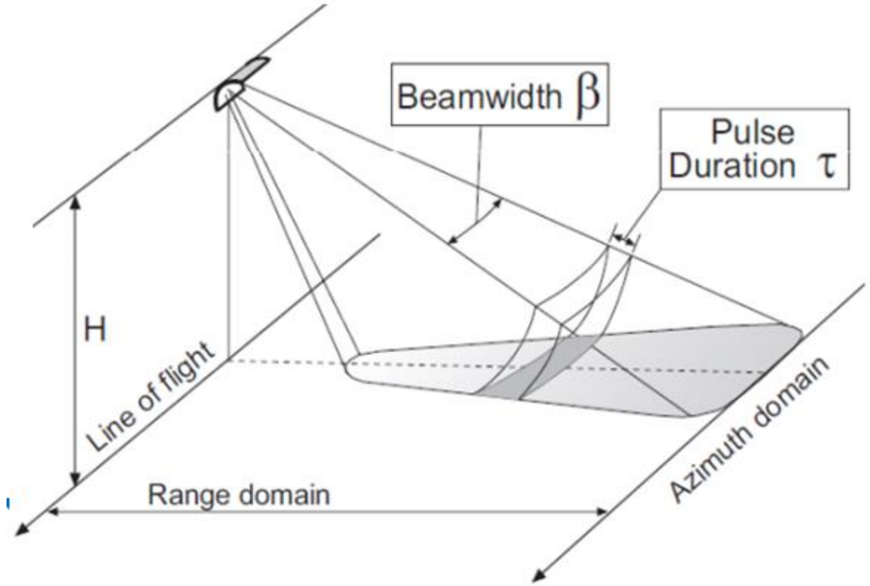
Credit: Erika Podest (NASA), Basics of Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar Imaging

- Geometry
- Resolution: from Real to Synthetic Apertures

Radar Imaging

- geometry



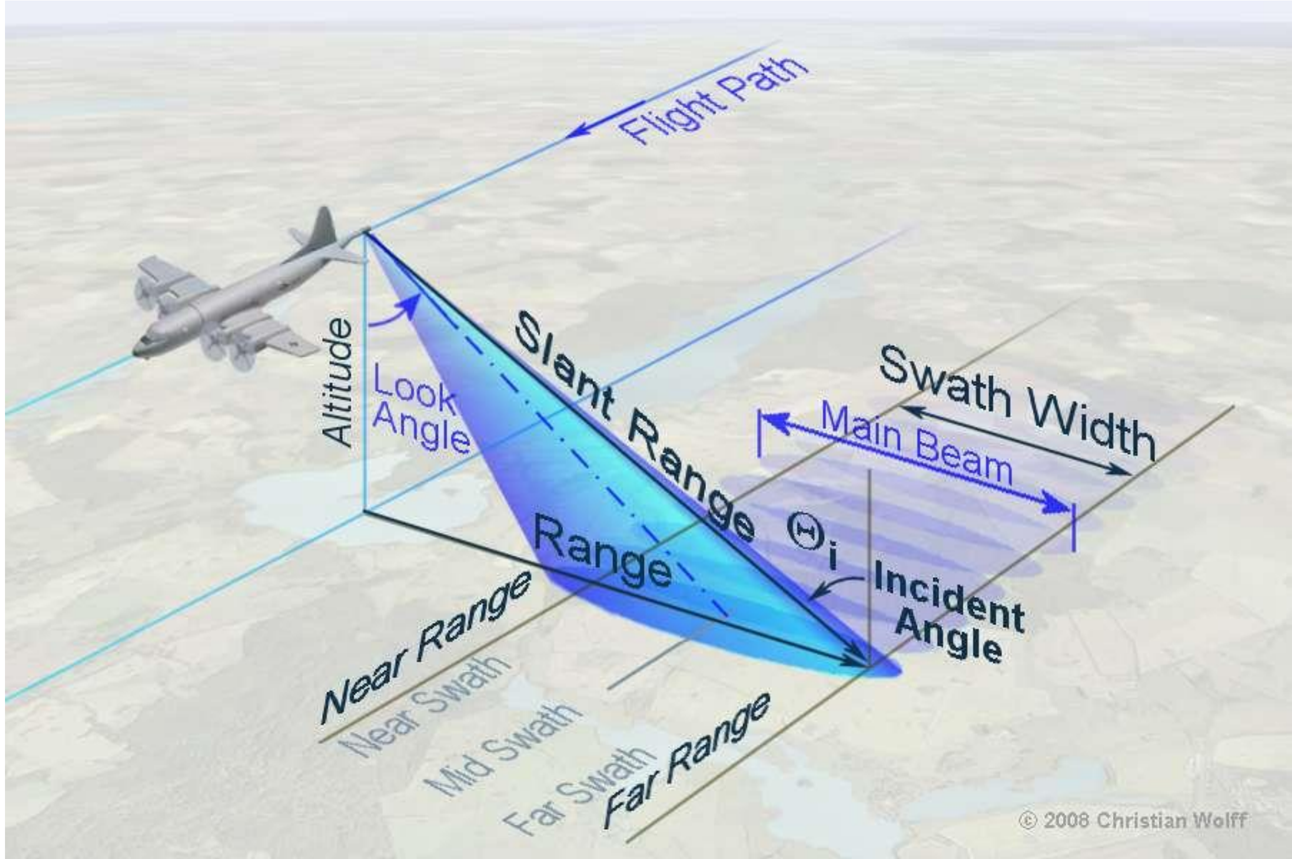
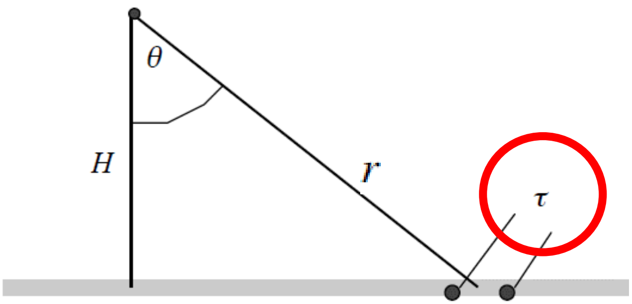
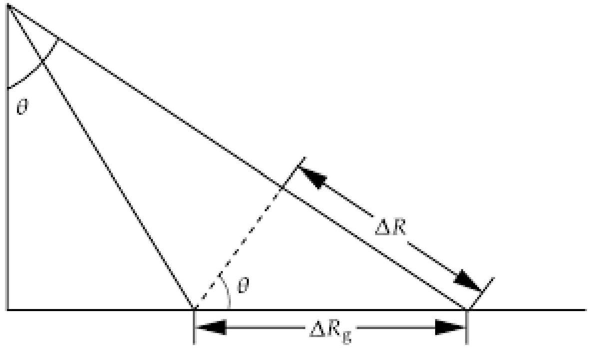


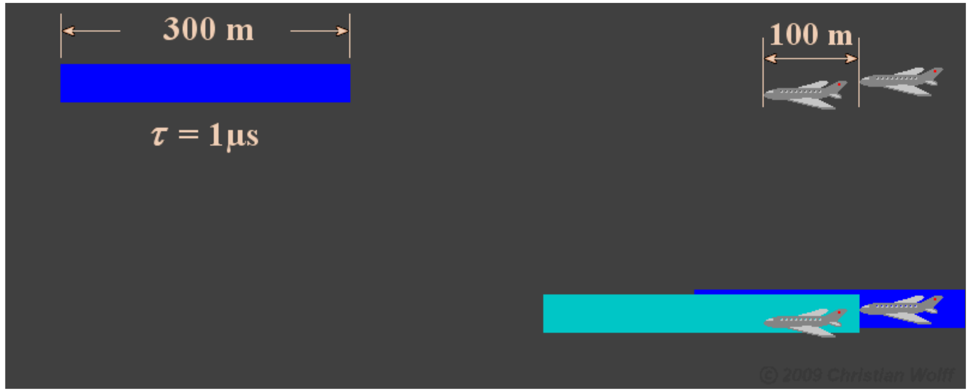
Image Credits: (left) David P. Lusch, Ph.D., Center for Remote Sensing & GIS, Michigan State University and (right) radartutorial.eu

Radar Imaging

- range resolution

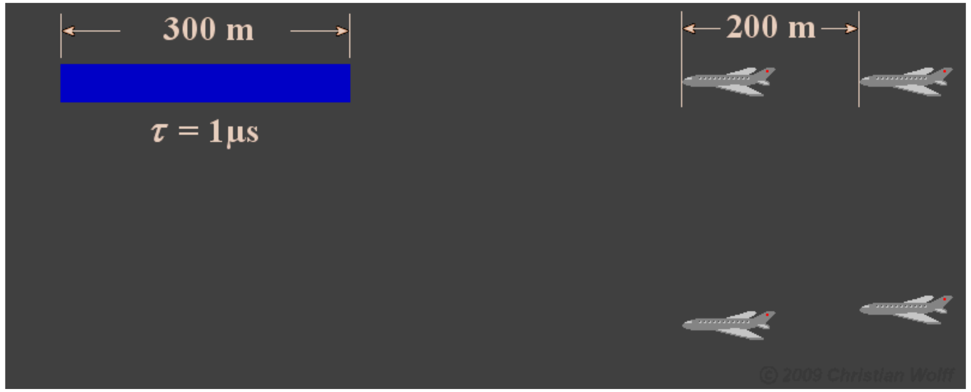






$$\delta_{r\_slant} = \frac{c\tau}{2}$$

slant range resolution



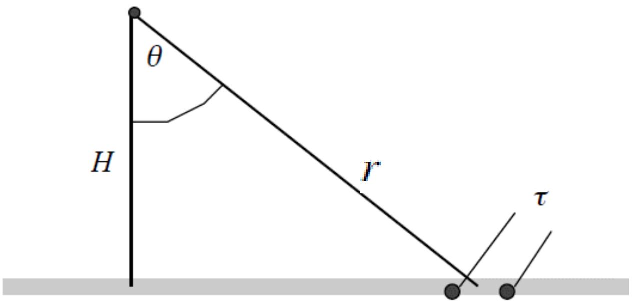
$$\delta_{r\_ground} = \frac{c\tau}{2}\frac{1}{sin\theta}$$

ground range resolution

Image Credits: (middle) Lauknes, Tom Rune. (2019). Long-Term Surface Deformation Mapping using Small-Baseline Differential SAR Interferograms. and (right) radartutorial.eu

