Radar Systems Engineering Lecture 18 Synthetic Aperture Radar (SAR)

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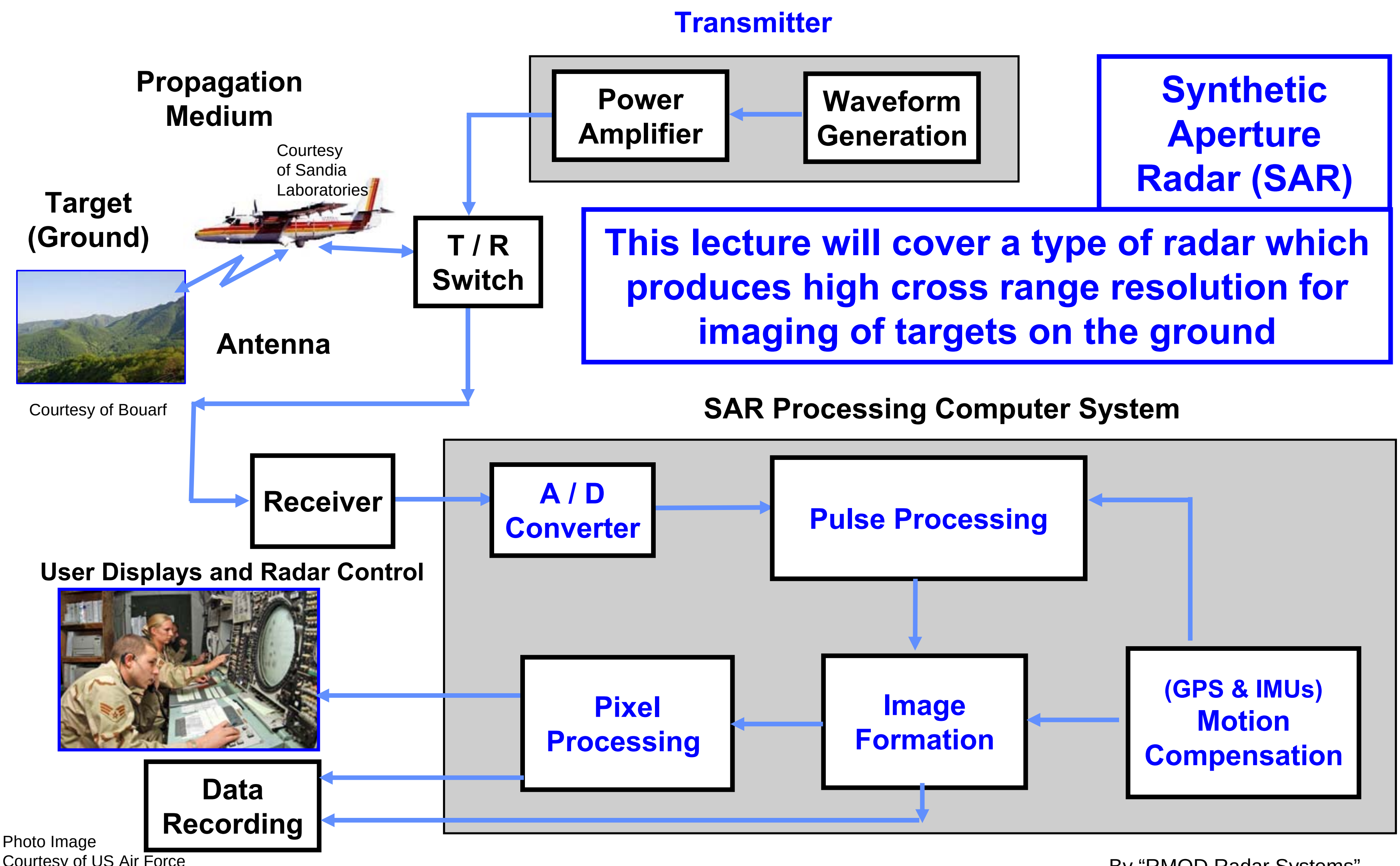
IEEE New Hampshire Section
Guest Lecturer

Block Diagram of Radar System

Synthetic Aperture Radar (SAR)

This lecture will cover a type of radar which produces high cross range resolution for imaging of targets on the ground



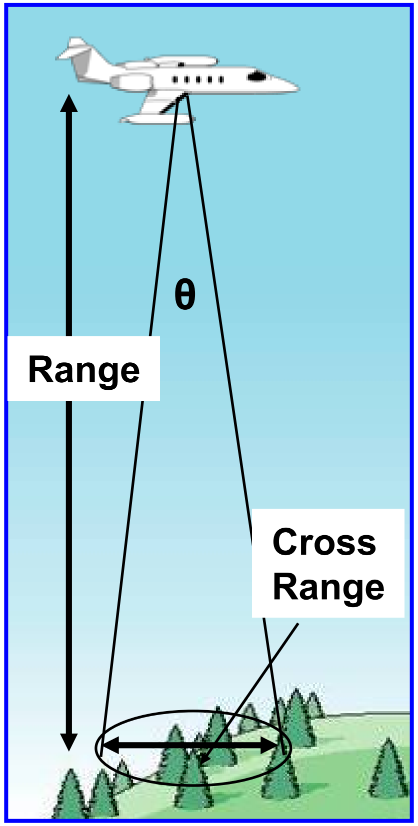
By "RMOD Radar Systems"

Outline

- Introduction
  – Why SAR
  – Airborne viewing
  – History (2 -3 VGS) 1 st image
  – Make graph of evolution
  – Lead into synthetic aperture via phased arrays
- SAR Basics
- Image Formation
- Advanced Image Formation Techniques
- SAR Examples
- Remote Sensing Applications
- Summary

By "RMOD Radar Systems"

Why Synthetic Aperture Radar (SAR)?



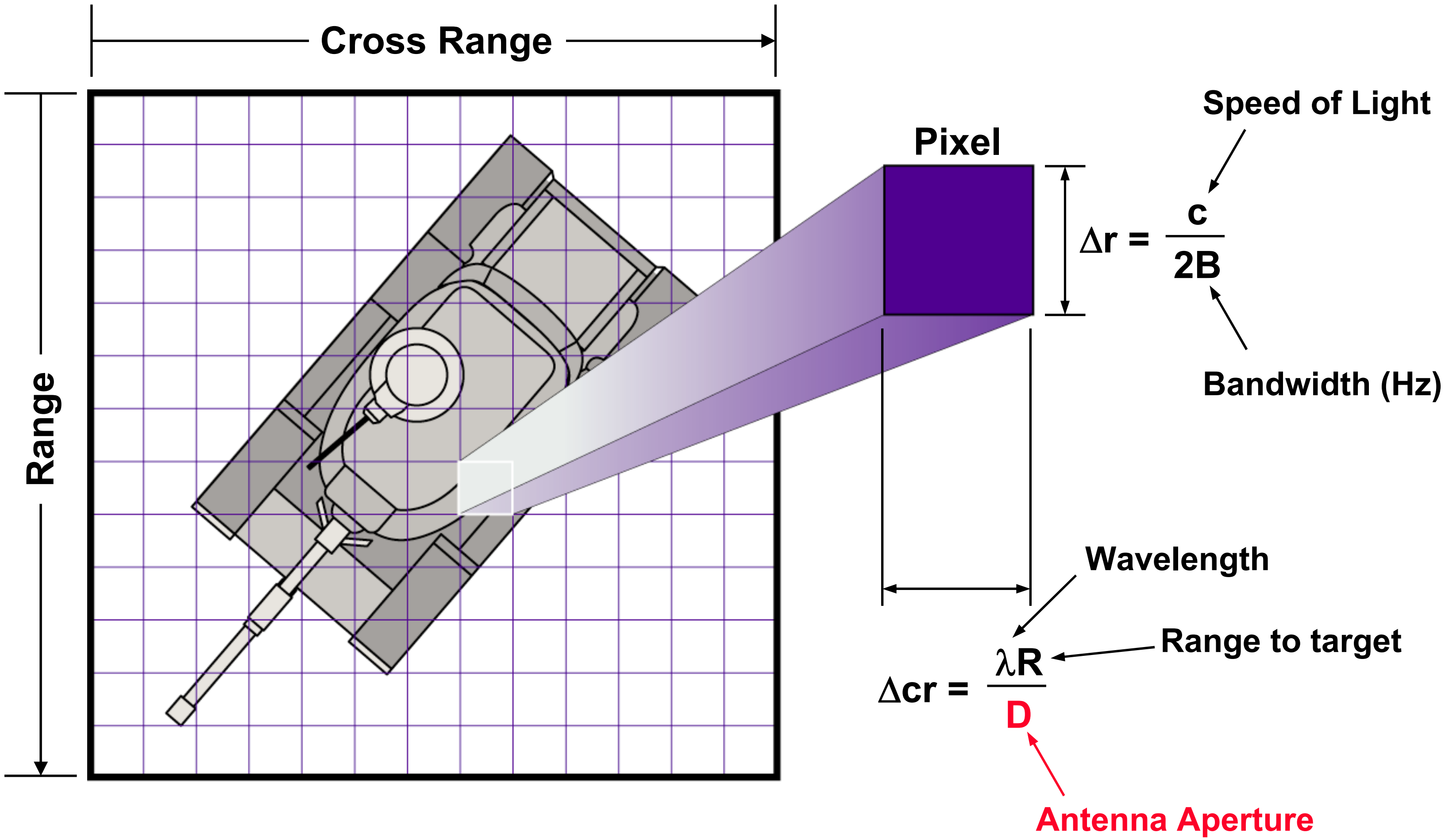
- Radar provides excellent range information
  - Can resolve in range down to inches
  - Not weather/cloud limited as visible and infrared sensors
- Good image resolution requires commensurate cross-range resolution
- Problem: The radar beam is far too wide and not matched to range resolution for good imaging of targets

Radar Parameters

Range = 100 km   Beamwidth = 0.2°   Bandwidth ≈ 500 MHz

Cross Range Resolution = R θ = 350m   Range Resolution = c/2 B ≈ 0.3 m

Radar Image



$$\Delta r = \frac{c}{2B}$$

$$\Delta cr = \frac{\lambda R}{D}$$

Imaging requires a large antenna

Courtesy of MIT Lincoln Laboratory
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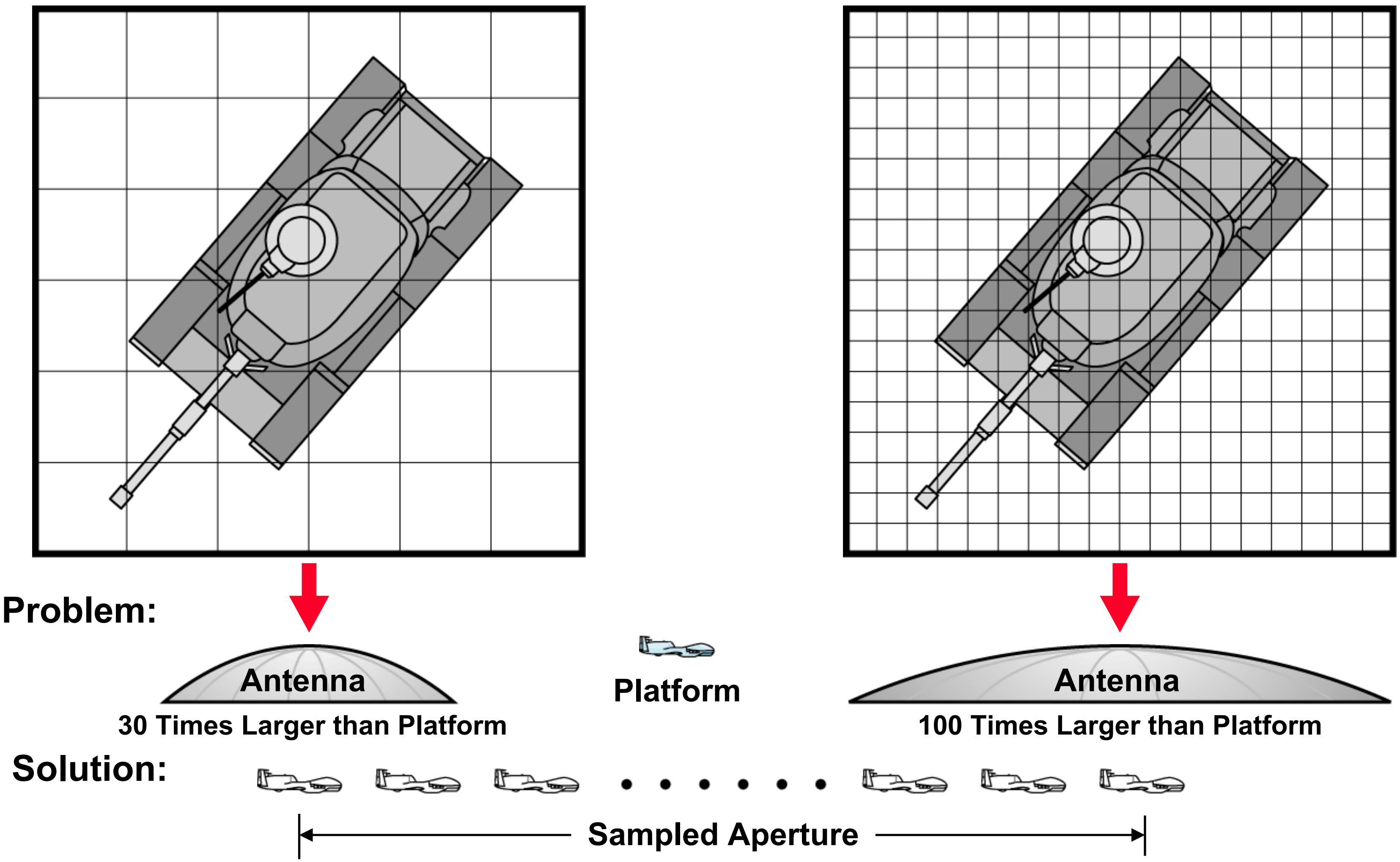
Synthetic Aperture Radar (SAR)



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Cross-Range Resolution with SAR

View SAR as a Phased Array Antenna

- **Passive Array Resolution**

$$\Delta cr = \frac{\lambda R}{D}$$

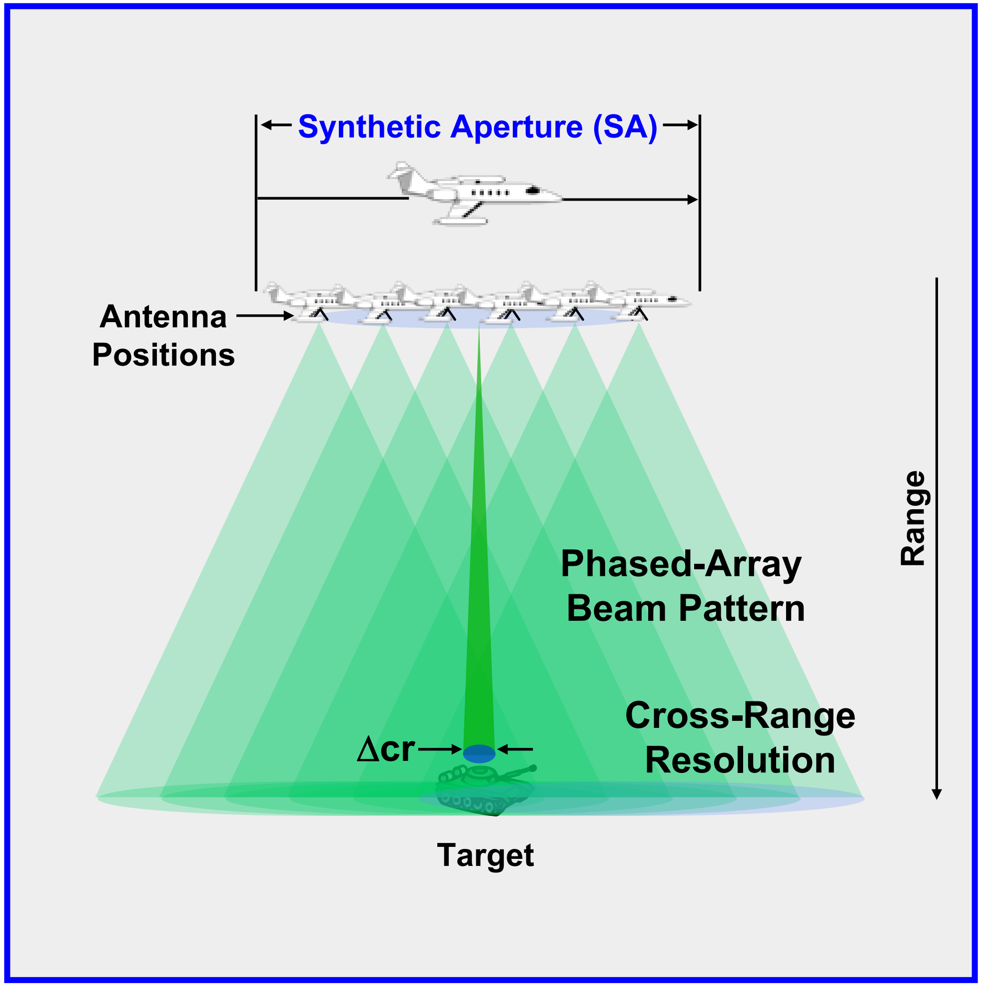
← Range (R)

Antenna Aperture (D)