Radar Imaging

- range resolution
  - chirp signal



$$\delta_{r\_slant} = \frac{c}{2B}$$

$$B = K_r \tau_p$$

K: chirp rate

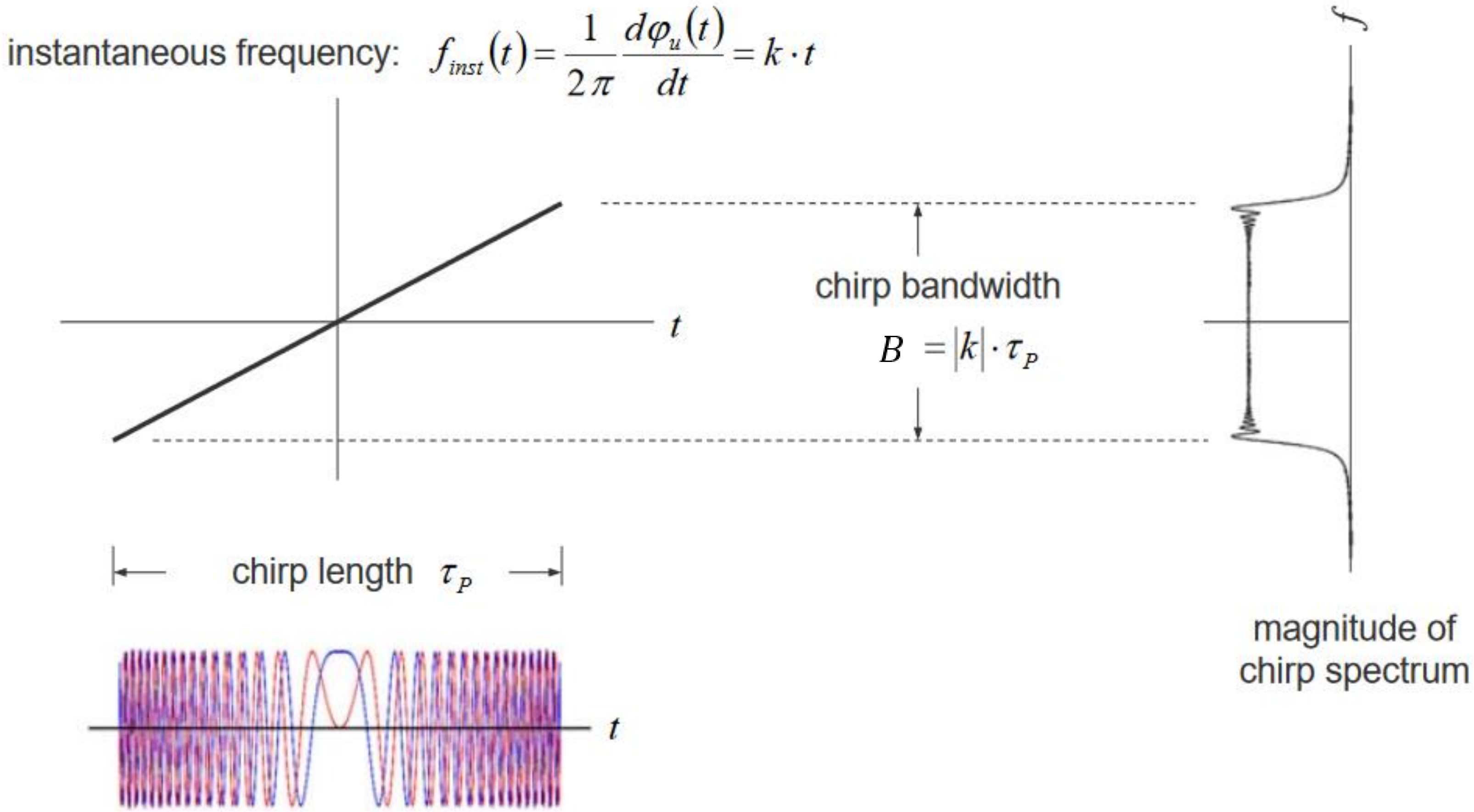


Image Credit: Uwe Sörgel, Signal Processing Lecture Notes

Radar Imaging

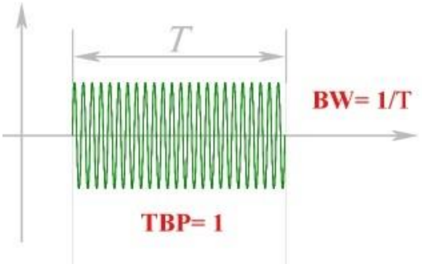
- Time-Bandwidth Product

$$\delta_{r\_slant} = \frac{c\tau}{2}$$

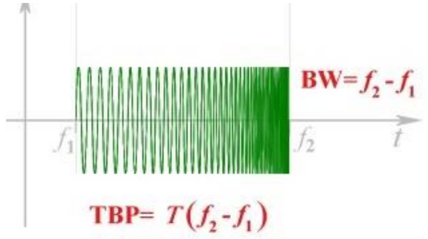
?

$$\delta_{r\_slant} = \frac{c}{2B}$$

Keyed on/off Pulse



Linear Frequency Modulated Waveform



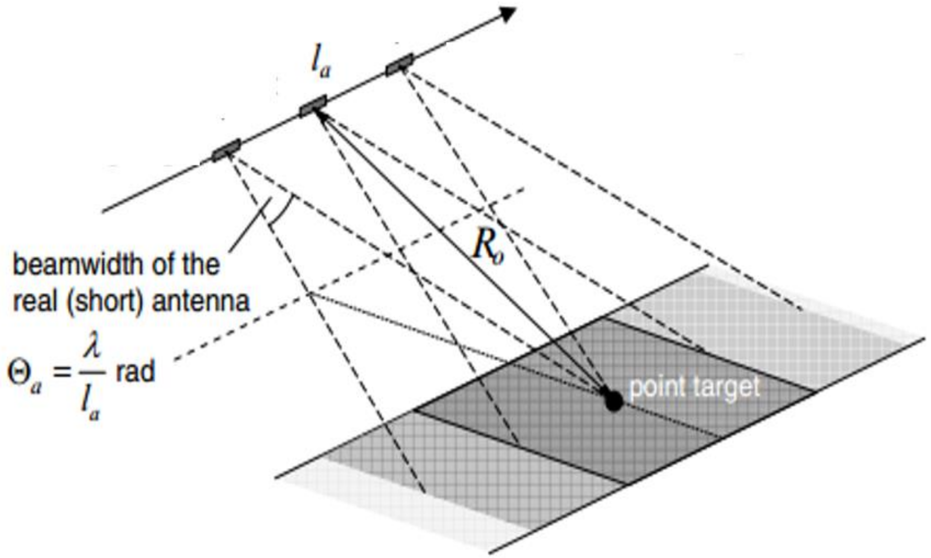
The keyed on/off modulated pulse radar with a pulse length of T has a bandwidth of 1/T . Its time-bandwidth product is therefore TBP = 1 and its range resolution depends directly on its pulse length.

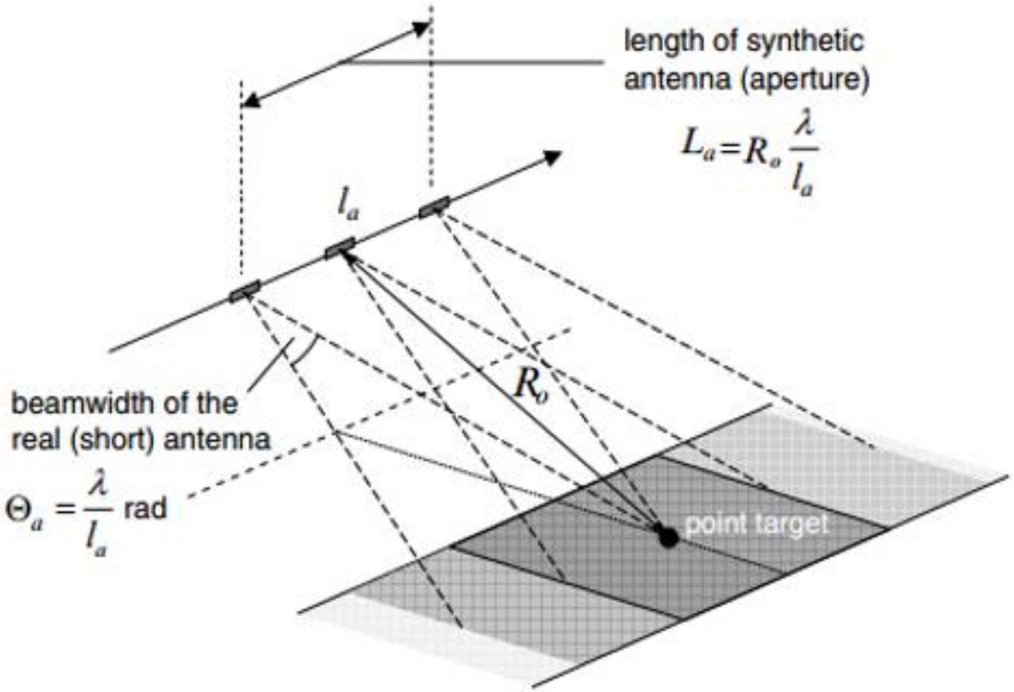
Radars using intrapulse frequency modulated waveforms may have TBPs of more than 100 up to 10 000. By linear frequency modulated waveform the bandwidth can be measured by the difference of the upper f2 and the lower frequency f1 : BW = Δf = f2 - f1, and its TBP= T·Δf.

Image Credit (middle) and Text Reference (right): radartutorial.eu

Radar Imaging

- azimuth resolution





Θ_{sa}: beamwidth of the synthetic aperture (rad)

$$\delta_a = \Theta_a R_0 = \frac{\lambda}{l_a} R_0$$

Real Aperture Radar

$$\delta_{sa} = \Theta_{sa} R_0 = \frac{\lambda}{2L_a} R_0 = \frac{\lambda}{2} \frac{1}{\Theta_a R_0} R_0 = \frac{\lambda}{2} \frac{l_a}{\lambda} \frac{1}{R_0} R_0 = \frac{l_a}{2}$$

Synthetic Aperture Radar

Image Credit: Richards, J.A., 2009. Remote sensing with imaging radar (Vol. 1). Berlin: Springer.

Radar Imaging

- from Real to Synthetic Aperture Radar

Carl Wiley and the Invention of the Synthetic Aperture Radar

(Carl Wiley, Patent in 1954)

United States Patent Office 3,196,436
Patented July 20, 1965

3,196,436
PULSED DOPPLER RADAR METHODS AND APPARATUS
Carl A. Wiley, Phoenix, Ariz., assignor to Goodyear Aerospace Corporation, a corporation of Delaware
Filed Aug. 13, 1954, Ser. No. 449,559
14 Claims. (Cl. 343—17)

This invention relates to pulsed radar methods and apparatus, and, more particularly, to terrain mapping radars borne by moving objects, for example, an airplane, and making use of the Doppler frequency shift phenomenon to obtain angular resolutions, and/or scanning in azimuth.

GOODYEAR

Goodyear Aircraft Corporation

AKRON 15, OHIO

June 4, 1952

Mr. Carl Wiley
Department 29-A
Basic Physical Research
Goodyear Aircraft Corporation
Litchfield Park, Arizona

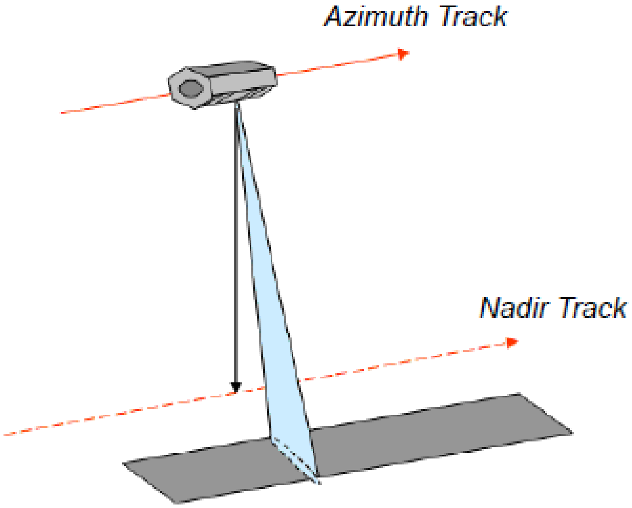
Dear Carl:

I was very happy to read your report GER-15-A and to find that you were able to prove that the system tested in the sonic simulator proved your prediction to be correct.

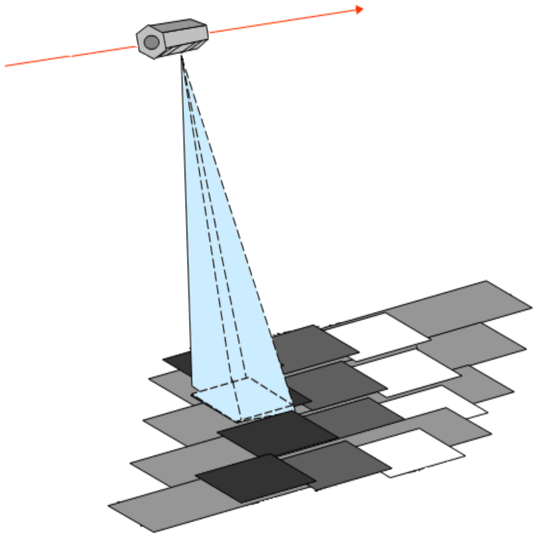
Synthetic Aperture Radar Imaging

- Imaging Modes
- Image Characteristics
- **Radar Backscatter**
- **Backscattering Mechanism**
- Image Formation

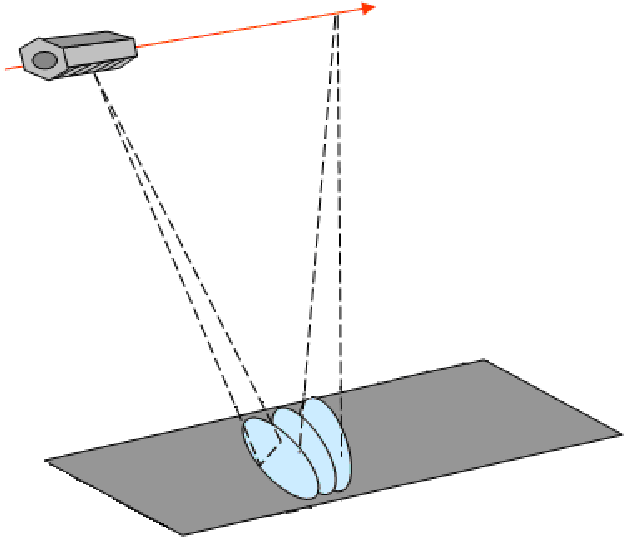
SAR Imaging Modes



stripmap



scanSAR



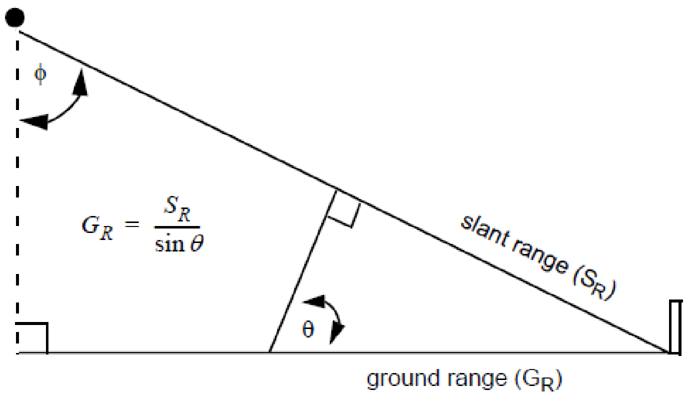
spotlight

Credit: Schättler, B., et al. "The TerraSAR-X payload ground segment: Pre-launch status and performance." Proc. CEOS SAR Calibration Workshop. 2006.

SAR Image Characteristics

- geometric distortion: the side-looking geometry of radar results in several geometric distortions, such as slant range scale distortions and relief distortions
  - slant range distortion

Figure 6: Slant Range vs. Ground Range Image Projection



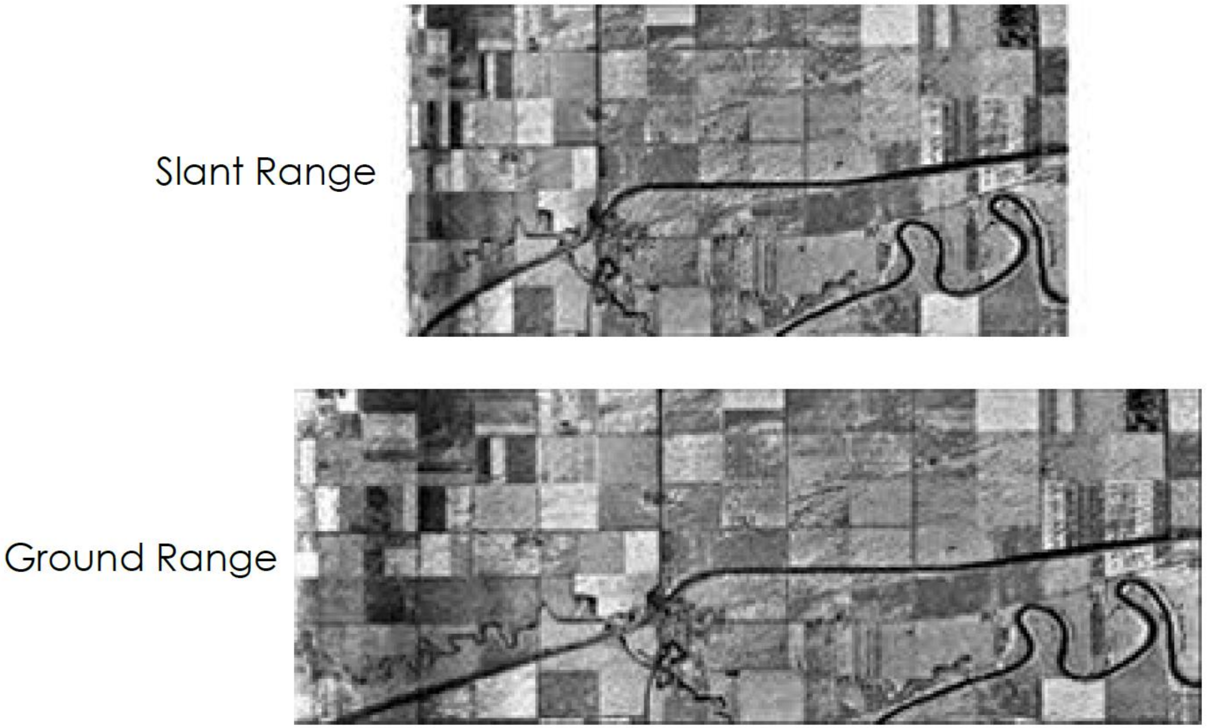
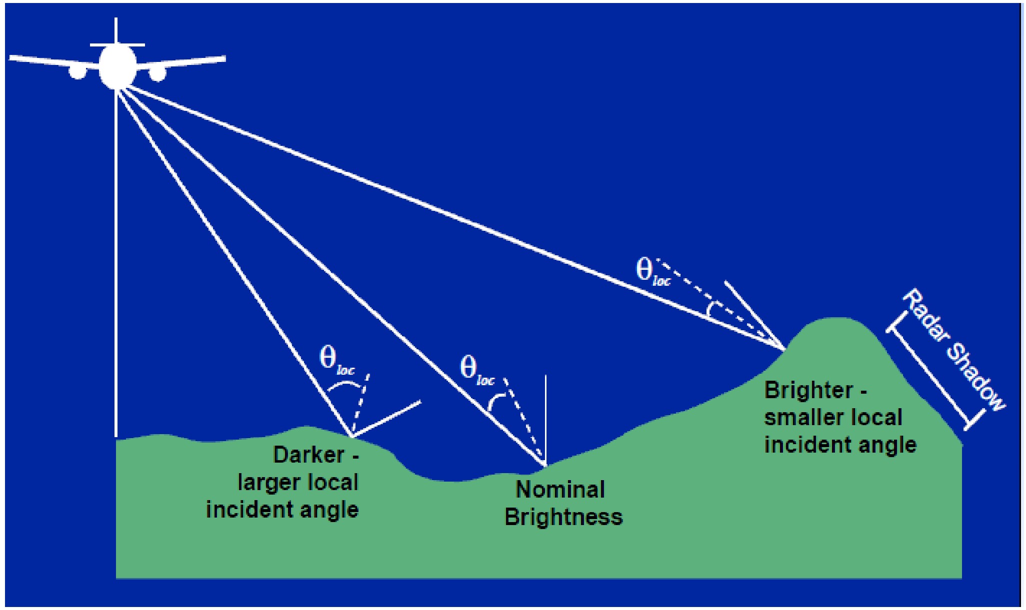


Image Credit: [Natural Resources Canada]

SAR Image Characteristics

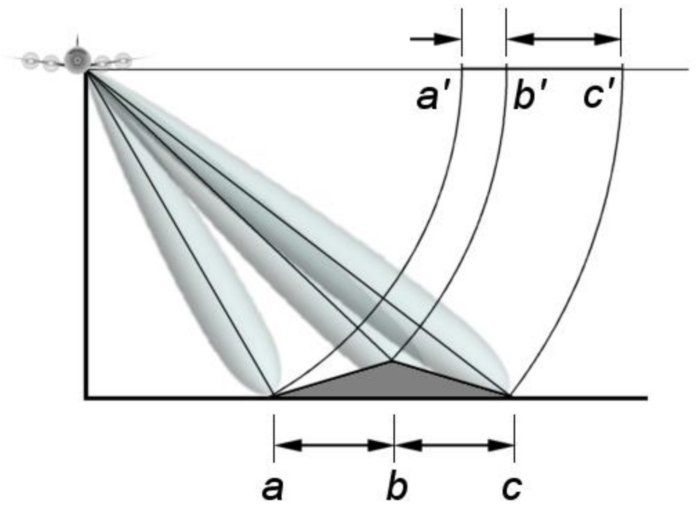
- geometric distortion
  - relief displacement
    - Local topographic slope can have a significant effect on image brightness
    - Local topographic slope causes changes in local incident angles
    - A small local incident angle results in brighter radar returns