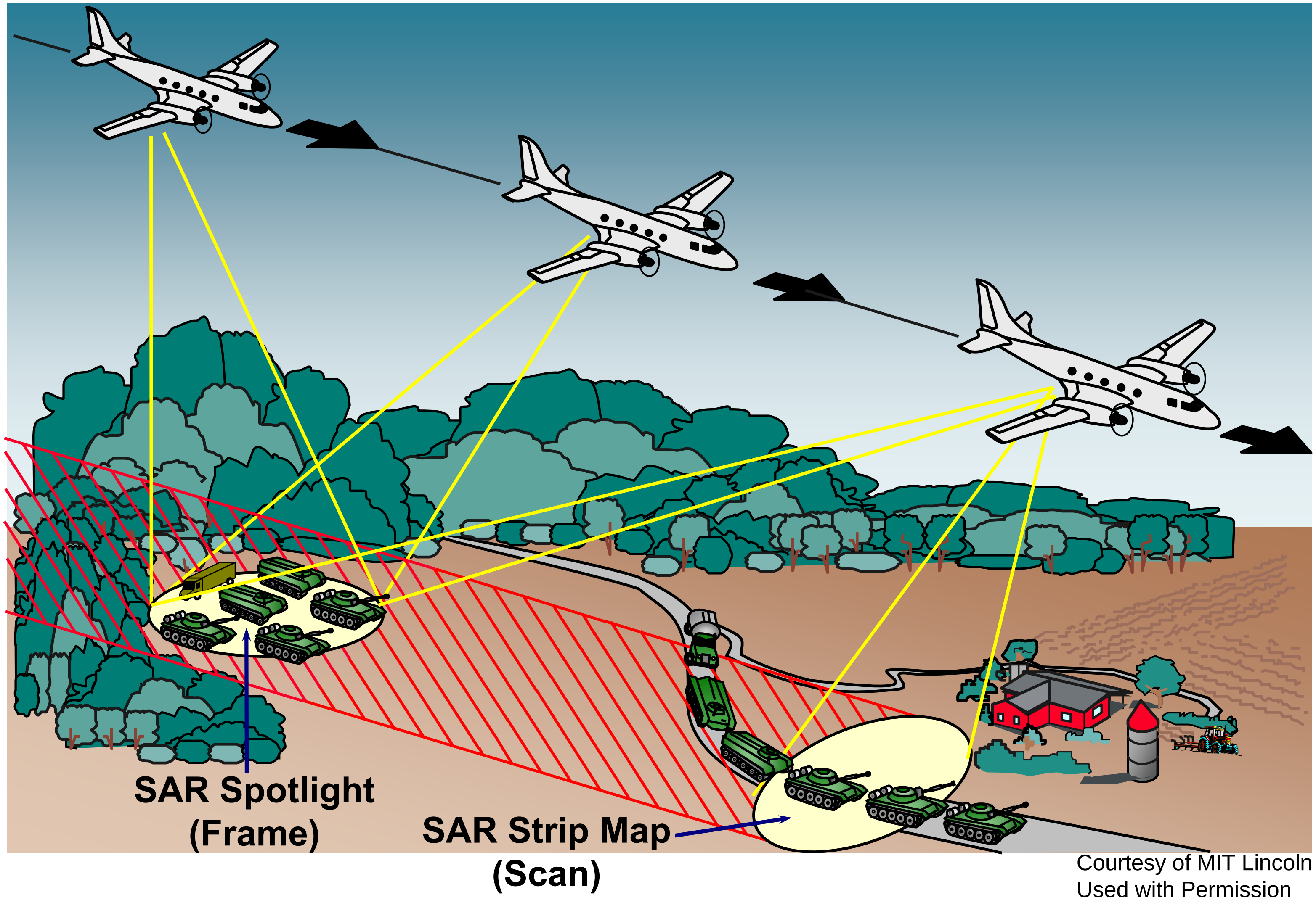
- **SAR Resolution**

$$\Delta cr = \frac{\lambda R}{2 \times SA}$$

Separated radar positions provide twice the phase shift



SAR Data Gathering Modes



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ADTS Radar

ADTS Advanced Detection Technology Sensor

- **Radar Features**
  - Synthetic and real aperture functions
  - Coherent and fully polarimetric
- **Radar parameters**
  - Frequency 32 GHz
  - Resolution 1 ft x 1 ft
  - Beamwidth 2 deg
  - Polarization Isolation 30 dB
  - Sensitivity (SAR Mode) S/N 10 dB for -30 dBm at 7 km

Courtesy of MIT Lincoln Laboratory
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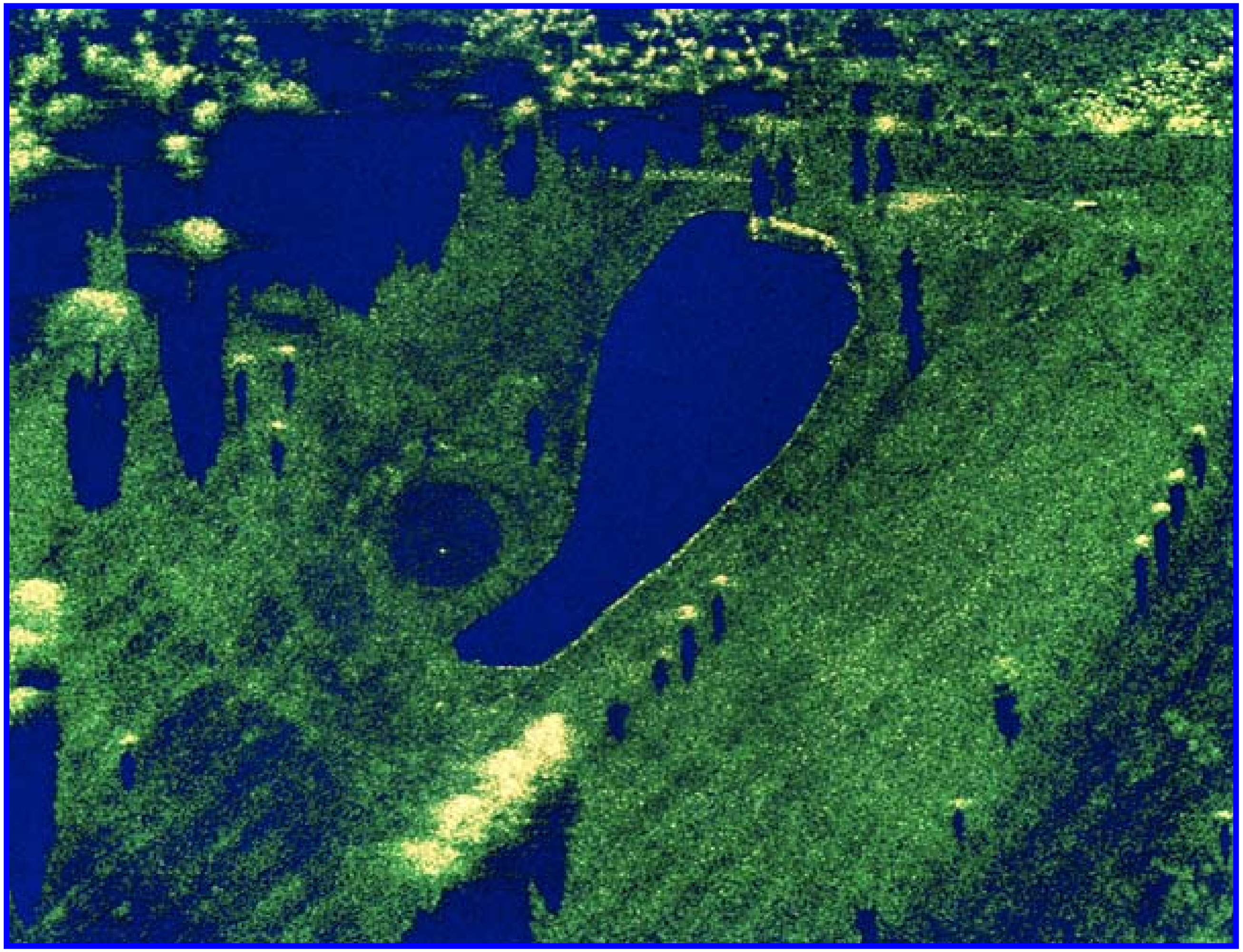
35 GHz SAR Image of Golf Course



- **Excellent resolution in both range and cross range dimensions**

Courtesy of MIT Lincoln Laboratory
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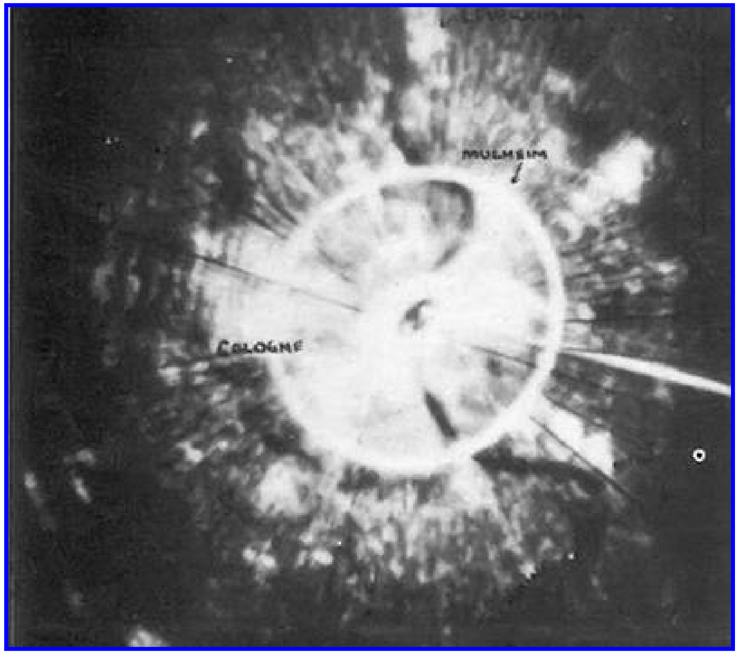
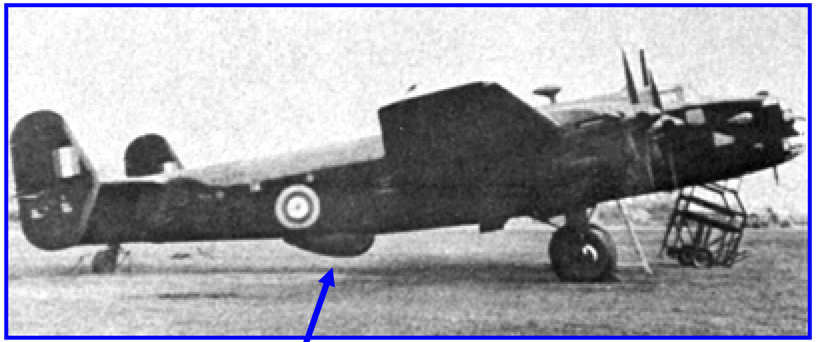
Radar Ground Mapping in World War II

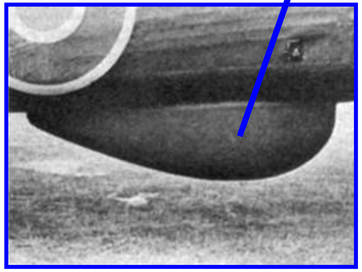
- During World War II, the British bombed Germany during the night time, while the US did the same during the daytime
- The H2S airborne, X-Band, ground mapping radar was the first to be developed and fielded, so the British could navigate at night and see where to bomb
  - Although its accuracy was poor, the particular cities and their characteristic shape, allowed these bombing missions to be as accurate as the technology of the day would allow

Radar Ground Map of Cologne, Germany, 1944. just after night bombing raid



British Lancaster Bomber (note H2S radome under belly)





H2S radome

H2S antenna (under radome)

Images Courtesy of United Kingdom Government

History of Synthetic Aperture Radar

The SAR concept was invented by Carl Wiley in 1951 while at Goodyear

1951

1950 1960 1970 1980

Willow Run Lab
Michigan

Early Demonstration
University of Illinois
1953

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

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1950 | 1960 | 1970 | 1980

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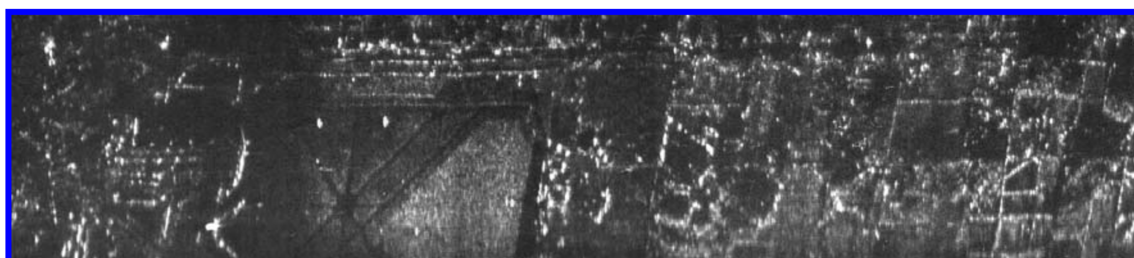
First successful focused airborne synthetic aperture radar image, Willow Run Airport and vicinity, August 1957.



Courtesy of University of Michigan

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

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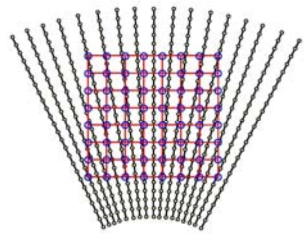

High Resolution (Polar Format) Processing 1978

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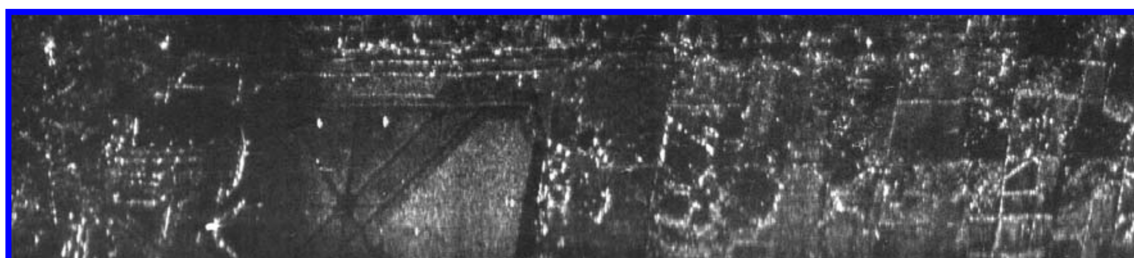

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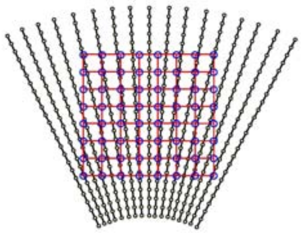

High Resolution (Polar Format) Processing

1978

1951

1950 — 1960 — 1970 — 1980

Early Demonstration
University of Illinois
1953

Willow Run Lab
Michigan

Seasat Image

Courtesy of NASA/JPL

Waves off Alaska's southern coastline near Yakutat

Seasat

Courtesy of NASA/JPL

SAR Antenna

1978

Seasat
1st Satellite with SAR Capability

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

History of Synthetic Aperture Radar

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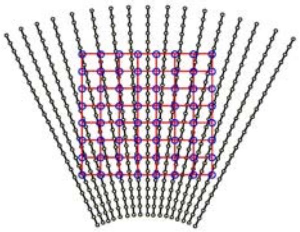

High Resolution (Polar Format) Processing

1978

Optical processing ← | → Digital processing

1979

1950 — 1960 — 1970 — 1980

Early Demonstration
University of Illinois
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Willow Run Lab
Michigan

Seasat Image

Courtesy of NASA/JPL

Sea Ice off Bank Is. Canada

Seasat

Courtesy of NASA/JPL

SAR Antenna

1978

Seasat
1st Satellite with SAR Capability

Optical Processing Using Coherent Holography based Laser Technology to Implement Fourier Transforms

History of Synthetic Aperture Radar

Optical processing ← | → **Digital processing**

1979

JSTARS

1988

Courtesy of USAir Force

1980 — **1990** — **2000**

Mid- 1980's

ASARS-2
Airborne
Military SAR

ASARS-2 on U-2

Courtesy of Jamesdale

History of Synthetic Aperture Radar

Optical processing ← | → Digital processing

1979

JSTARS

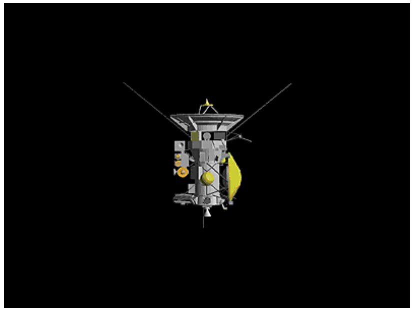
1988

Courtesy of USAir Force

Cassini Space Probe to Saturn

1997

Cassini Probe



Courtesy of NASA

1980 — 1990 — 2000

Mid- 1980's

ASARS-2 Airborne Military SAR

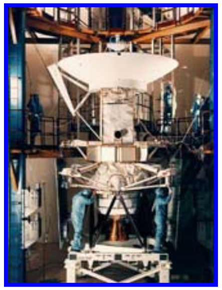
1989

Magellan Probe to Venus

ASARS-2 on U-2

Courtesy of Jamesdale

Magellan Probe



Courtesy of NASA

Magellan SAR Image of Venus (resolution `~ 100m)