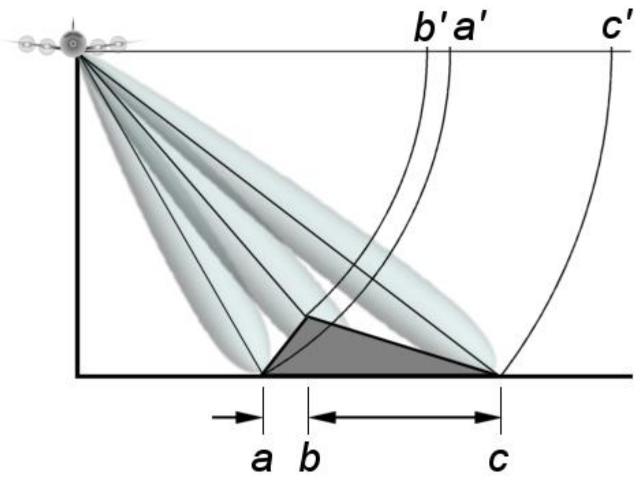
SAR Image Characteristics

- geometric distortion
  - relief displacement

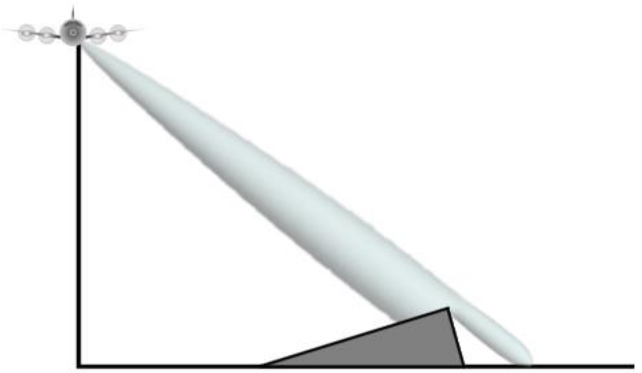
foreshortening



layover



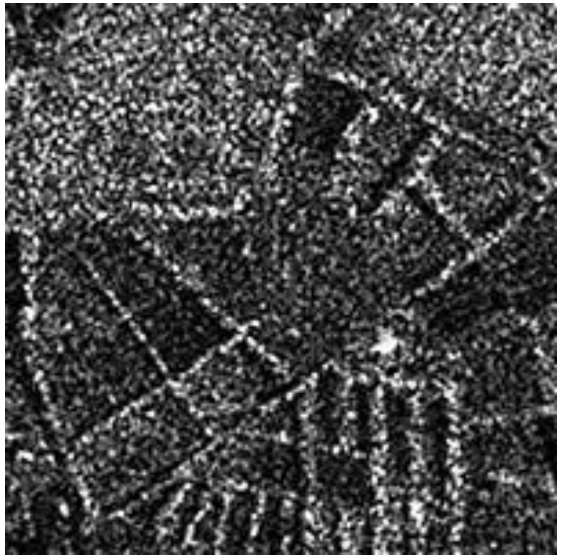
shadowing



Credit: radartutorial.eu

SAR Image Characteristics

- Speckle
  - The presence of several scatterers within each SAR resolution cell generates the so-called ‘speckle’ effect that is common to all coherent imaging systems
  - This speckle effect is a direct consequence of the superposition of the signals reflected by many small elementary scatterers (those with a dimension comparable to the radar wavelength) within the resolution cell



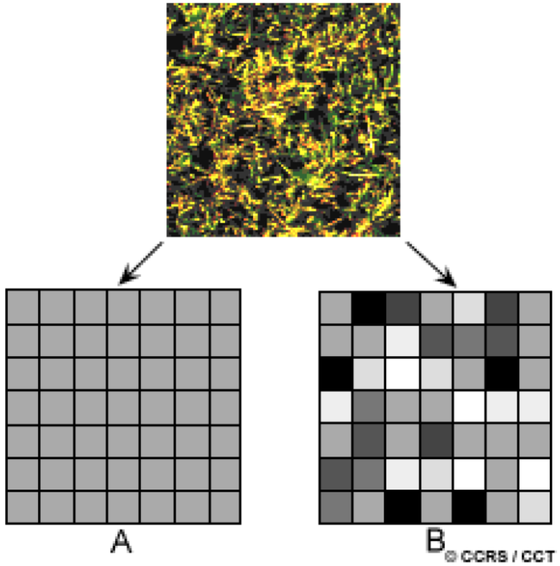


Image Credit: Natural Resources Canada

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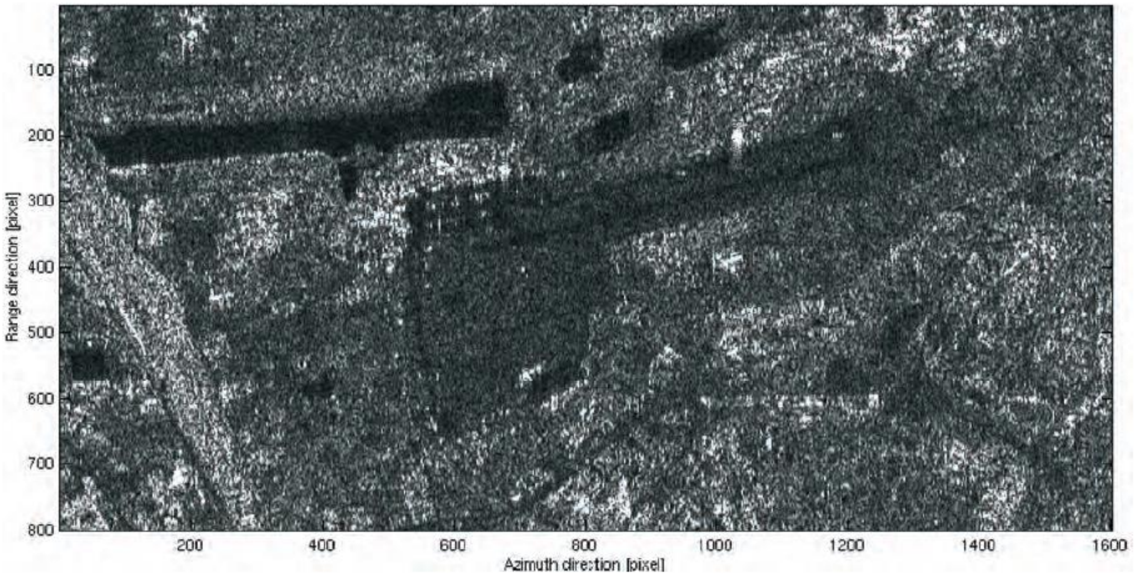


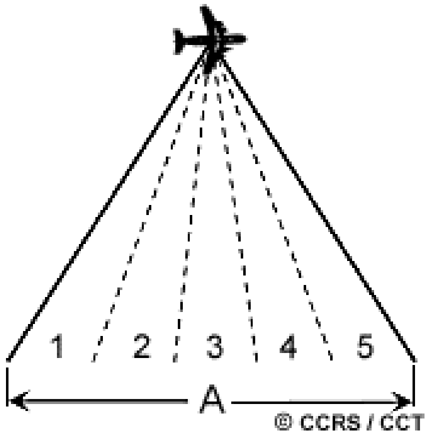
ERS2 SAR image, Linate airport In the western part of Milan (Italy)

Optical image of Linate airport taken from SPOT satellite

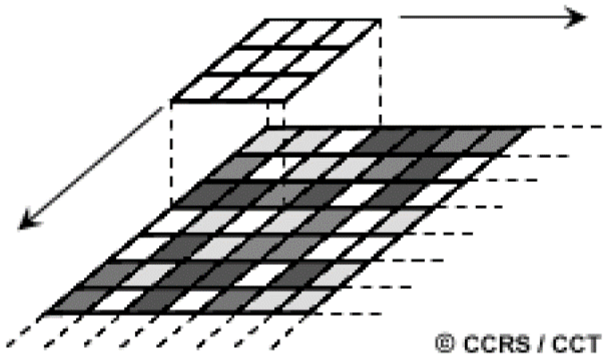
Image Credit: Ferretti, Alessandro et al. “InSAR Principles-Guidelines for SAR Interferometry Processing and Interpretation.” (2007).

SAR Image Characteristics

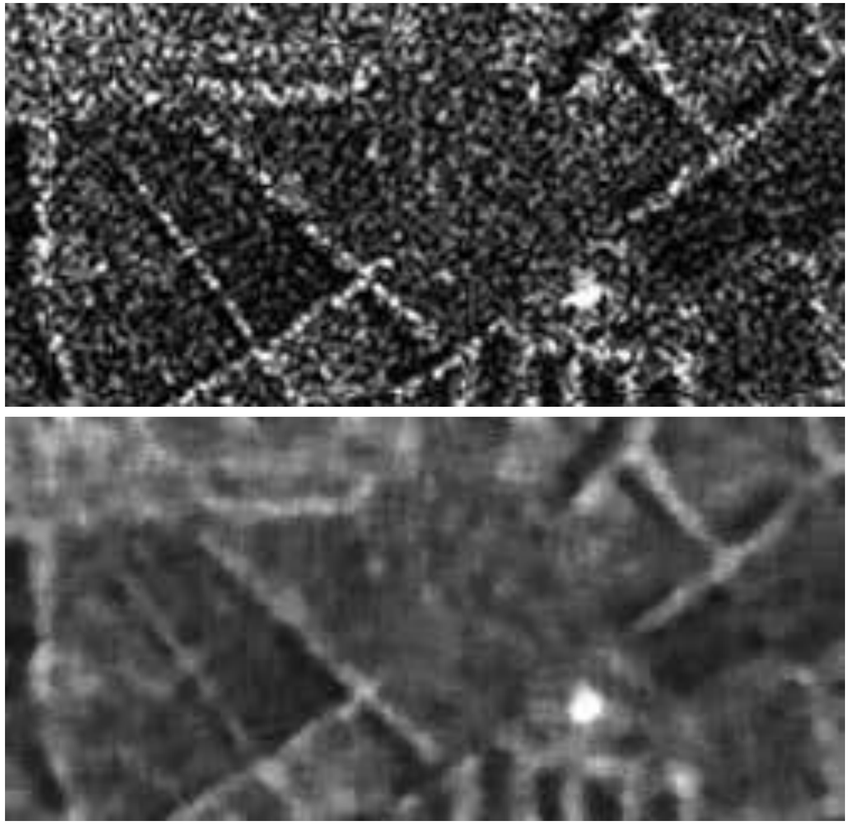
- Speckle reduction
  - multi-looking
  - low-pass filtering



multi-looking



spatial filtering



This graphic shows a radar image before (top) and after (bottom) speckle reduction using an averaging filter.

Credit: [Natural Resources Canada]

Radar Backscatter

- frequency or wavelength: radar parameter
  - Here is an example of a forested scene: X-band (~3 cm) is usually scattered off the top-of-canopy, the C-band (~5 cm) return will be from the twigs and small branches while L-band (~23 cm) may give a return from the larger branches, truck or even the ground P-band will penetrate most vegetation to yield a ground return

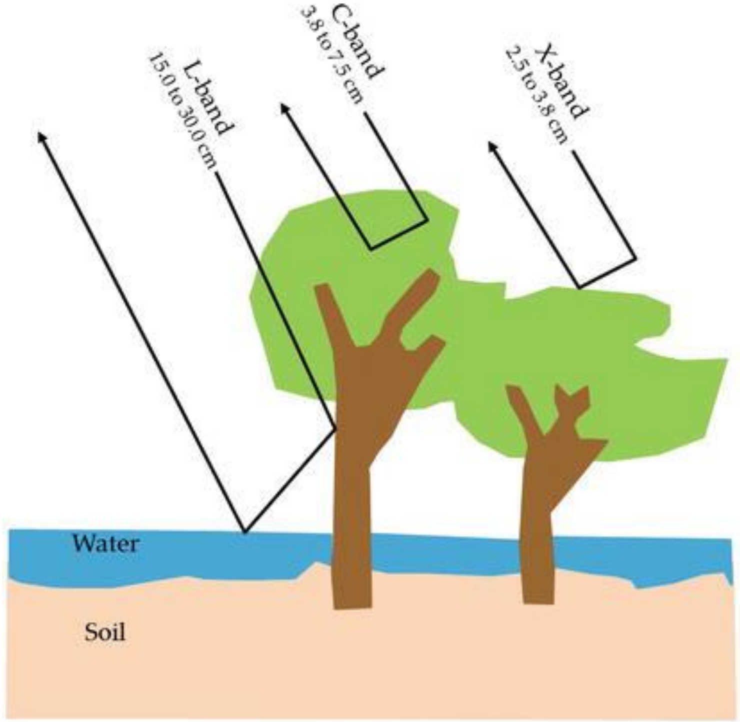


Image Credit: Dabboor, M. and Brisco, B., 2018. Wetland Monitoring and Mapping Using Synthetic Aperture Radar. In Wetlands Management-Assessing Risk and Sustainable Solutions. IntechOpen.