Courtesy of NASA/JPL

History of Synthetic Aperture Radar

Optical processing ← | → Digital processing

1979

JSTARS 1988

Courtesy of US Air Force

F-35 Aircraft

Courtesy of US Air Force

F-35 APG-81 Radar

Courtesy of US Air Force

Has SAR Mode

1980 — 1990 — 2000

Mid- 1980's

ASARS-2 Airborne Military SAR

1989

Magellan Probe to Venus

Sandia SAR on Twin Otter

Courtesy of Sandia National Laboratories

ASARS-2 on U-2

Courtesy of Jamesdale

Magellan Probe

Courtesy of NASA

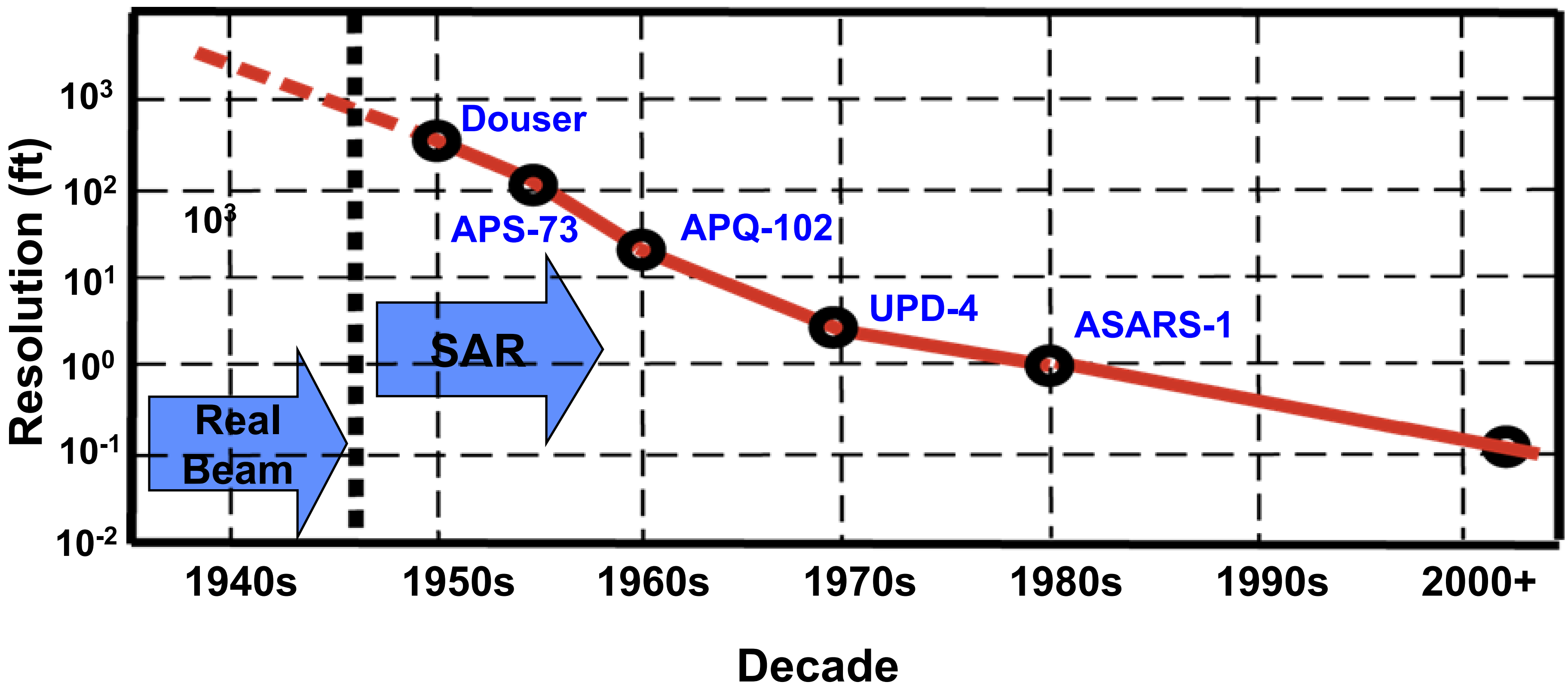
Pentagon

Capital Building

K_U Band 1 ft resolution

Images Courtesy of Sandia National Laboratories

Evolution of SAR Resolution



Courtesy of Lockheed Martin
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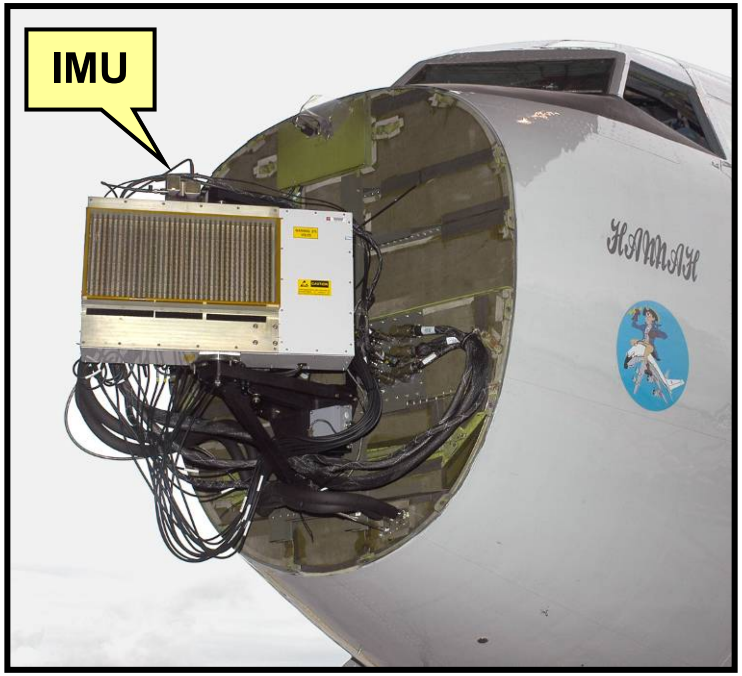
LiMIT* SAR Installation on 707

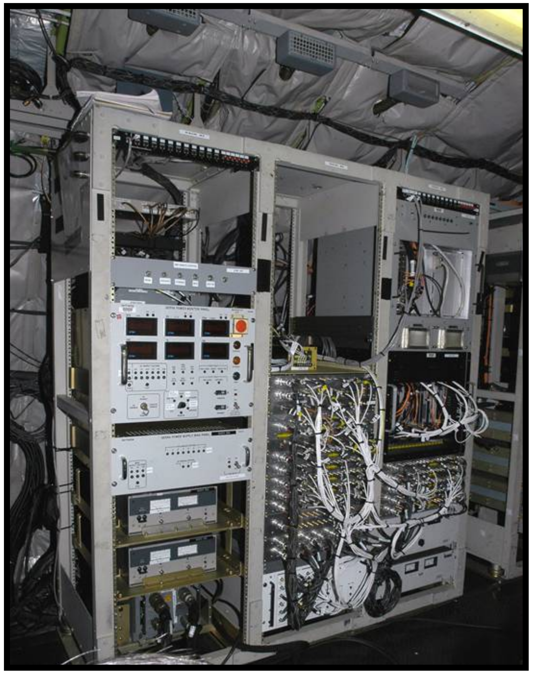
* Lincoln Multi-Mission ISR Testbed

Boeing 707 Aircraft

Active Electronically Scanned Array (AESA)



Receivers and A/D



3.5 TB RAID

Sierra Vista, AZ, 16 August 2005
30 cm Limit* SAR

500 m × 830 m

*** Lincoln Multi-Mission ISR Testbed**

Courtesy of MIT Lincoln Laboratory
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Missions and Platforms

- **Misssions**
  - **Military**
    - Intelligence, Surveillance, and Reconnaissance
    - Treaty verification
  - **Remote Sensing**
    - Earth surveillance - Icecap erosion
    - Planetary characterization - Magellan probe mapping Venus
    - Ocean currents monitoring
    - Many other roles
- **Platforms**
  - Aircraft
  - Satellites
  - Space probes

SAR Platforms – Airborne Systems

Global Hawk

Courtesy of US Air Force

LIMIT- Lincoln Multi-Mission ISR Testbed

Courtesy of MIT Lincoln Laboratory
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F-35 APG-81 Radar

Courtesy of Northrop Grumman

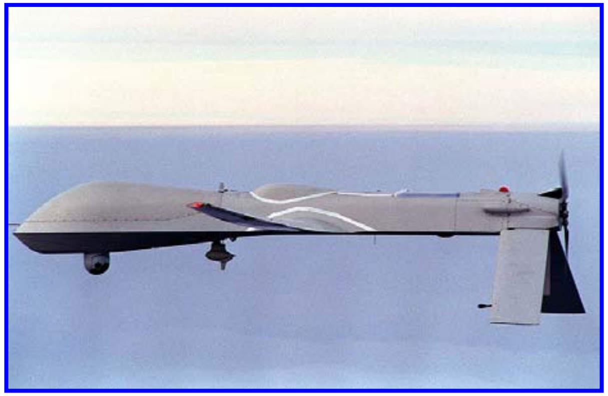
F-35 Aircraft

Courtesy of US Air Force

JSTARS

Courtesy of US Air Force

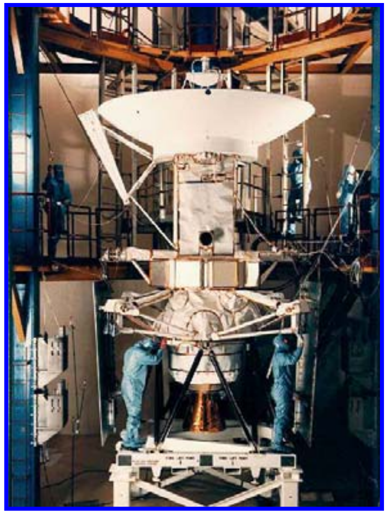
Predator



Courtesy of Department of Defense

SAR Platforms – Satellites / Space Probes

Magellan Mission to Venus



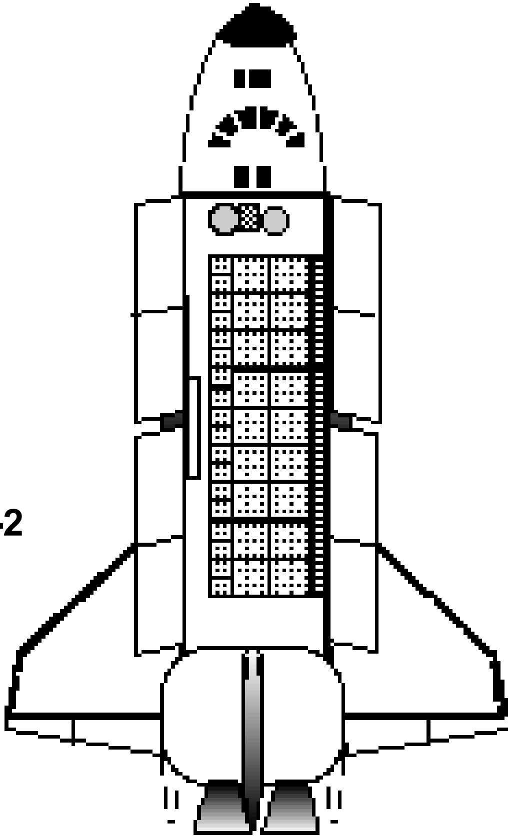
Courtesy of NASA

German SAR Lupe

Courtesy of Marshall 80

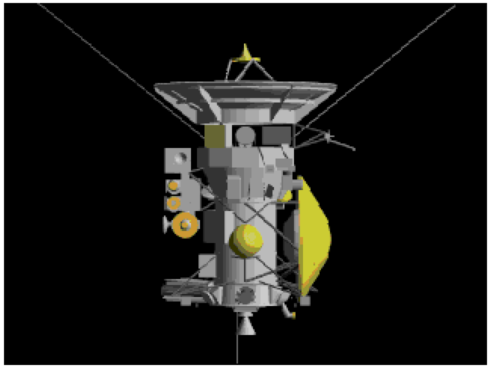
Courtesy of Sandia Laboratory

Shuttle Imaging Radar (C/X) SAR



Courtesy of NASA

Cassini Probe to Saturn and Jupiter



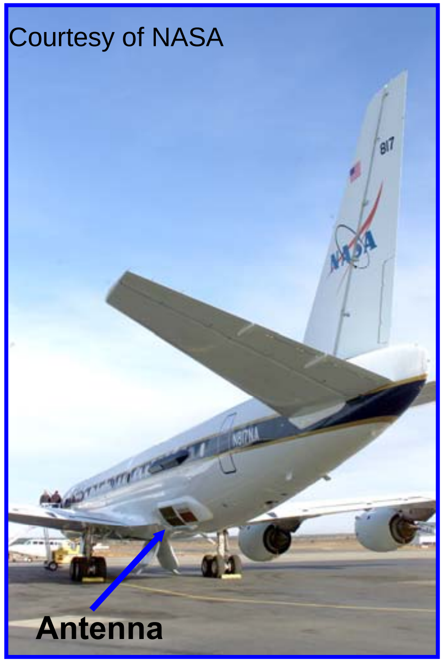
Courtesy of NASA

European Remote Sensing Satellite-2

Courtesy of poppy

SAR Airborne Platforms for Remote Sensing

NASA AirSAR on DC-8



Sandia SAR on Twin Otter

Courtesy of Sandia Laboratories

Sandia AMPS SAR on P-3 Aircraft

Courtesy of Sandia Laboratories

ERIM SAR DHC-4Aircraft

Courtesy of US Air Force

Outline

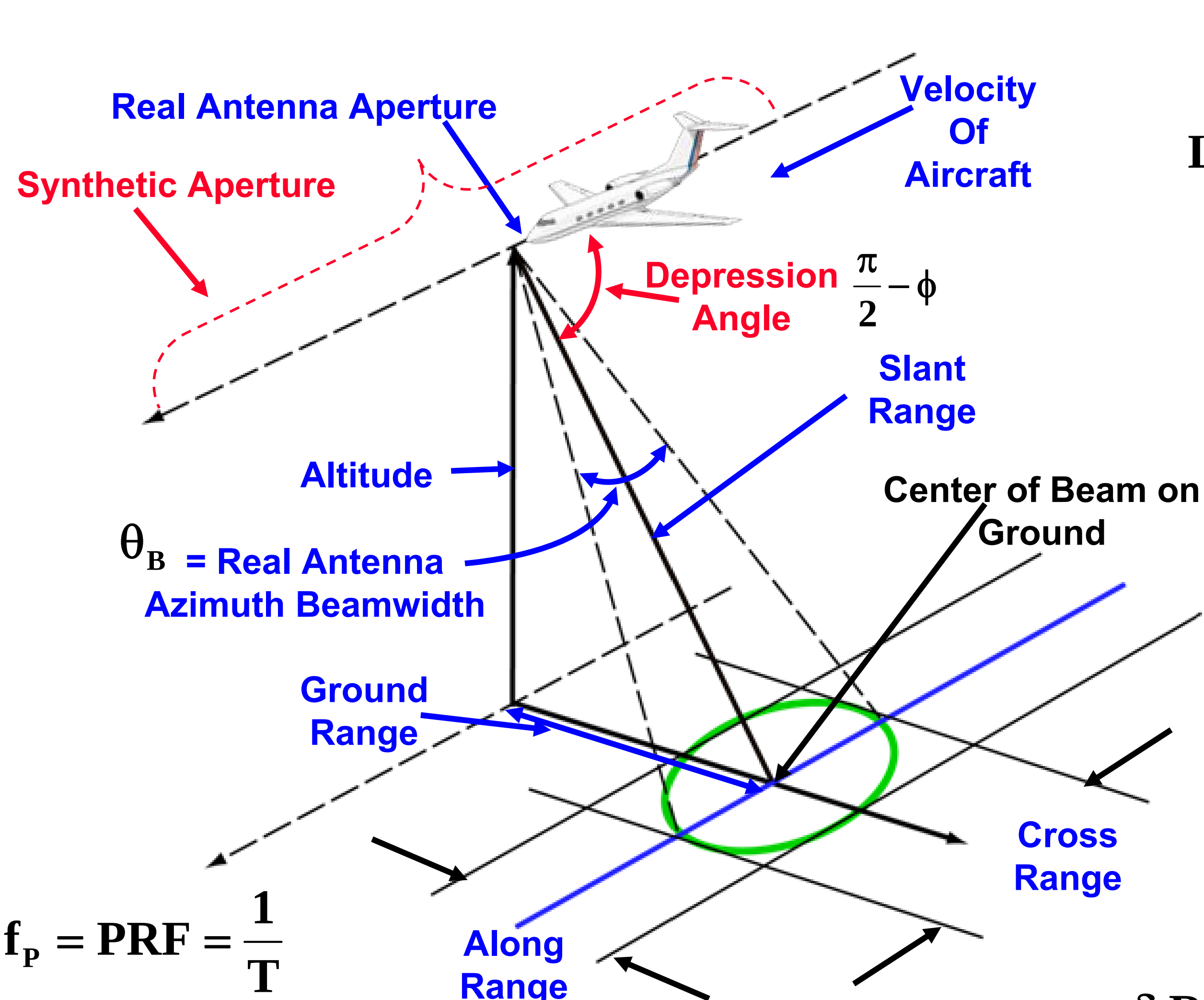
- Introduction

- SAR Basics
  - Airborne geometry
  - Cross range accuracy limits
    Real aperture radar, unfocussed SAR, focused SAR
  - Range velocity interaction
  - Range gate traveling
  - Prf limitations
  - Range and Doppler ambiguities
  - Limits to swath size
  - Signal processing evolution

- Image Formation
- Advanced Image Formation Techniques
- SAR Examples
- Remote Sensing Applications
- Summary

By “RMOD Radar Systems”

Airborne SAR Geometry



$$f_P = PRF = \frac{1}{T}$$

$$BW = Bandwidth = \frac{1}{t}$$

D = Real Antenna Aperture (Along track antenna length)

L_{SA} = Length of Synthetic Aperture

λ = Radar Wavelength

R = Slant Range

R_G = Ground Range

v = Aircraft velocity

h = Altitude of Aircraft

c = Speed of Light

ϕ = Angle of Beam wrt to vertical

R_{CR} = Cross Range on Ground

R_{AR} = Along range on Ground

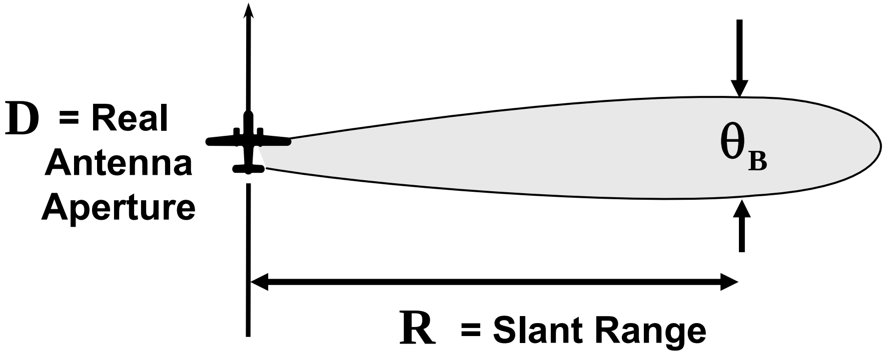
δR_{CR} = Cross Range Resolution

δR_{AR} = Range Resolution

Cross Range Resolution Limits

- **Real Aperture**
- **Synthetic Aperture**
  - **Unfocussed SAR**
  - **Focused SAR**

Cross Range Resolution Limits (Real Aperture Radar)



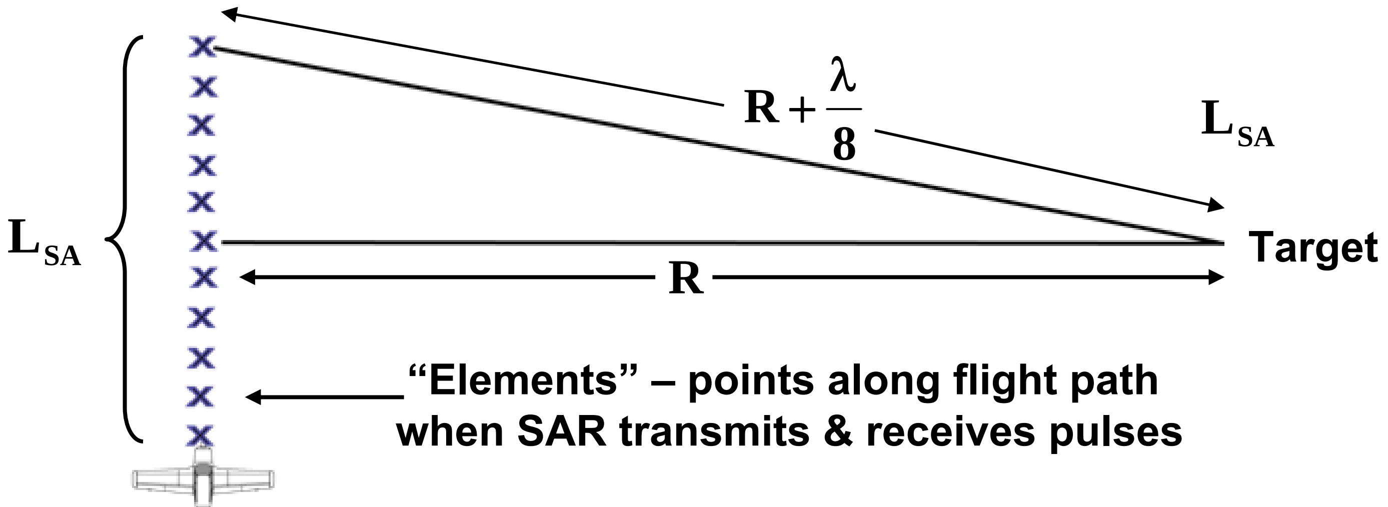
$$\theta_B = \frac{\lambda}{D}$$

$$\delta R_{CR} = \theta_B R = \frac{\lambda R}{D}$$

Cross Range Resolution (Real-Aperture Antenna)

- For an X=Band ($\lambda = 3\,\mathrm{cm}$) and an antenna aperture ($D = 3\,\mathrm{m}$), the cross range resolution would be $\delta R_{CR} = 1\,\mathrm{km}$ at a range of 100 km
- This is far, far larger than an easily attainable range resolution with 10% bandwidth
- Synthetic Aperture Radar (SAR) allows measurement of high cross range resolution by using the aircraft motion to generate a long antenna aperture sequentially rather than simultaneously as with the above example

Cross Range Resolution Limits (Unfocused Synthetic Aperture Radar)



- **When the path from radar to the target deviates in range (phase) more than $\lambda / 8$ from the range at the center of the synthetic aperture then the target echo will not be in focus.**
- **When this happens the SAR is "Unfocused" and the cross range resolution becomes** $\delta R_{CR} = 2\sqrt{R\lambda}$
- **Corrections can be applied to fix this defocusing effect**
  - **The factor of 2 appears, in the cross range resolution because of the 2 way path of the SAR vs a conventional antenna**
  - **Unfocused SARs are not used, because digital refocusing is so cost effective**

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)

- This limit in resolution because of operation in the far field is fixed by adding a phase term to each received signal correcting for the spherical nature (Fresnel region) of the wavefront.

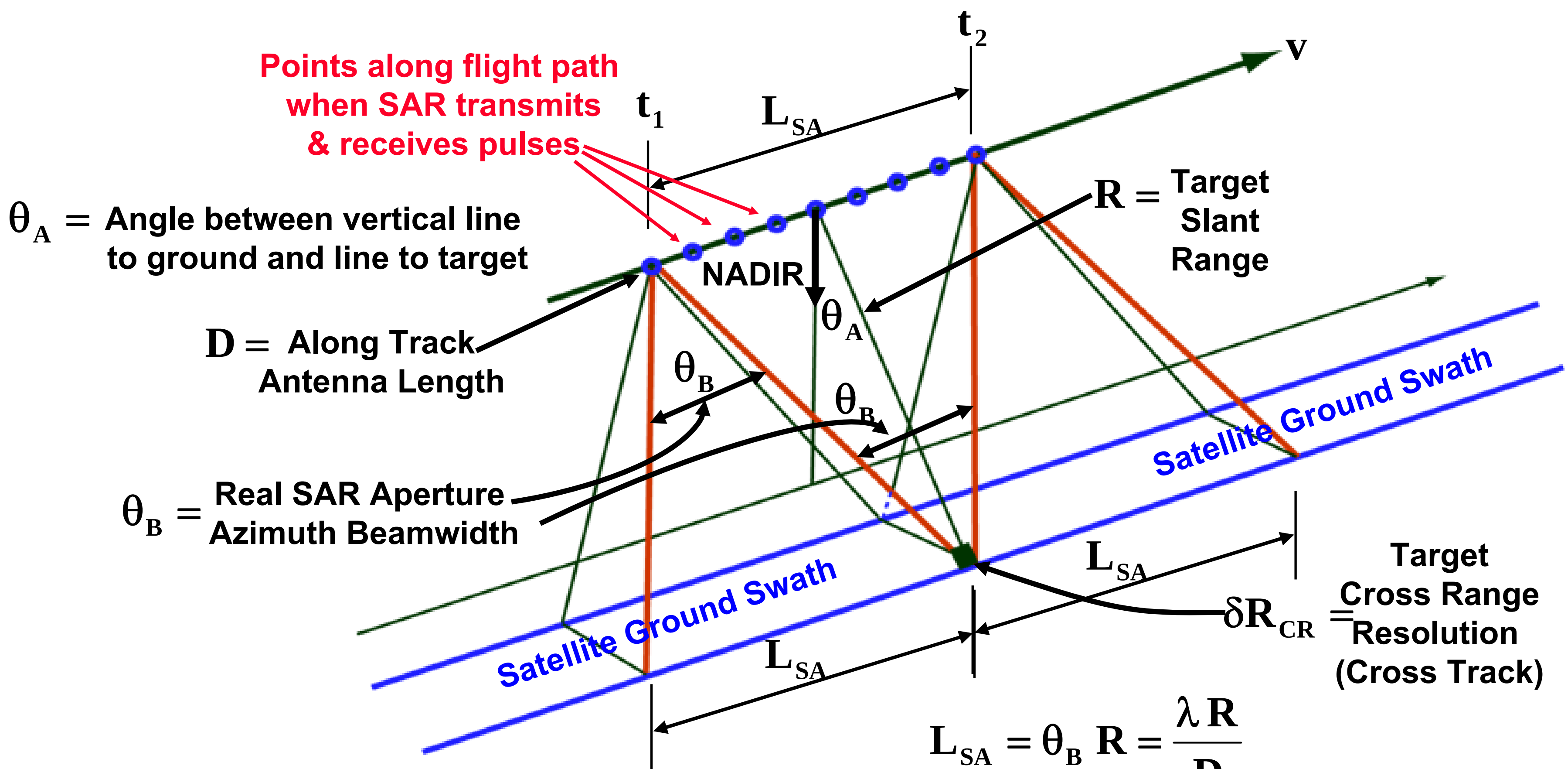
- $\Delta\varphi = \dfrac{2\,\pi\, y^2}{\lambda\, R}$ is the phase term

- y is the of the distance from the element to be corrected to the center of the synthetic aperture

- The correction is different for each range R and the angular resolution, after this correction, is the same as that in the far field

Adapted from Skolnik, from Reference 1

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)



$$L_{SA} = \theta_B \, R = \frac{\lambda R}{D}$$

$$\text{Integration Time} = \frac{L_{SA}}{v} = \frac{\lambda R}{v D}$$

$$\delta R_{CR} = \frac{\lambda}{2 L_{SA}} R = \frac{\lambda R}{\frac{2 \lambda R}{D}} = \frac{D}{2}$$

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)

- The new aperture is $L_{SA} = \frac{\lambda R}{D}$
- The cross range resolution of the focused SAR is

$$\delta_{CR} = \frac{\lambda}{2 L_{SA}} R = \frac{\lambda R}{2 \frac{\lambda R}{D}} = \frac{D}{2}$$

$$\delta R_{CR} = \frac{D}{2}$$

- The resolution of a focused SAR is independent of range and the wavelength and depends solely on the dimension D of the real antenna

Cross Range Resolution Limits (Focused Synthetic Aperture Radar)

- **As was mentioned 2 slides before, the factor of 2 in the beamwidth appears, in the cross range resolution because of difference between a SAR (2 way path) and a conventional antenna**
  - **Conventional antennas with the same length have a one way pattern equal to the two way pattern of a SAR, but the SAR antenna has ½ the beamwidth**
  - **The higher sidelobes of the SAR antenna usually cause weighting to be applied on the receive end.**

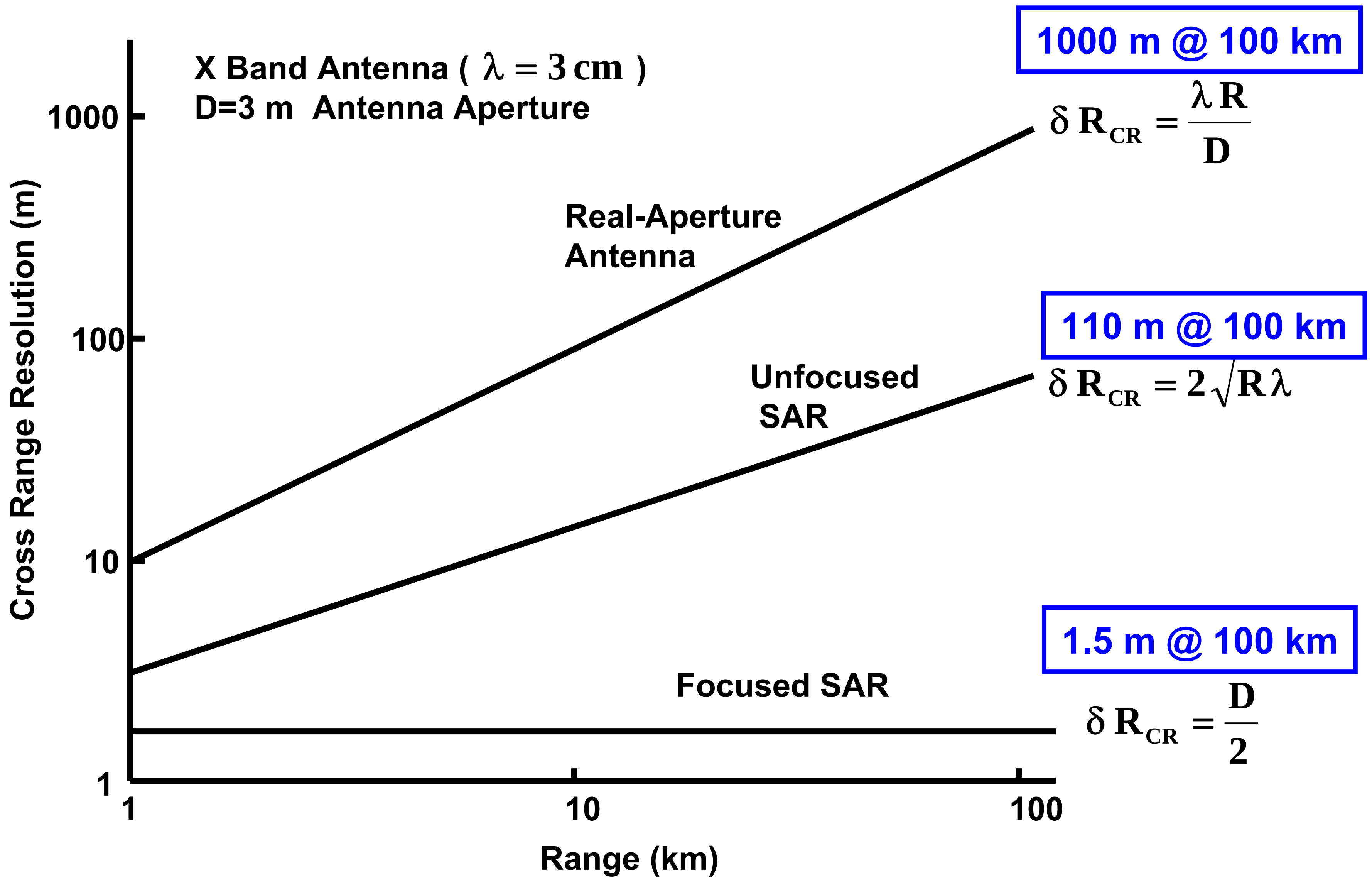
Two Way Patterns with Uniform Weighting

SAR ➔
$$\approx \frac{\sin\left(2\pi\left(L_{SA}/\lambda\right)\sin\theta\right)}{2\pi\left(L_{SA}/\lambda\right)\sin\theta}$$

Conventional Antenna ➔
$$\approx \frac{\sin^2\left(\pi\left(L/\lambda\right)\sin\theta\right)}{\left(\pi\left(L/\lambda\right)\sin\theta\right)^2}$$

Adapted from Skolnik, from Reference 1

Radar Cross Range Resolution



Constraints on Resolution and Swath Size

- **Range ambiguity constraints**
- **Avoidance of antenna grating lobes**
- **Influence of grazing Angle**

Range ambiguity Constraints

- As was lectured earlier, the PRF (pulse repetition rate) of the radar must be
  - Low enough so that range measurements are unambiguous
  - High enough to avoid foldover caused by grating lobes
    When spacing between elements is too large
  - High enough to avoid angle ambiguities

- Thus coverage (swarth size) and resolution can not be independently chosen

Avoidance of antenna grating lobes

- To avoid grating lobe problems , the position of the first grating lobe of the synthetic array should be located at the first null of the element pattern (of the real antenna)

- The synthetic array's first maximum is positioned at

$$\theta_G = \frac{\lambda}{2 d_E} = \frac{\lambda f_P}{2 v}$$

- The first null is $\theta_N \approx \lambda / D$

- θ_G has to be $\geq \theta_N$ to avoid grating lobes

$$f_P \geq \frac{2 v}{D} = \frac{v}{\delta R_{CR}}$$

Note: $d_E = \dfrac{v}{f_P}$

SA = Synthetic Array

θ_G = 1st grating lobe max. of SA

d_E = Spacing between elements in SA

D = width of antenna

θ_N = 1^{st} null of real antenna

This equation is for a focused SAR

Avoidance of antenna grating lobes

- Combining the constraint that the waveform be capable of unambiguous range detection with the previous equation yields

$$\frac{v}{\delta R_{CR}} \leq f_P \leq \frac{c}{2 R_U}$$

- From which it follows:

$$\frac{R_U}{\delta R_{CR}} \leq \frac{c}{2 v}$$

- For uniformly illuminated antenna patterns and other ideal conditions that were assumed, the PRF constraint equations become

$$1.53 \frac{v}{\delta R_{CR}} \leq f_P \leq \frac{c}{1.53 \text{ x } 2 R_U} \quad \text{and} \quad \frac{R_U}{\delta_{CR}} \leq \frac{c}{4.7 \; v}$$

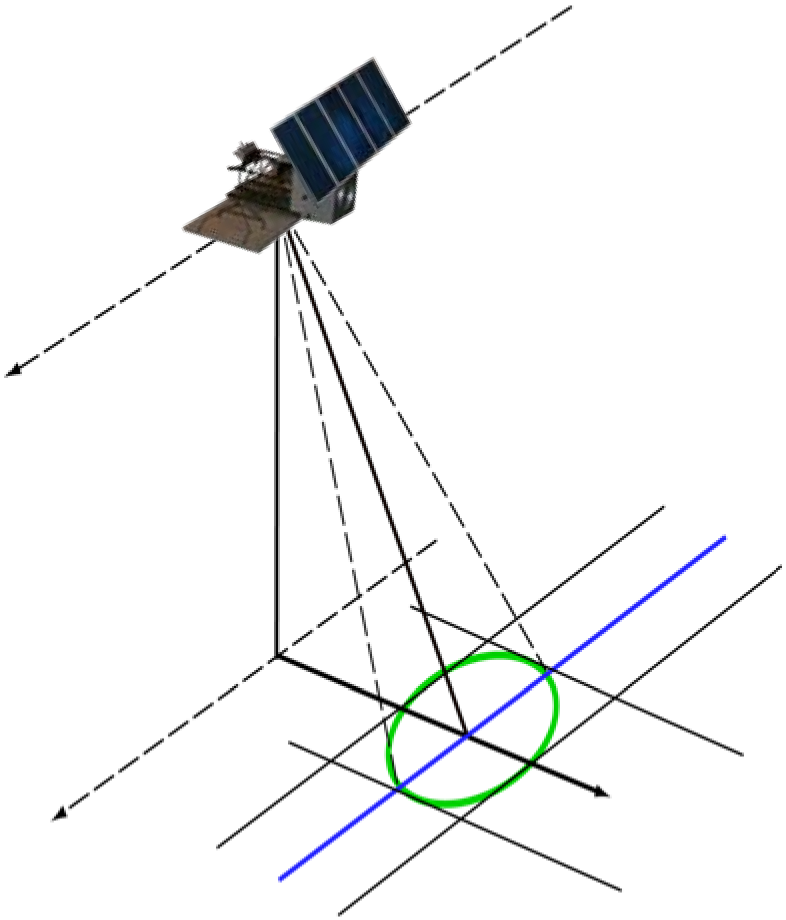
- Essentially the same results are obtained with a cosine illumination weighting