Radar Backscatter

- polarization : radar parameter
  - For any frequency, the transmitted signal can have one of these electric-field vectors
    - horizontal (H)
    - vertical (V)
  - Possible modes
    - HH
    - VV
    - VH
    - HV
    - Quad-Pol

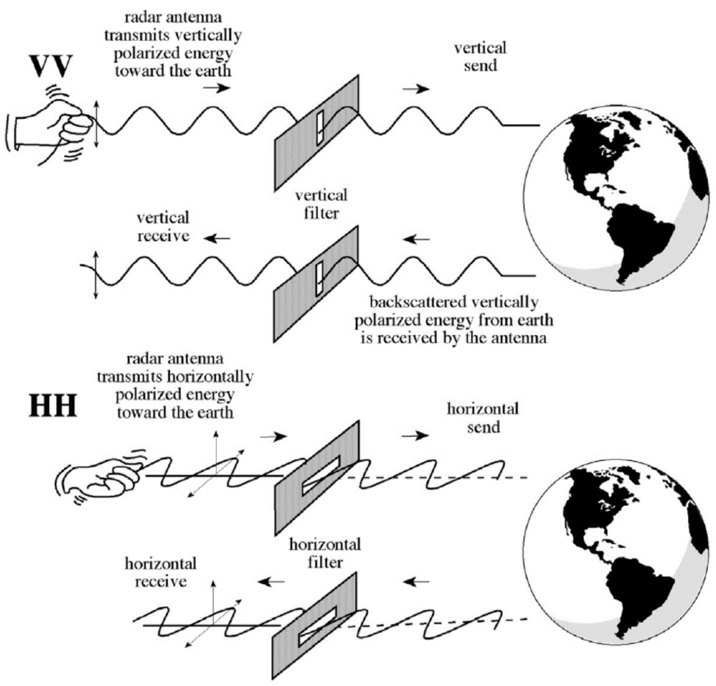


Image Credit: J.R. Jensen, 2000. Remote Sensing of the Environment

Radar Backscatter

- polarization : radar parameter

  - Polarization will determine, along with frequency, the nature of the radar wave-target interaction. Very generally
    - vertical polarization is preferable for oceanographic studies
    - horizontal polarization is preferable for land study

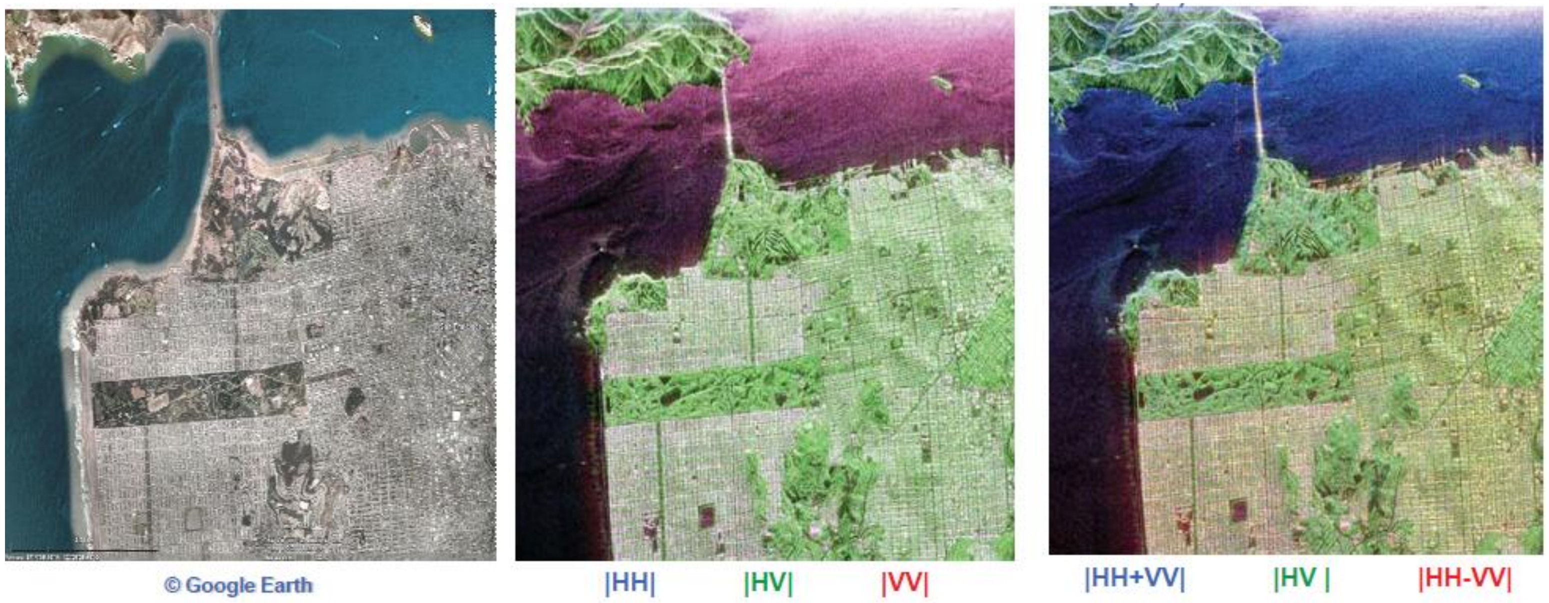


Image Credit: Eric Pottier (ESA), Polarimetry Basics, Advanced Training Course on Land Remote Sensing

Radar Backscatter

- incidence angle : radar parameter
  - Microwave interactions with the surface are complex, and different scattering mechanisms may occur in different angular regions
  - Returns due to surface scattering are normally strong at low incidence angles and decrease with increasing incidence angle, with a slower rate of decrease for rougher surfaces

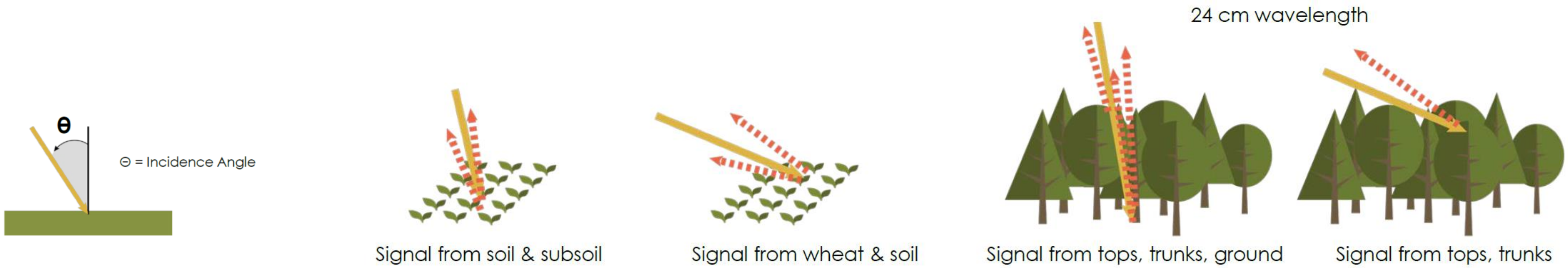
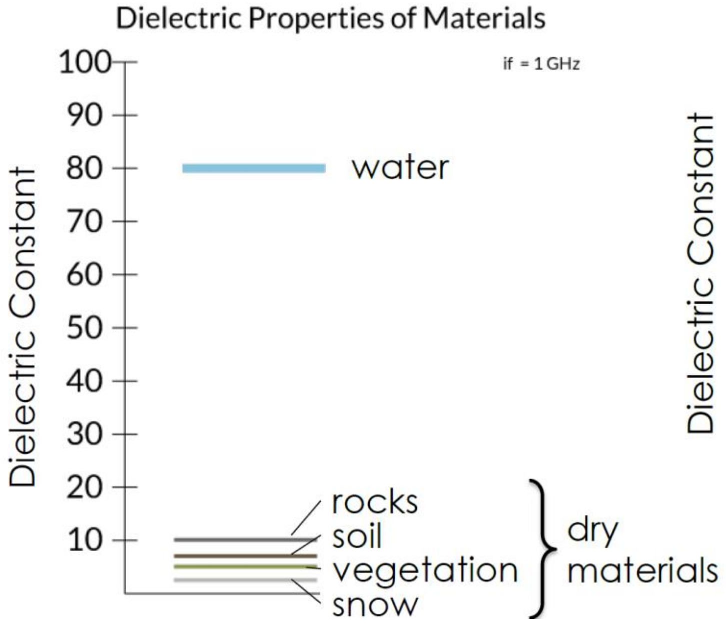


Image Credit: Erika Podest (NASA), Basics of Synthetic Aperture Radar (SAR)

Radar Backscatter

- dielectric content : surface parameter
  - Wetter objects appear bright, and drier targets appear dark (The exception to this is a smooth body of water, which will act as a flat surface and reflect incoming pulses away from the sensor. These bodies will appear dark)



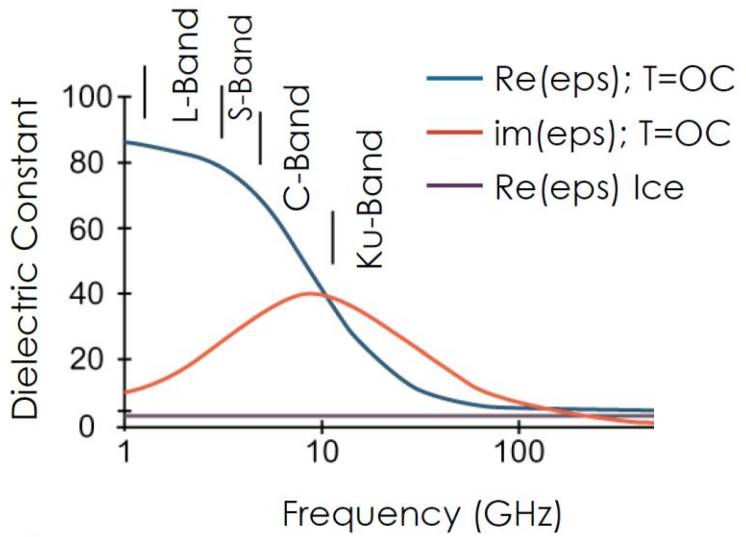
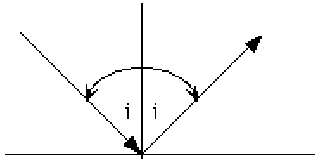
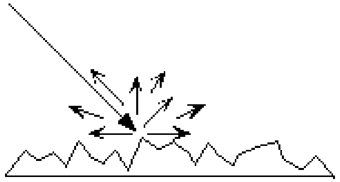