Influence of Grazing Angle

- The swath width S_W is often much smaller than the maximum radar range
- In addition, the beam projected onto the ground is impacted by the grazing angle ϕ of the beam (also reducing the needed maximum unambiguous range
- These factors impact the previously derived constraint equations so that

$$\frac{R_U}{\delta R_{CR}} \leq \frac{c}{4.7\ v} \quad \text{becomes} \quad \frac{S_W}{\delta R_{CR}} \leq \frac{c}{4\, v \cos\phi}$$

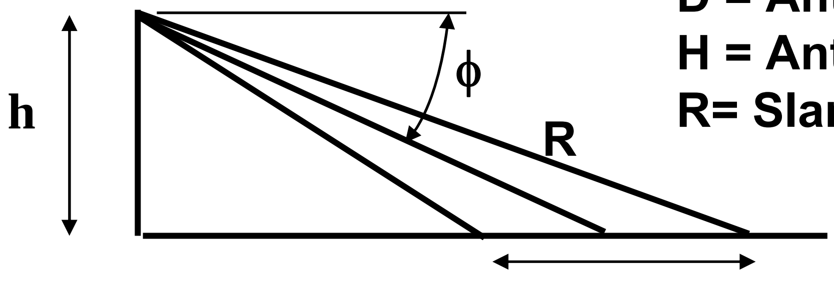
Focused SAR Example



- **A synthetic aperture radar operates at a center frequency of 5.5 GHz, with a pulse bandwidth (BW) of 500 MHz. The SAR is satellite based. Its altitude is 565 km and moves with a velocity of 7.0 km/sec. The SAR antenna has dimensions of 5.2 m (along the track) by 1.1 m in height. The antenna is oriented such that the antenna beam boresight angle and the ground are at an angle of 40 degrees.**

Focused SAR Example

- **1. Find the antenna footprint size (cross range and along track)?**



R_{AR} = Swath size- along range track
R_{CR} = Swath size- cross range
D = Antenna size cross parallel to altitude vector
H = Antenna size parallel to velocity vector of SAR
R= Slant Range to target

Along range footprint size = $$\approx \frac{h(\lambda / D)}{\cos^2 \phi} \approx 48.2\ \text{km}$$

Cross range footprint size = $$\approx \frac{h}{\cos \phi} \frac{\lambda}{H} = 7.8\ \text{km}$$

Focused SAR Example

- 2. What is the distance from the center of the radar beam footprint to the satellite ground track?

$$R_{Footprint\ Center} = h \tan\phi = 474.1\ km$$

- 3. Assuming the radar's size, what is the range resolution and cross range resolution for the "real-aperture "antenna?

$$\delta R_{AR} = \frac{\Delta R}{\sin\phi} = \frac{1}{\sin\phi}\frac{c}{2\,BW} = \frac{(3 \text{ x } 10^8)}{(0.623)(2)(500 \text{ x} 10^6)} = 0.482\ m$$

$\delta R_{CR} =$ Is the same same as the footprint size = 7.8 km

Focused SAR Example

- 4. When used in a SAR mode, what is the minimum PRF that will avoid grating lobe issues?

$$PRF_{MIN} = \text{Minimum PRF to avoid grating lobes}$$

$$PRF_{MIN} = 2\,v / H = 2.69\,KHz$$

- 5. What is the maximum PRF that will achieve a reasonable unambiguous range?

PRF_{MAX} Maximum PRF such that range is measured unambiguously

$$PRF_{MAX} = \frac{c}{2\,R_U\ \sin\phi} = 7.3\,kHz$$

Note: R_U is the maximum footprint size = 48.2 km

Focused SAR Example

- 6. For a PRF (f_P) of 5 KHz, how far does the satellite move in one PRI (pulse repetition Interval)?
  - f_P of 5 KHZ with aircraft traveling at v = 7 km/sec =>

Time between pulses $= \mathrm{PRI} = \dfrac{1}{f_P} = \dfrac{1}{5{,}000\ \mathrm{Hz}} = 0.2\ \mathrm{m\,sec}$

Distance moved $= 0.2\,\mathrm{m\,sec}\ \ \mathrm{x}\ \ 7\,\mathrm{km/sec} = 1.4\ \mathrm{m}$

Antenna element spacing ≈ 25.5 so grating lobes are issue

Angle of 1st grating lobe $\theta_G = \sin^{-1}\left(\dfrac{\lambda f_P}{2\,v}\right) = 1.16\ \mathrm{deg}$

Since element beamwidth $= \dfrac{\lambda}{H} = .608\ \mathrm{deg}$ grating lobes not a problem

$$= \frac{\lambda f_P}{2\,v} > \frac{\lambda}{H} \quad \text{no problem with grating lobes}$$

Focused SAR Example

7. Returns are processed for 0.8 sec, with the focusing computations, What is the length of the synthetic aperture?

Number of pulses processed = processing time x PRF

$$= 0.8\,\text{sec x } 5{,}000\text{ pulses / sec} = 4{,}000\text{ pulses}$$

The synthetic aperture length = time x velocity of platform

$$L_{SA} = 0.8\,\text{sec x } 7.0\text{ km / sec} = 5.6\text{ km}$$

- 8. Is this length consistent with keeping a point within the beam footprint for the computation?

Yes, the cross range footprint was calculated earlier as 7.8 km, so the data to be processed will be within the footprint of the beam, because the synthetic aperture length (5.6 km) is less than the footprint size.

Focused SAR Example

- 9. When the system is operating as per questions 6-8, what are the achieved along range and cross range resolutions?

$$\delta R_{AR} = \frac{\Delta R}{\sin\theta} = \frac{1}{\sin\theta_B}\frac{c}{2\,BW} = \frac{(3 \times 10^8)}{(0.623)(2)(500 \times 10^6)} = 0.482\,m$$

Same as calculated in problem 4, part a

$$\delta R_{CR} = R\frac{\lambda}{2}\frac{}{L_{SA}} = \frac{\lambda\, h \sec\phi}{2\,L_{SA}} = 3.62\,m$$

- 10. How does your result compare with the theoretically best resolution possible for a focused SAR?

Along range resolution = same as calculated earlier

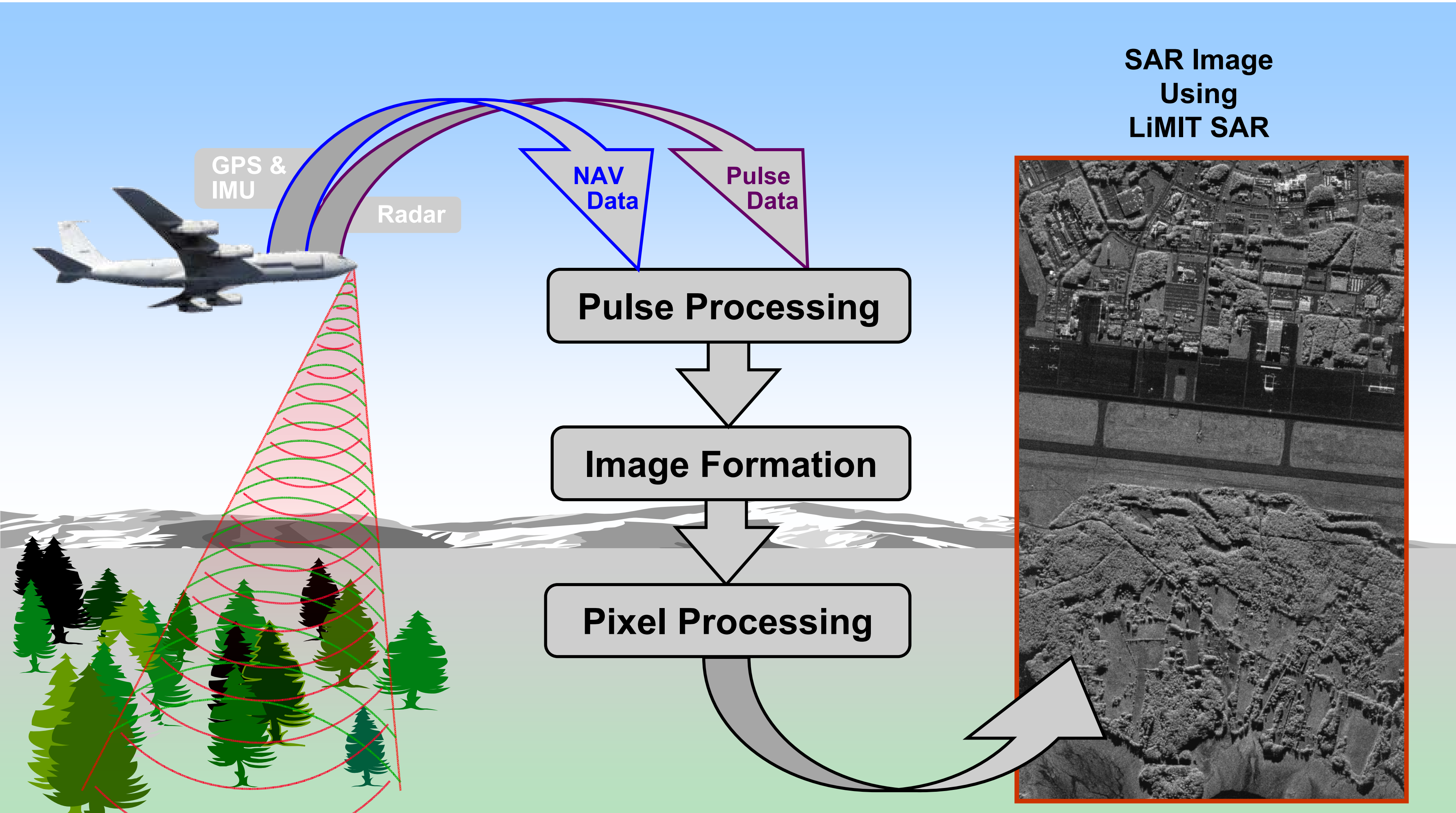
Cross range resolution = 3.62 m (theoretical best =H/2= 2.6 m) because we did not integrate along the flight path as long as was possible, while still keeping the target spot in the beam as the radar moved

Outline

- Introduction
- SAR Basics
- Image Formation
  - Overview
  - Polar to cart transformation
  - Autofocusing
  - Target Motion Compensation
  - Shadowing (measurement of object height)
- Advanced Image Formation Techniques
- SAR Examples
- Remote Sensing Applications
- Summary

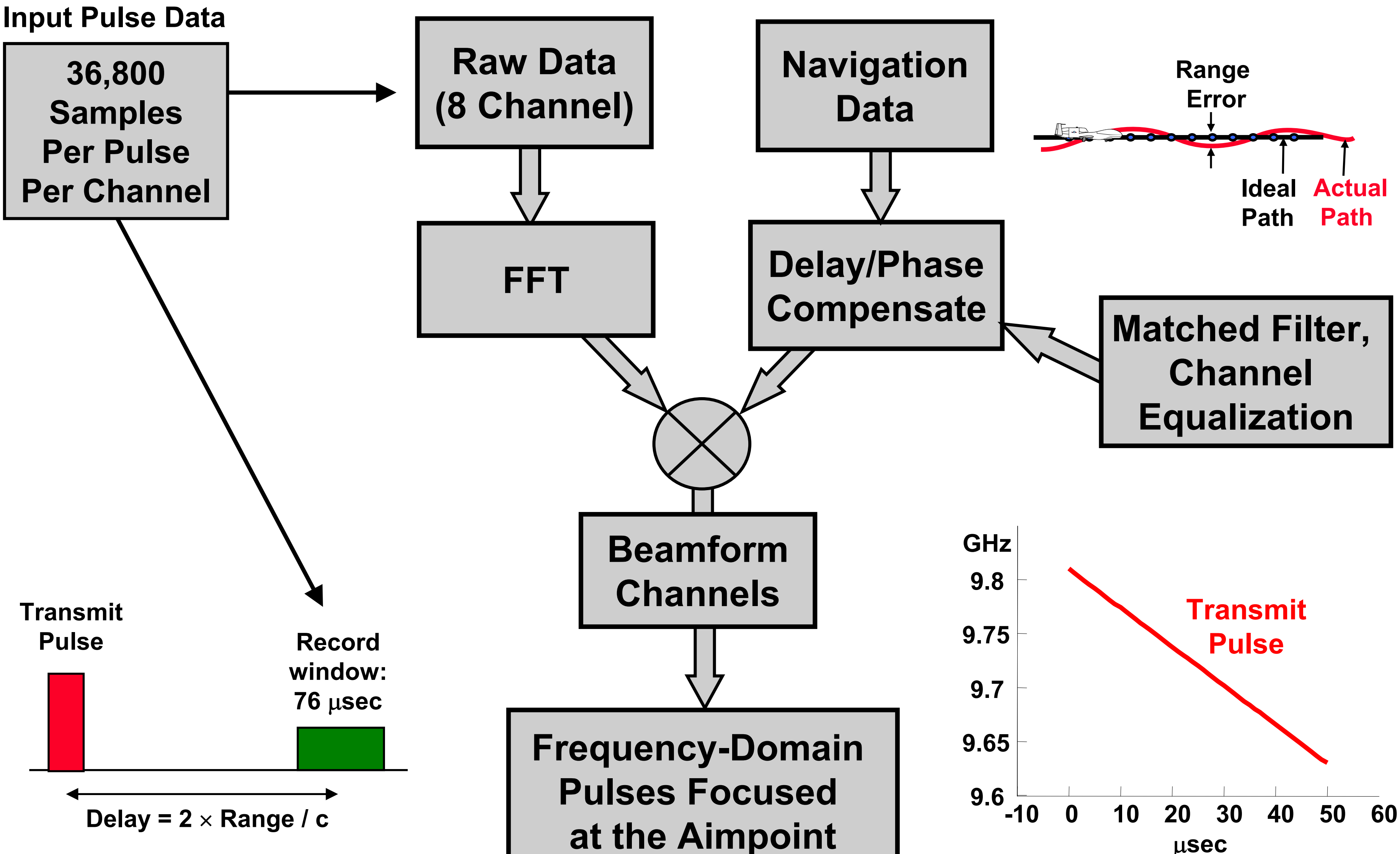
By "RMOD Radar Systems"

SAR Processing Flow



Courtesy of MIT Lincoln Laboratory
Used with Permission

Pulse Processing (LiMIT Example)



Courtesy of MIT Lincoln Laboratory
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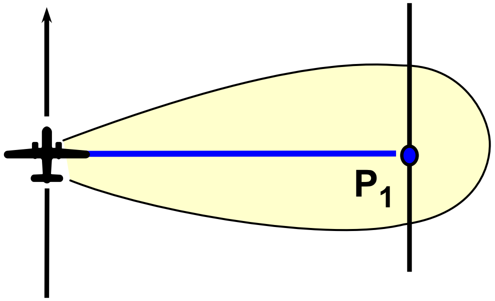
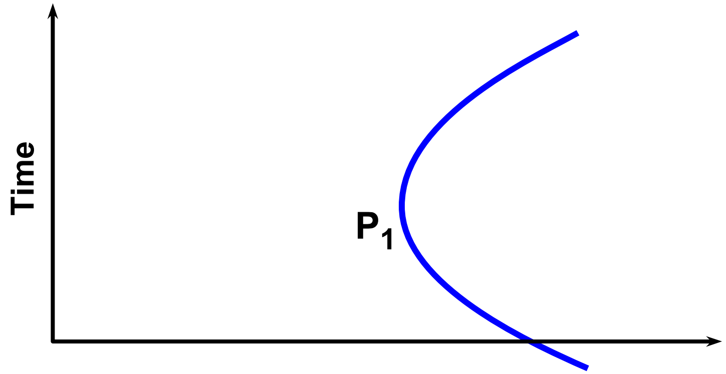
Image Formation Issues

- Focus on Center Point Only
- Range Migration of Target's Phase during Data Collection
- Transforming Data from Polar Format to Cartesian Format
  - Very efficient for digital processing
- Exact Focusing of Target Data

Problem: Range Walk Defocus

- Target "walks" through many range bins during collection





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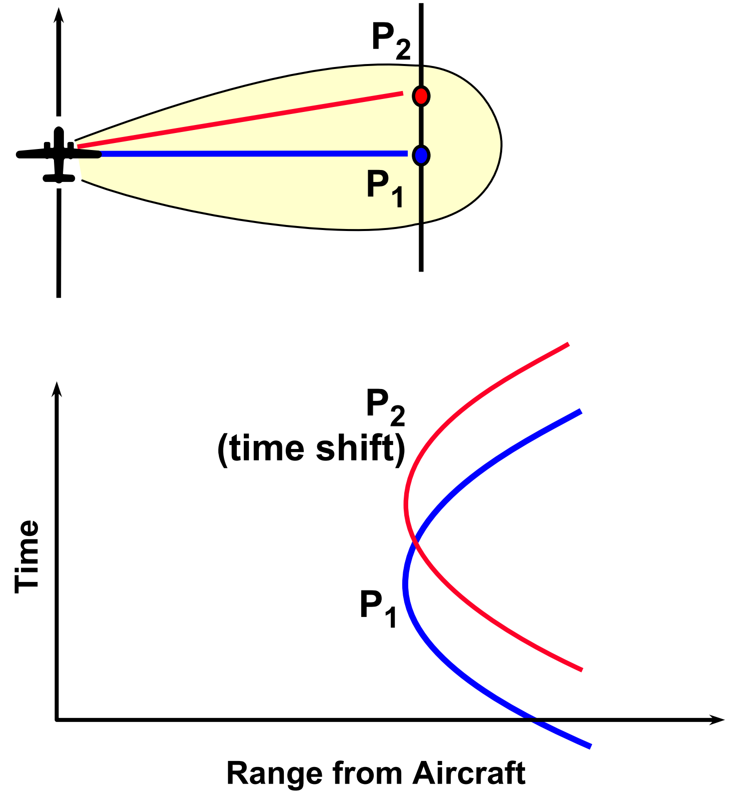
Problem: Range Walk Defocus

- Target "walks" through many range bins during collection



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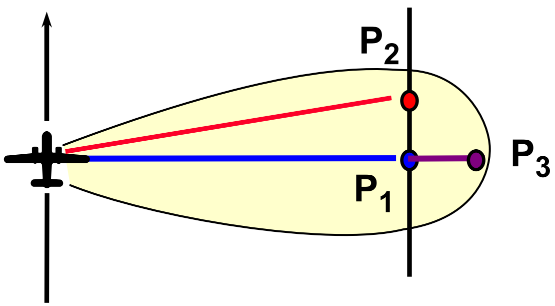
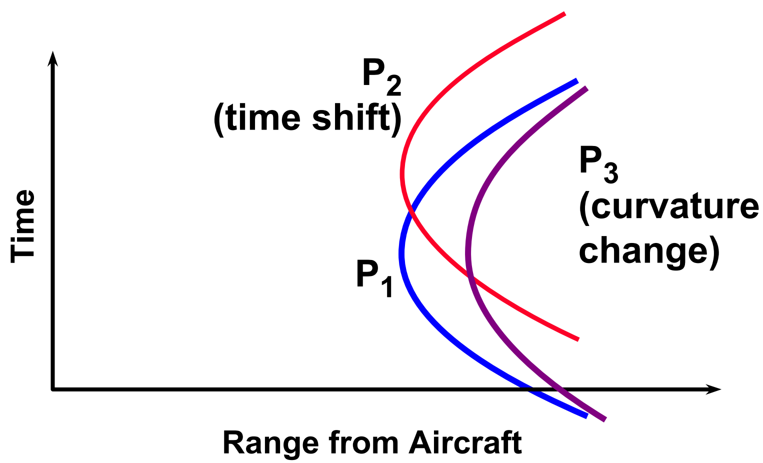
Problem: Range Walk Defocus

- Target "walks" through many range bins during collection





Solutions

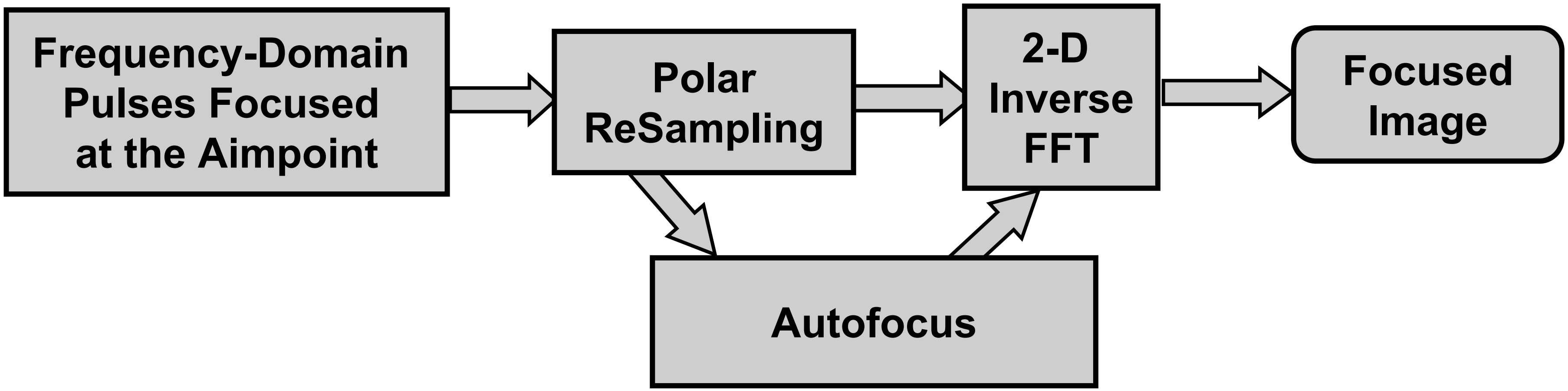
Increasing Computational Complexity

- Focus center point only } Low resolution
- "Polar Format"
  - very efficient
  - area limited
- "Range Migration"
  - wide area
  - linear flight path
- Exact focusing
  - no limitations

} High Resolution

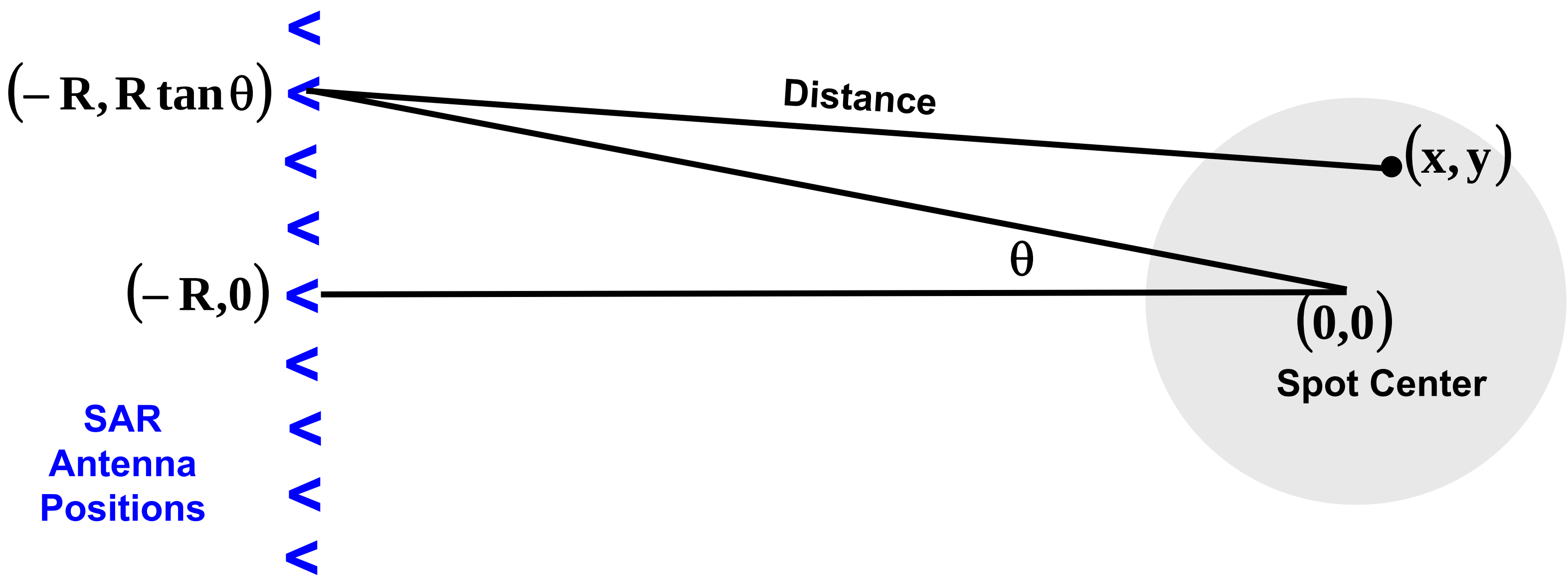
Courtesy of MIT Lincoln Laboratory
Used with Permission

Image Formation Block Diagram



- As a SAR moves by a fixed target, direction of the radar's $\vec{k}$ (wave number) changes.
- When digital processing techniques (FFTs) are used in SAR image formation, it is important for the scattered electric field samples, $\vec{E}\left(\vec{k}\right)$, to be uniformly spaced in $\vec{k}$ space.

Far-Field Spotlight Phase Response

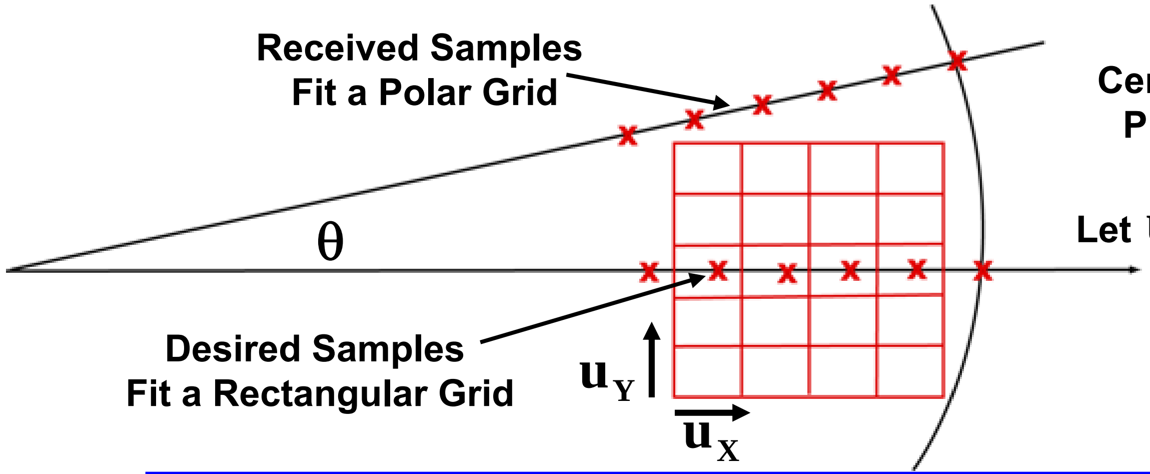


$$\phi(x,y) = -4\pi \frac{f}{c}\sqrt{(x+R)^2 + (y - R\tan\theta)^2} \qquad \left(= -4\pi \frac{\text{Distance}}{\lambda} \right)$$

$$= -4\pi \frac{f}{c} \frac{R}{\cos\theta}\left(1 + \frac{x\cos^2\theta}{R} - \frac{y\sin\theta\cos\theta}{R}\right) \qquad \left(\text{For } R > \frac{4y^2}{\lambda} \right)$$

Centered Phase $= \phi(x,y) - \phi(0,0) \approx -4\pi \frac{f}{c}(x\cos\theta - y\sin\theta)$

Polar ReSampling



Centered Phase $= -4\pi \frac{f}{c}(x\cos\theta - y\sin\theta)$

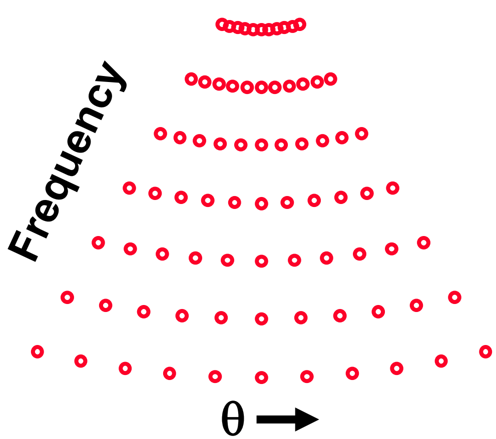
Let $u_X = f\cos\theta$ and $u_Y = f\sin\theta$

Centered Phase $= \frac{4\pi}{c}(x u_X - y u_Y)$

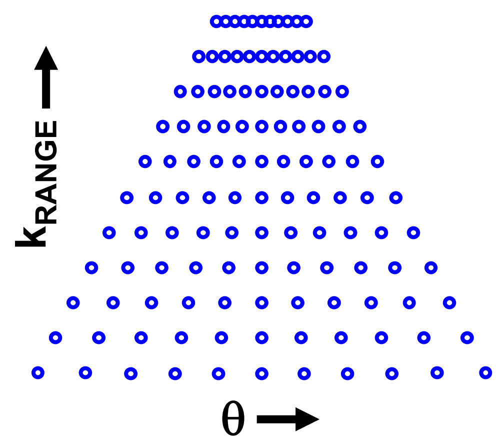
Point response has linear phase in (u_X, u_Y) enabling FFT focusing

Polar Resampling Process

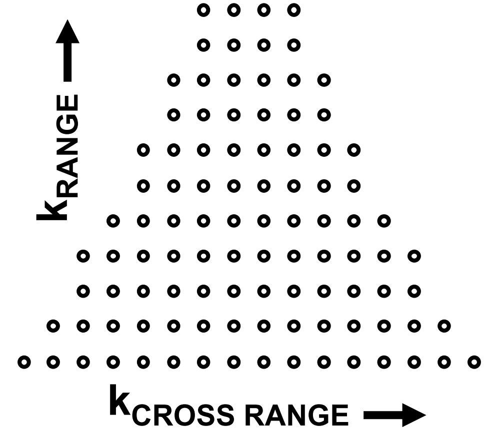
Raw Data



STEP I



STEP II

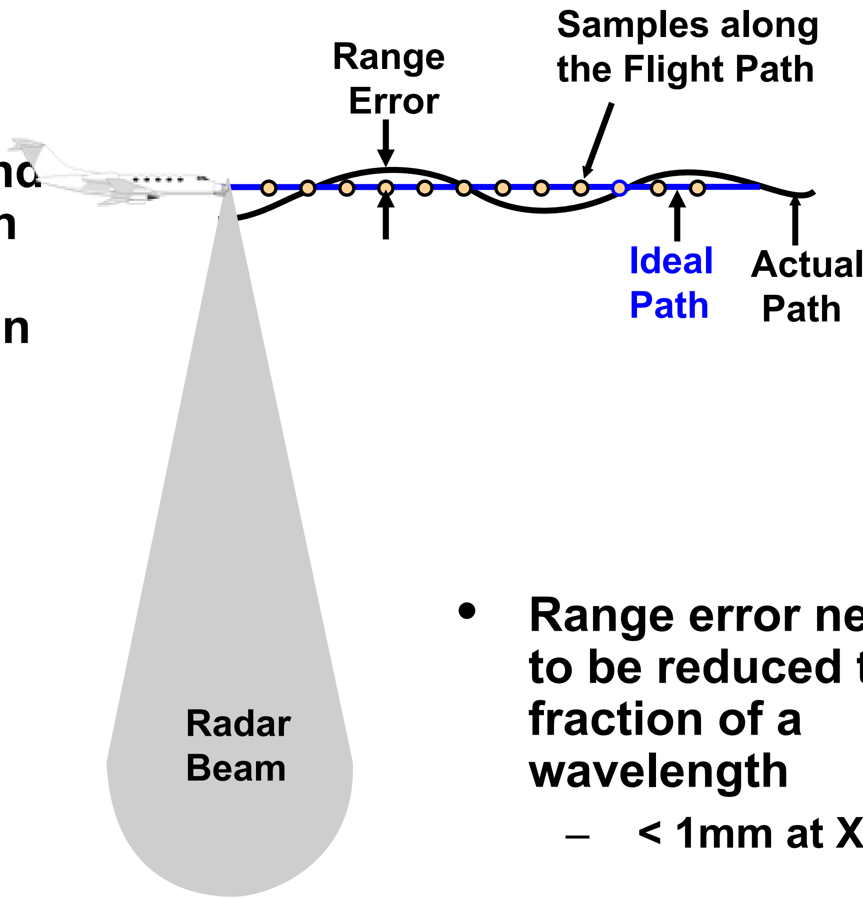


Motion Compensation

- Platform motion must be measured very accurately and input to the image formation process or the image will suffer significant degradation in resolution

- Airborne platforms employ GPS and IMU systems to derive range errors

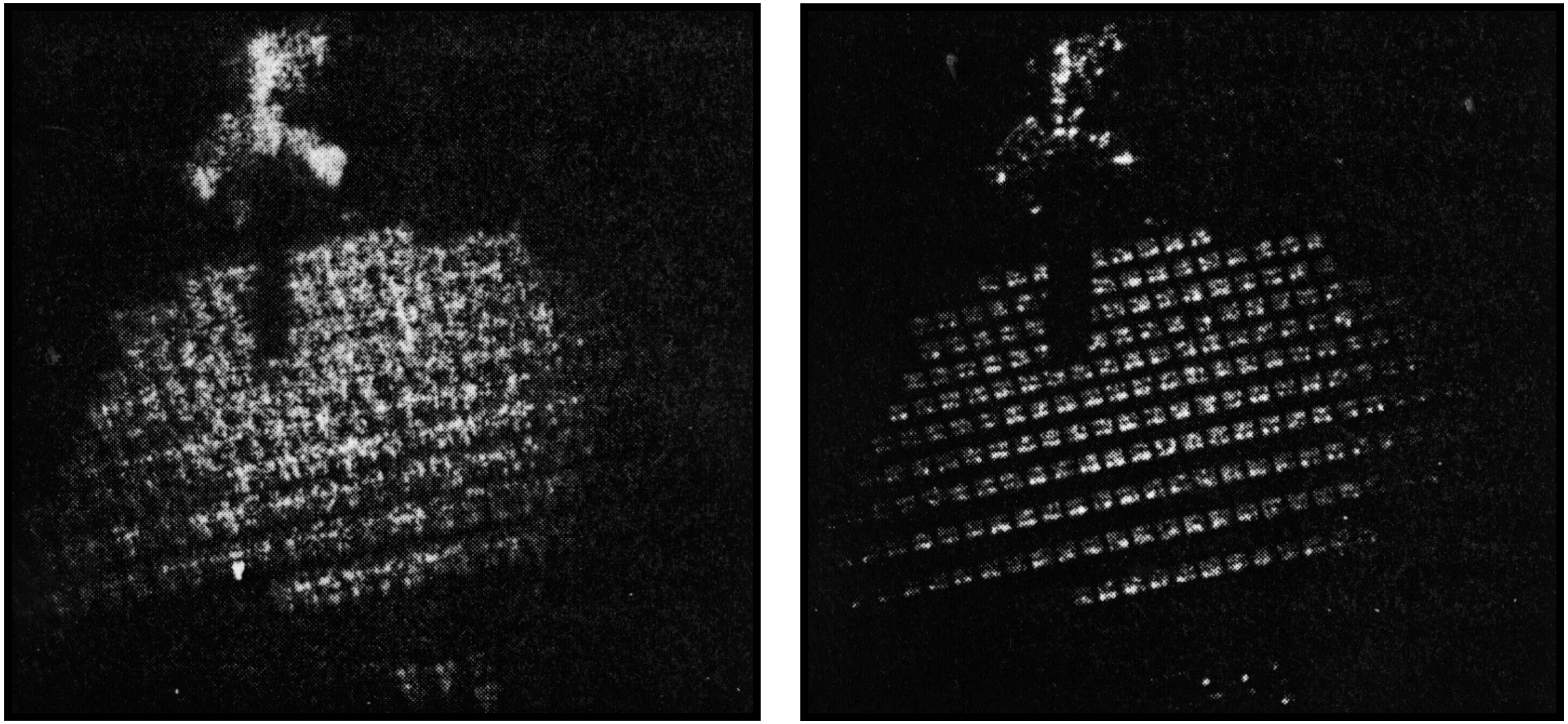
- Satellites and space probe missions vehicles employ orbital models