Image Credit: Erika Podest (NASA), Basics of Synthetic Aperture Radar (SAR)

Backscattering Mechanisms

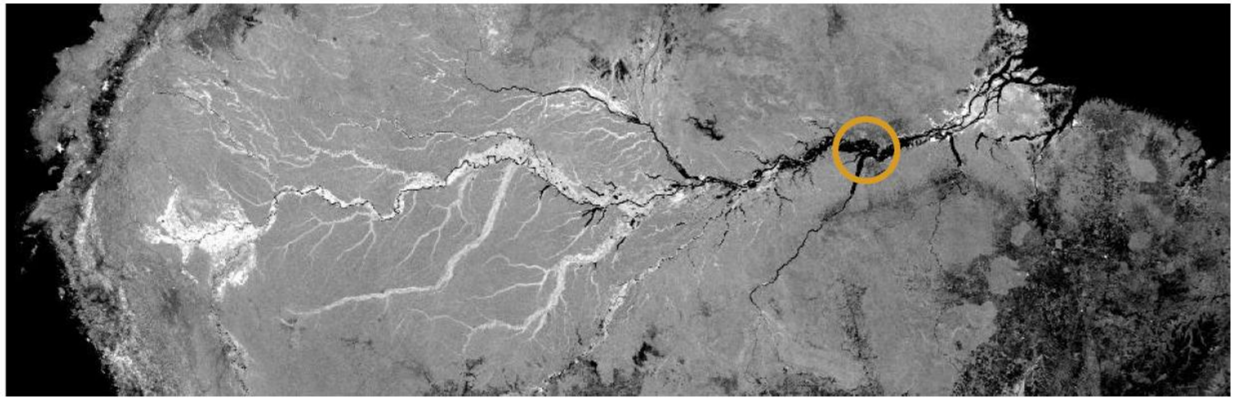


Reflection off a smooth surface
The angle of incidence, i, equals the angle of reflection.



Scattering off a rough surface
The variation in surface height is on the order of the incoming signal's wavelength.

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



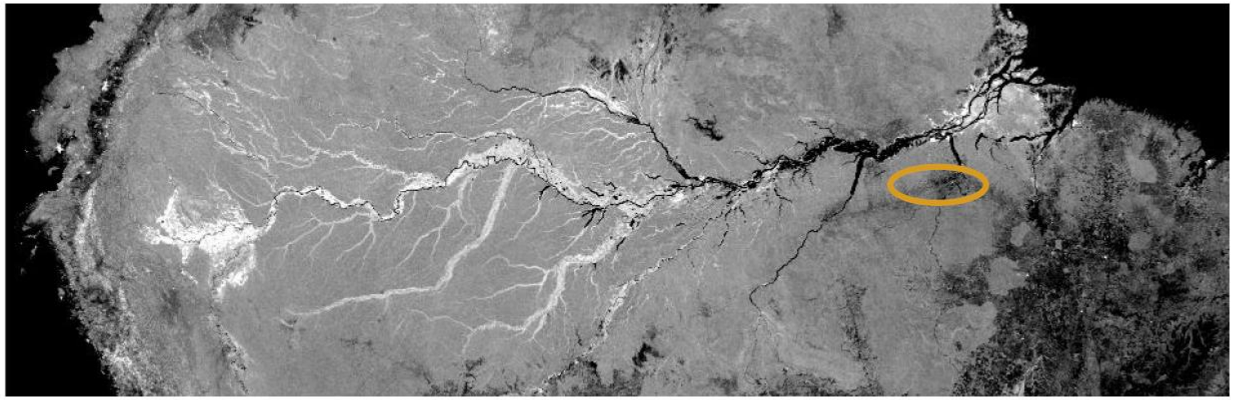
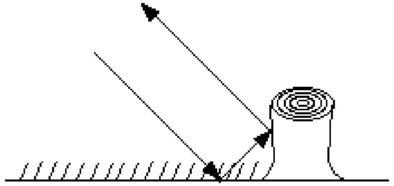
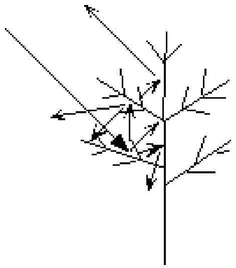


Image Credits: (left) [ESA] and (right) Erika Podest (NASA), Basics of Synthetic Aperture Radar (SAR)

Backscattering Mechanisms

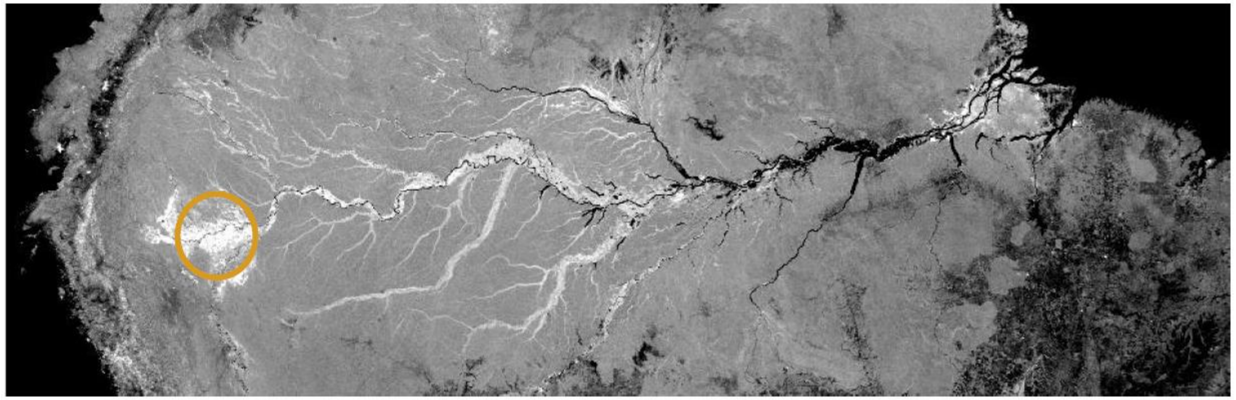


Double Bounce
One possible natural occurence – reflecting off two smooth surfaces, grass and a freshly-cut tree's stump



Volumetric Scattering
Example scattering in a tree

SMAP Radar Mosaic of the Amazon Basin
April 2015 (L-band, HH, 3 km)



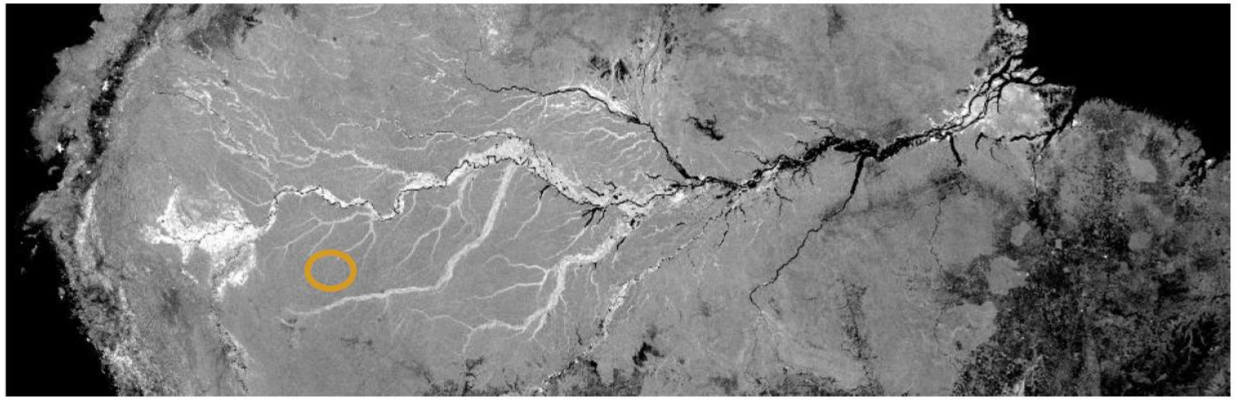
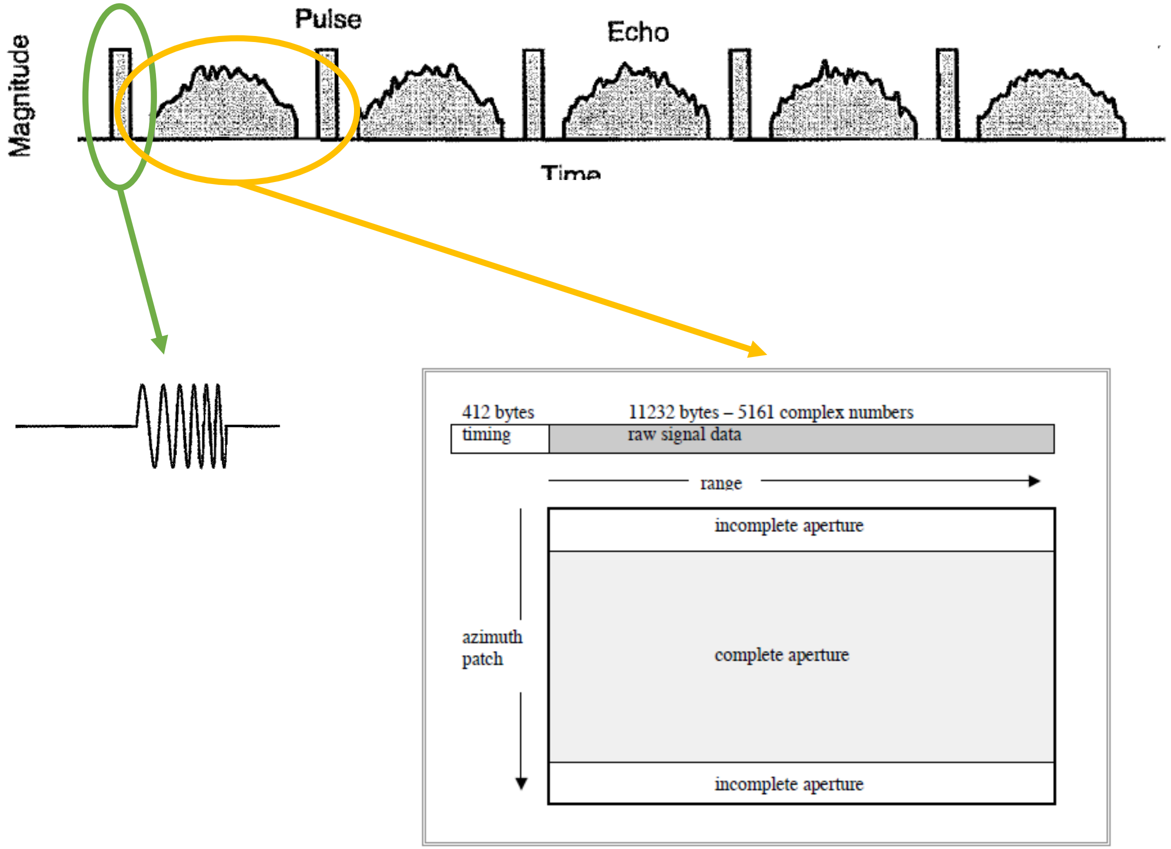
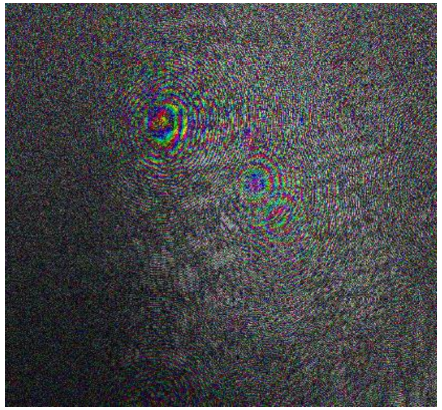


Image Credits: (left) [ESA]() and (right) Erika Podest (NASA), Basics of Synthetic Aperture Radar (SAR)

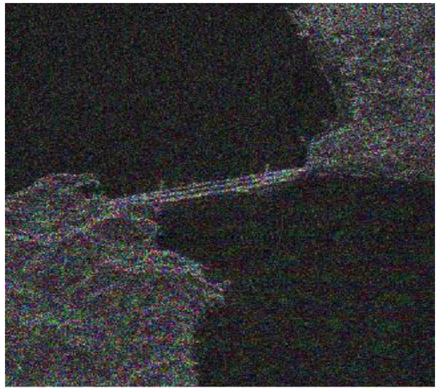
SAR Image Formation

- SAR data





SAR image formation



RADARSAT-1 fine beam data set from the San Francisco

Image Credits: (left) Schlutz, M., 2009. Synthetic aperture radar imaging simulated in MATLAB and (right) Rudi Gens

SAR Image Formation

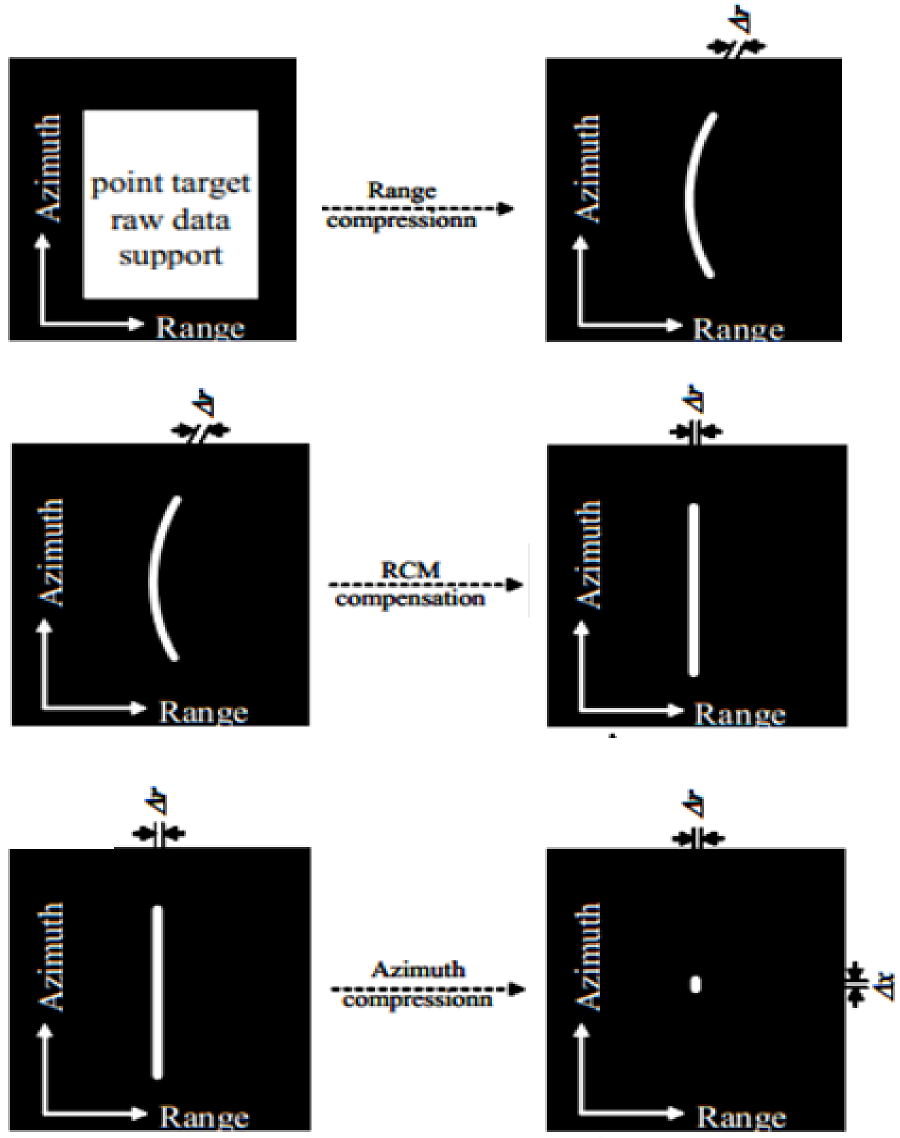
- The digital SAR processing is the procedure that converts the raw signal data into a single look complex (SLC) image
- There are several SAR processing algorithms available, and each has its advantages and disadvantages. Some of these algorithms are
  - Range Doppler Algorithm
  - Chirp Scaling Algorithm
  - Omega-K Algoritm
  - SPECAN Algorithm

SAR Image Formation

- Range Doppler Algorithm (RDA)

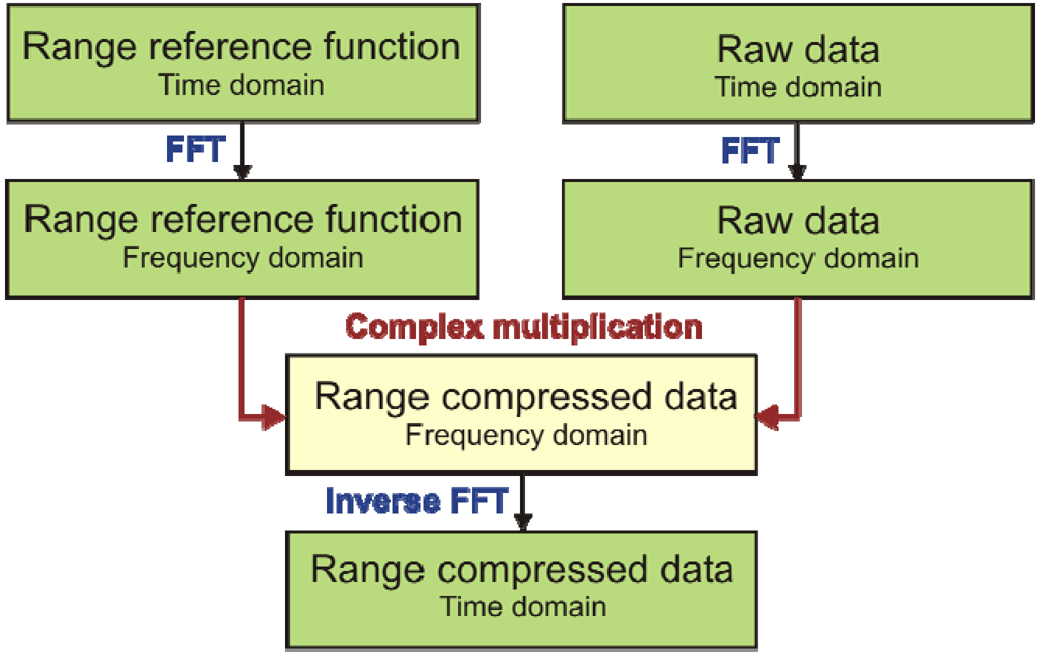
  In Range Doppler Algorithm the unfocused raw SAR data is compressed in range and azimuth direction making effective use of fast Fourier transforms (FFTs)

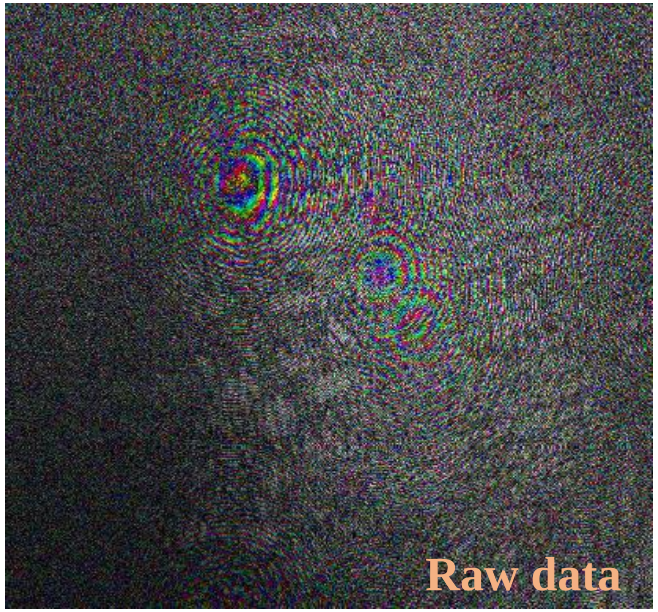
- RDA follows three main steps
  - Range Compression
  - Range Cell Migration Correction
  - Azimuth Compression