- Range error needs to be reduced to a fraction of a wavelength
  - < 1mm at X-Band

Autofocus Algorithm Techniques

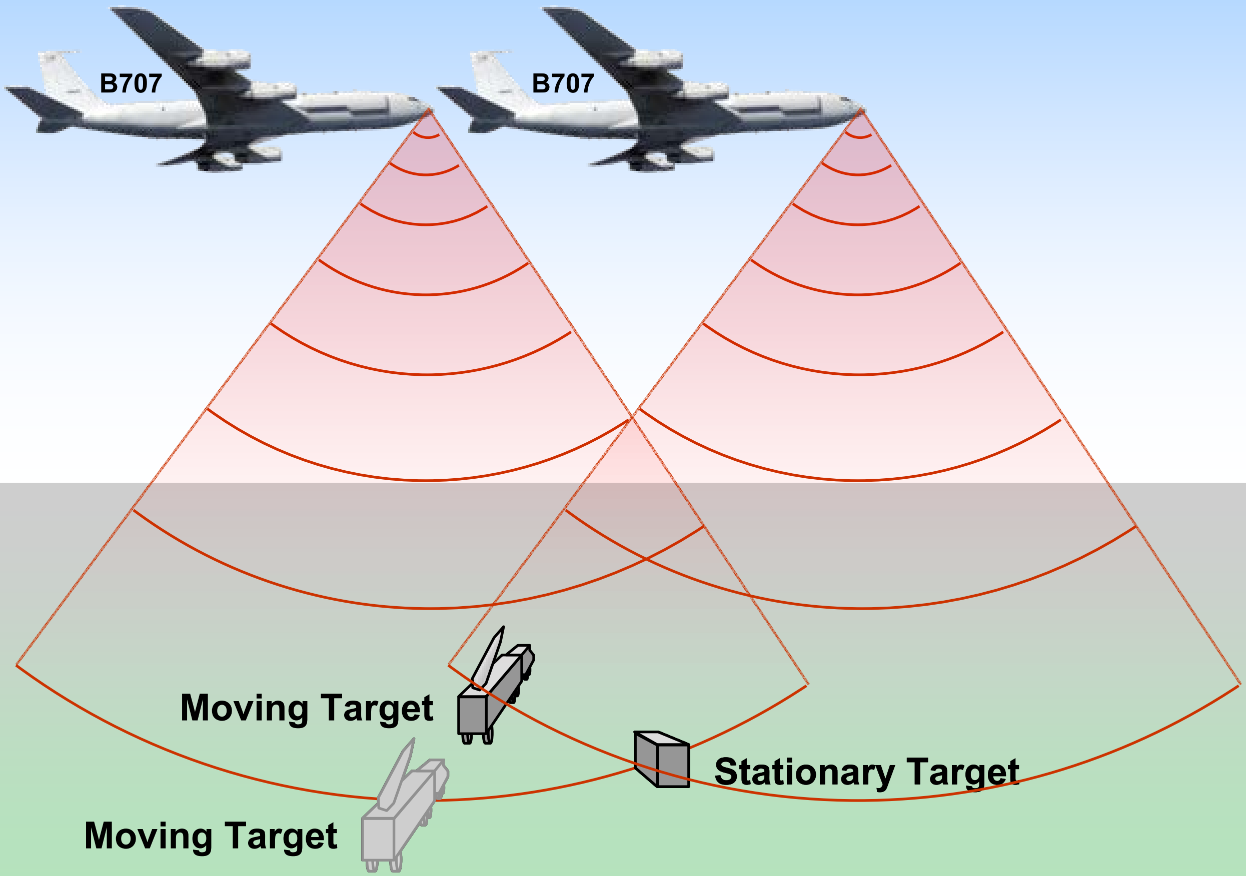
- **Automatic algorithm to remove motion-induced phase errors**



Courtesy of Sandia National Laboratories

- **Example: Phase-Gradient Algorithm (Ghiglia, See Reference 7)**
  - **Scene: Array of solar reflectors in New Mexico**
- **A number of other autofocus techniques are described in Reference 1)**

Moving Target Displacement in SAR

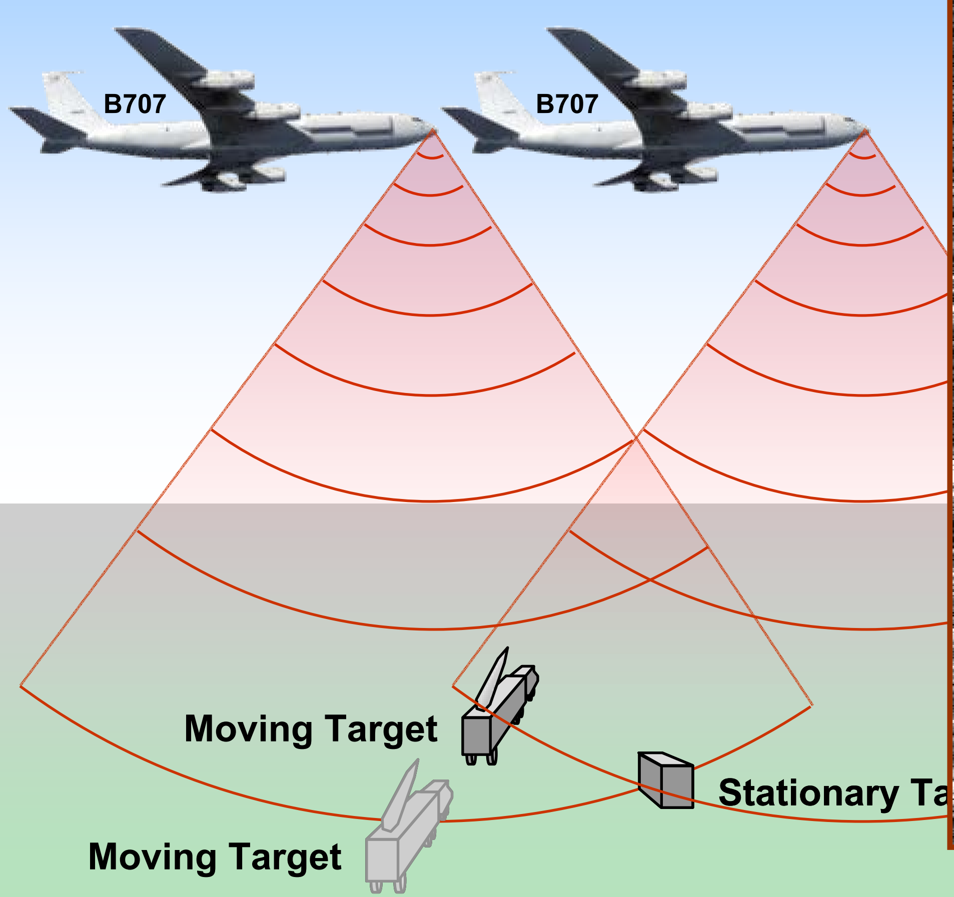


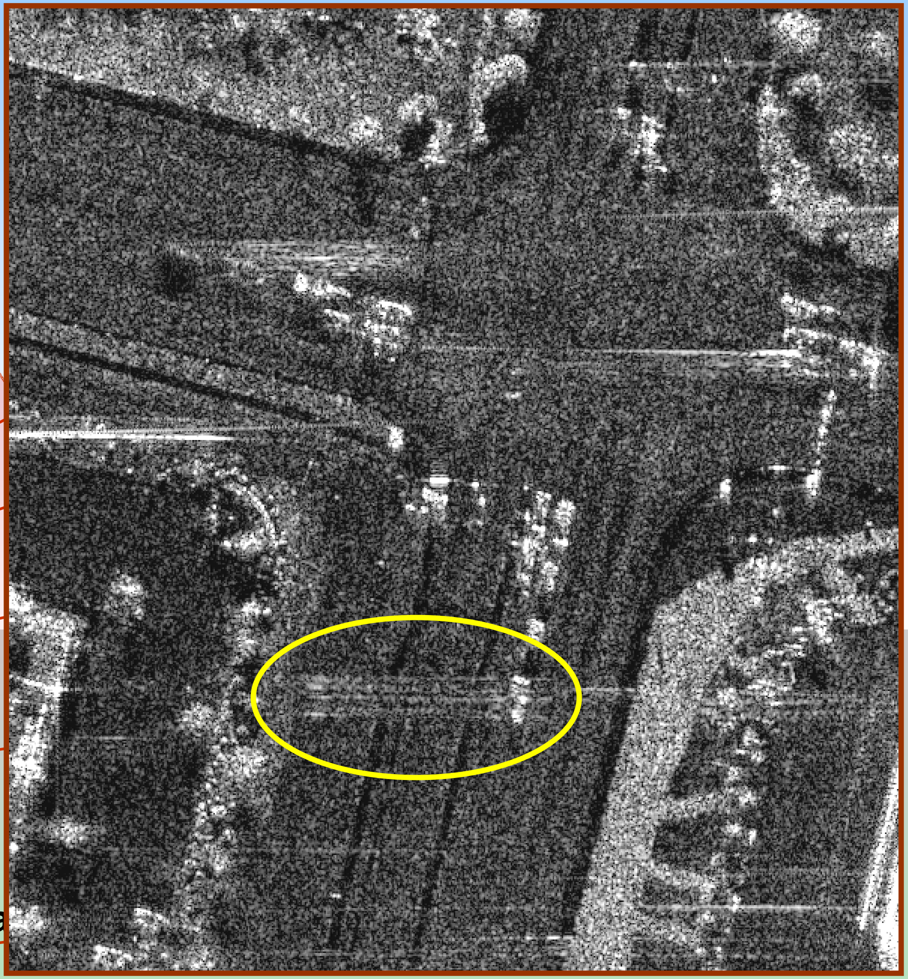
- Vehicle and stationary target are at the same range at the start of collection
- Vehicle and stationary target are at the same range at the end and throughout the collection

SAR cannot distinguish the moving vehicle from the stationary target

Courtesy of MIT Lincoln Laboratory
Used with Permission

Moving Target Displacement in SAR





Courtesy of MIT Lincoln Laboratory
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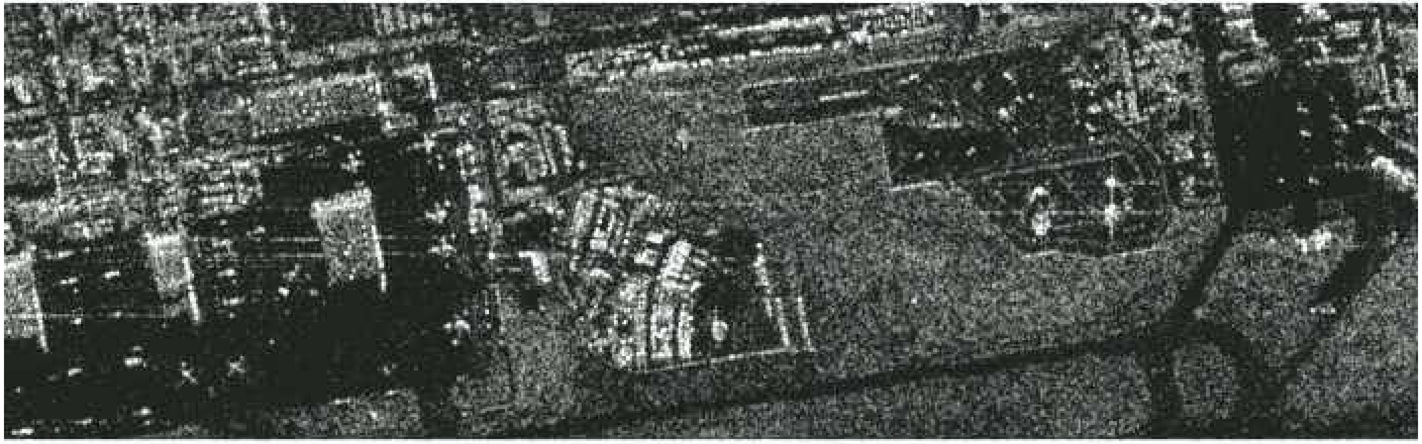
Motion Compensation Example

Motion Compensated



Uncompensated

Courtesy of Sandia National Laboratories

Sandia Ku-Band (15 GHz) SAR carried by the Sandia Twin Otter aircraft.
Resolution of SAR data is 3 meters

Shadowing of Ground Objects

SAR Image of Washington Monument

Courtesy of General Dynamics,
Used with Permission

Use of Shadows to Measure Object Height

The length of the shadow of an object generated by SAR image may be calculated (assuming a flat earth) by the following obvious equation:

$$h_{TARGET} = L_{SHADOW}\left(\frac{H_{SAR}}{R_G}\right)$$

Where:

- h_{TARGET} **= The height of the target**
- L_{SHADOW} **= The length of the shadow of the object**
- H_{SAR} **= The altitude of the SAR**
- R_G **= The ground range from SAR to target**

Outline

- Introduction
- SAR Basics
- Image Formation
- Advanced Image Formation Techniques
  - Interferometric SAR 1 and 2 Techniques
  - FOPEN
  - Vector processing and DeGraff Methods
- SAR Examples
- Remote Sensing Applications
- Summary

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Interoferometric SAR (InSAR)

- Interferometric SAR uses 2 SAR images
  - Taken at slightly different altitudes
  - Coherently compared to obtain high resolution information resulting in measurement of the height of targets or terrain in the image
- 2 aircraft/satellites making 1 pass or 1 system making 2 passes over the same terrain
- Phase ambiguity problem must dealt with to obtain absolute height measurements

One Pass InSAR

• More Expensive; (2 antennas, receivers, A/D converters

•Simultaneous collection of data implies identical scene

•Processing on platform feasible

•Example: NASA SRTM project (Reference 10)

Two Pass InSAR

• No special HW; SAR flown twice over same terrain

• Difficult motion compensation problem

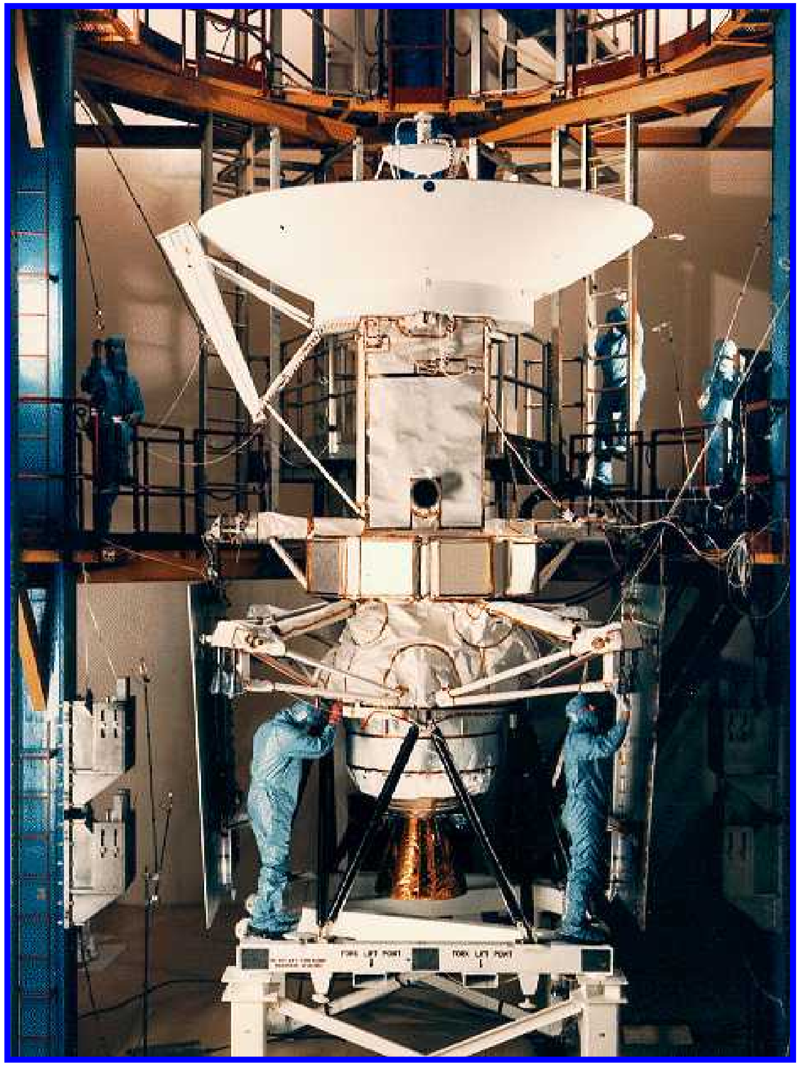
•Excellent vertical resolution because of long baseline (difficult problem)