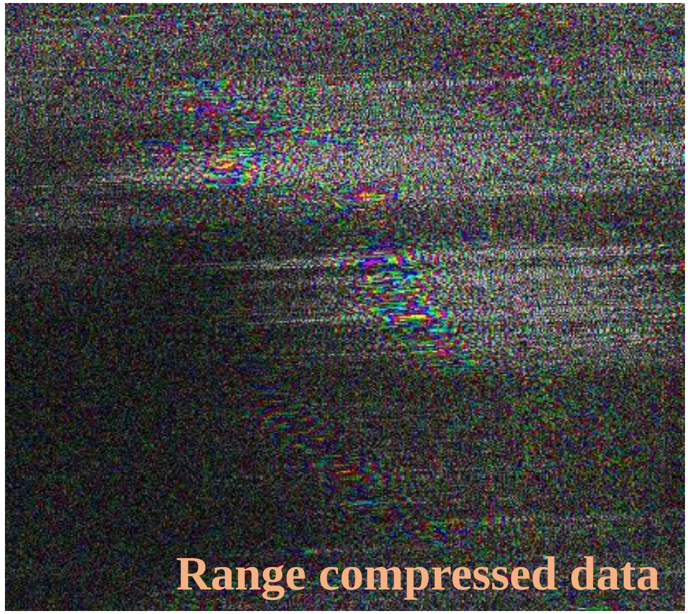


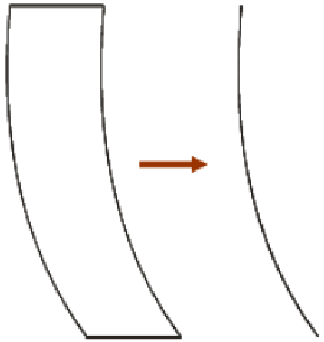
SAR Image Formation

- Range Doppler Algorithm (RDA)
  - range compression







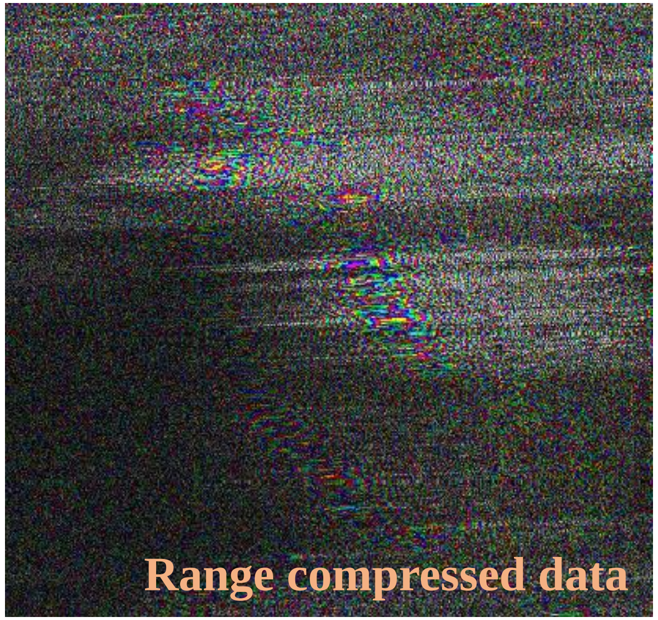


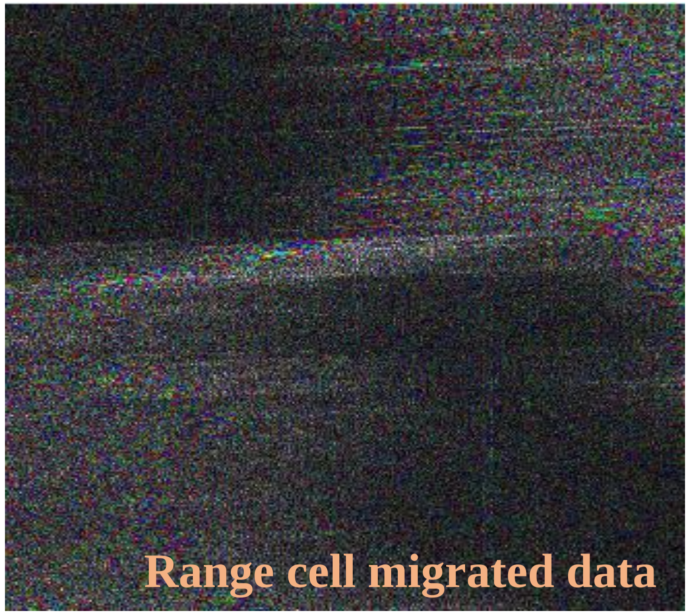
RADARSAT-1 fine beam data set from the San Francisco

Credit: Rudi Gens

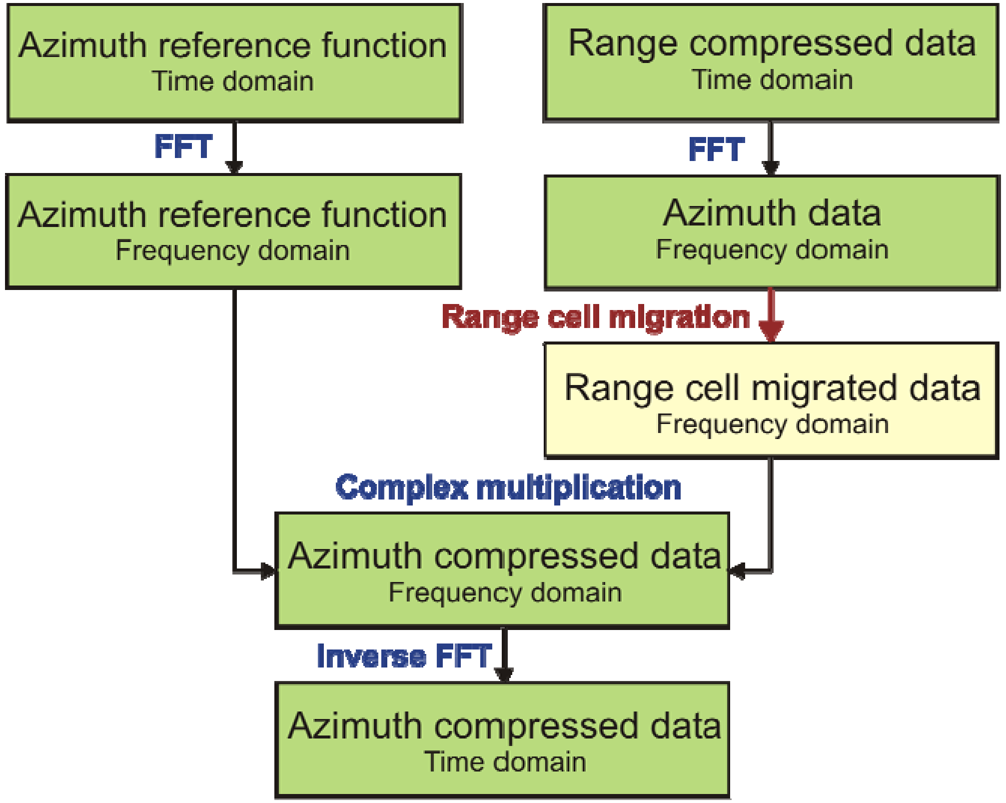
SAR Image Formation

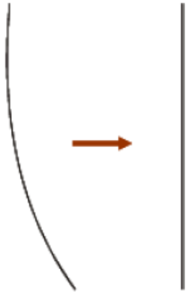
- Range Doppler Algorithm (RDA)
  - range cell migration correction





RADARSAT-1 fine beam data set from the San Francisco

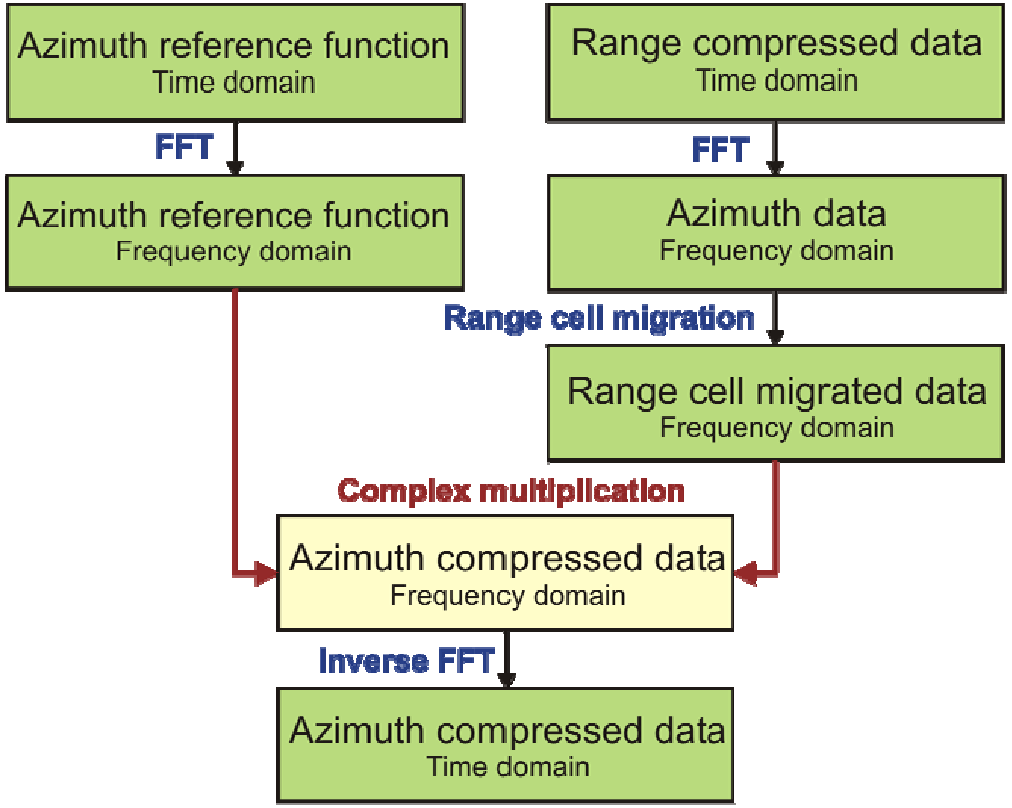


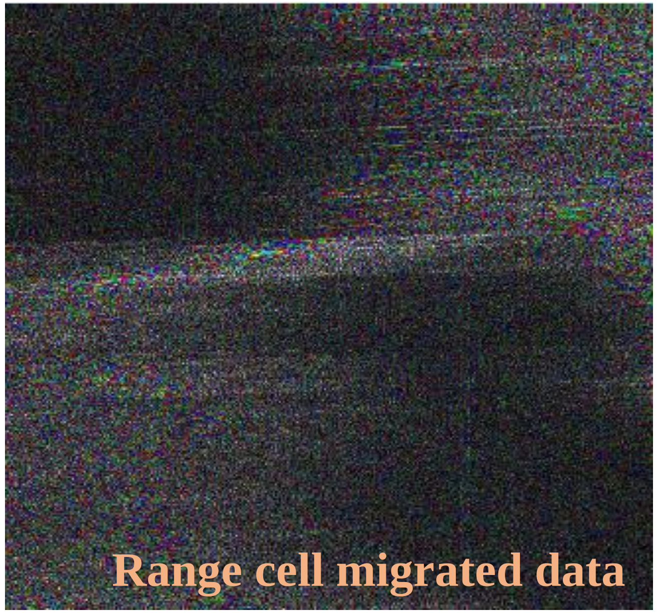


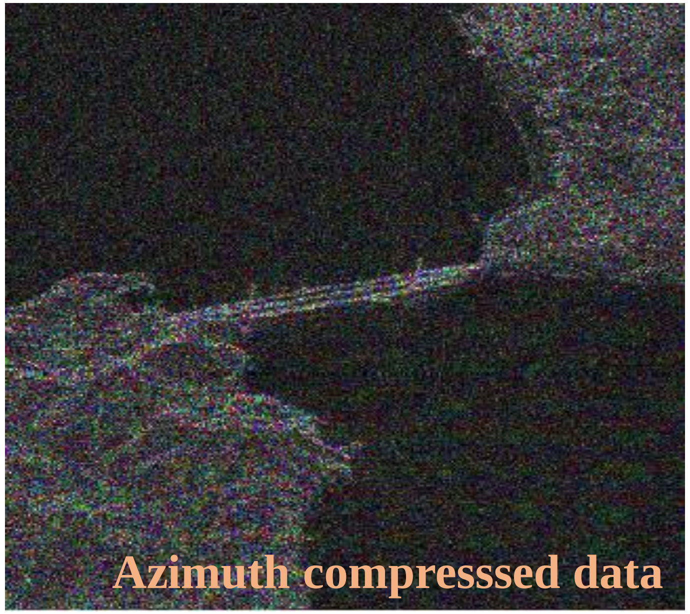
Credit: Rudi Gens

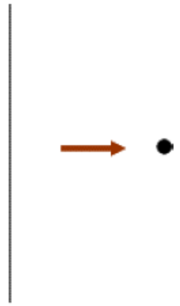
SAR Image Formation

- Range Doppler Algorithm (RDA)
  - azimuth compression









RADARSAT-1 fine beam data set from the San Francisco

Credit: Rudi Gens

Any Questions?