• Example: Magellan mapping of Venus

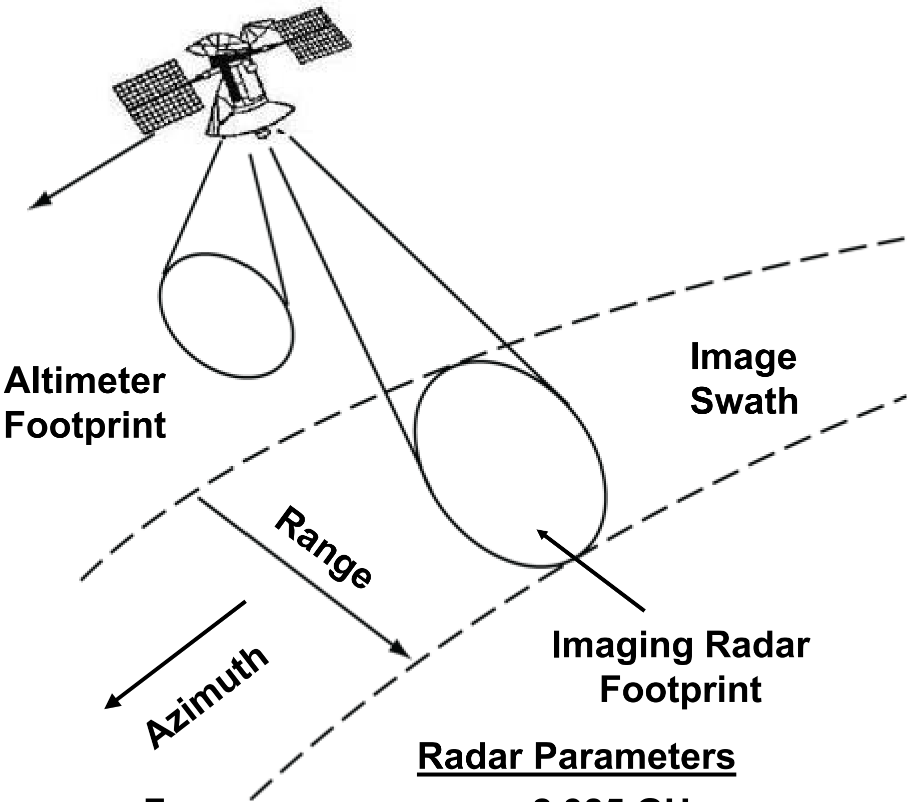
See R, J, Sullivan; Reference 3 (pp 17-30-33) or Reference 4 pp 224-228 for detailed derivations of these 2 approaches

Synthetic Aperture Radar on Magellan Mission to Venus

Spacecraft before Launch



Courtesy of NASA

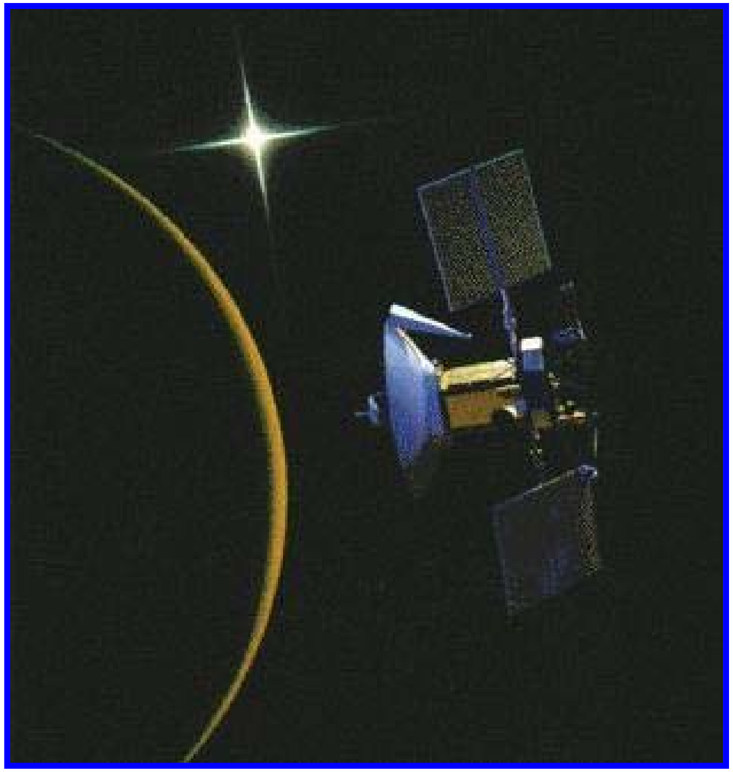


Radar Parameters

Frequency	2.385 GHz
Peak Power	325 watts
Antenna Diameter	3.7 m
Pulse Length	26.5 microseconds
PRF	4400 - 5800 Hz
Resolution	
Range	~150 m
Cross Range	~150 m

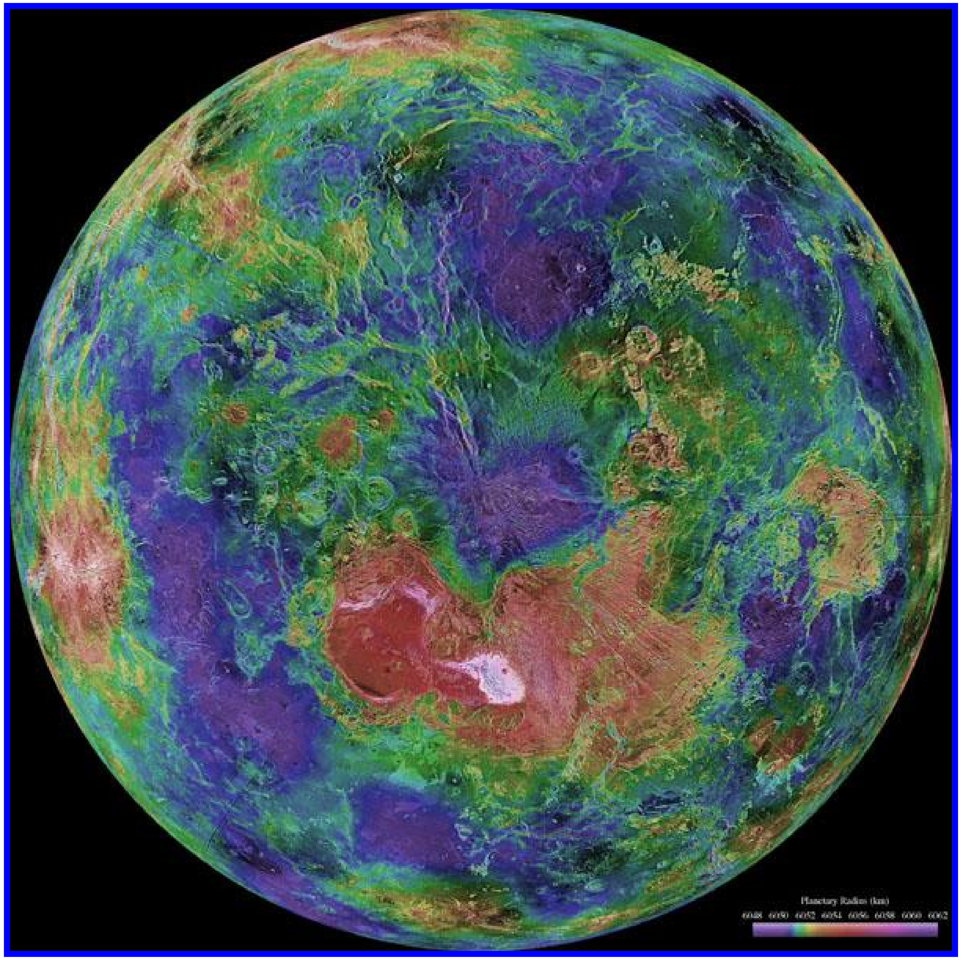
Magellan SAR Mapping of Venus

Visualization of Magellan Orbiting Venus



Courtesy
of NASA

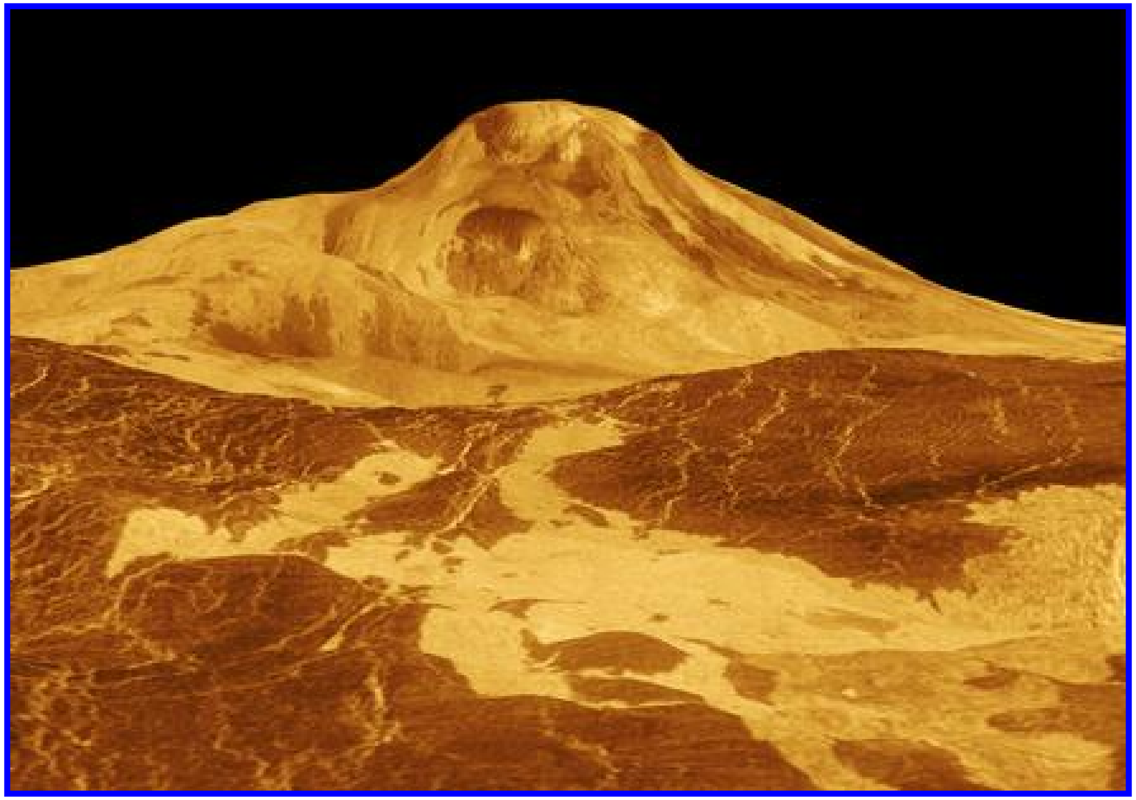
Map of Venus taken by Magellan SAR Radar



Courtesy
of NASA

Magellan Space Probe of Venus

Magellan SAR data was used with radar altimetry to develop a 3-D map of the surface



- **Maat Mons is an 8-km high volcano and is named for an Egyptian goddess of truth and justice.**
- **Lava flows extend for hundreds of km to the base of Maat Mons.**
- **The viewpoint is located 560 kilometers north of Maat Mons at an elevation of 1.7 km**

Courtesy of NASA/JPL

- **The vertical scale in this perspective has been exaggerated 22.5 times.**
- **Simulated color and a digital elevation map are used to enhance small-scale structure.**
- **The color hues are based on images recorded by the Soviet Venera 13 & 14 spacecraft.**

FOPEN – Foliage Penetration SAR

- Although higher microwave frequencies do not penetrate foliage
  - Frequencies in the UHF and VHF Band have been used to penetrate foliage since the late 1960's

- The large fractional bandwidth requirements and long integration time (motion compensation) requirements for successful SAR operation have presented significant technical challenges, particularly in antenna design

- In addition, the wide real antenna beam angle is an issue probably requiring use of range migration algorithms

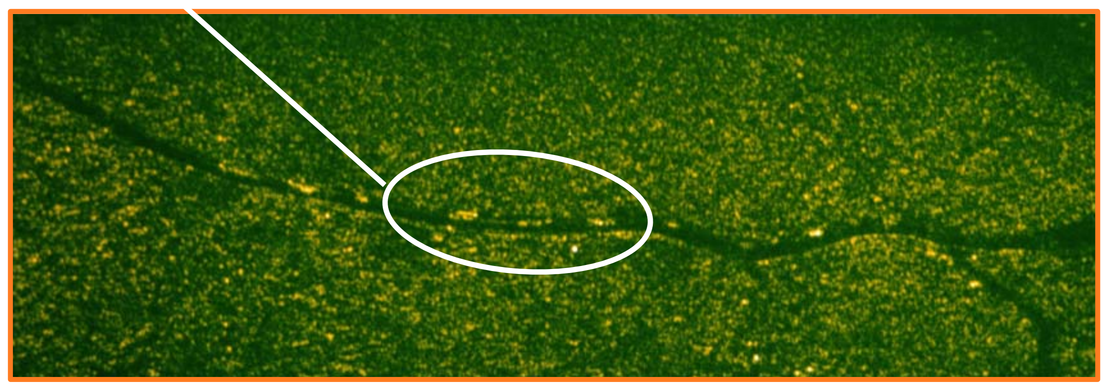
- Not withstanding these challenges, a no. of authors have published papers, exhibiting detection of vehicles, under trees, with UHF FOPEN SAR

Microwave SAR & UHF SAR Comparison

- **Depression angle: 45°, Resolution: 1 m x 1 m**
- **Vehicles masked by trees, along logging road in Maine**

Photograph

35 GHz SAR



UHF (FOPEN) SAR

Courtesy of MIT Lincoln Laboratory
Used with Permission

High-Definition Vector Imaging

- **Description**
  - Modern spectrum estimation techniques (superresolution) applied to multidimensional data
- **Benefits**
  - Resolution improvements
  - Sidelobe and speckle reduction
  - Feature enrichment
- **Goals**
  - Automatic recognition of military targets via radar
  - Exploitation-quality data from limited imagery

See G. R. Benitz
Reference 8 for a much more detailed account

Courtesy of MIT Lincoln Laboratory
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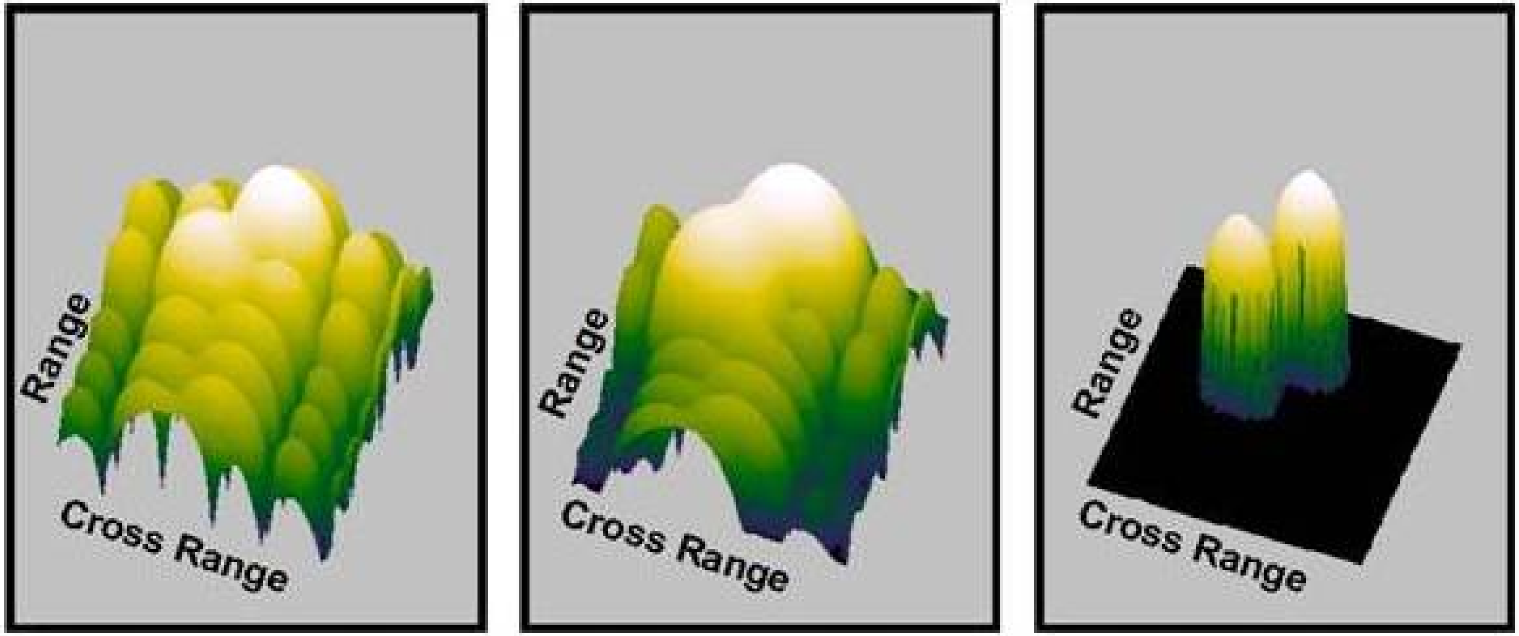
- **Two point-scatterers at high SNR**
  - **60 dB dynamic range**



Fourier Transform (2-D FFT) | Weighted Fourier Transform (Conventional) | High-Definition Vector Imaging

See G. R. Benitz
Reference 8 for a much more detailed account

Courtesy of MIT Lincoln Laboratory
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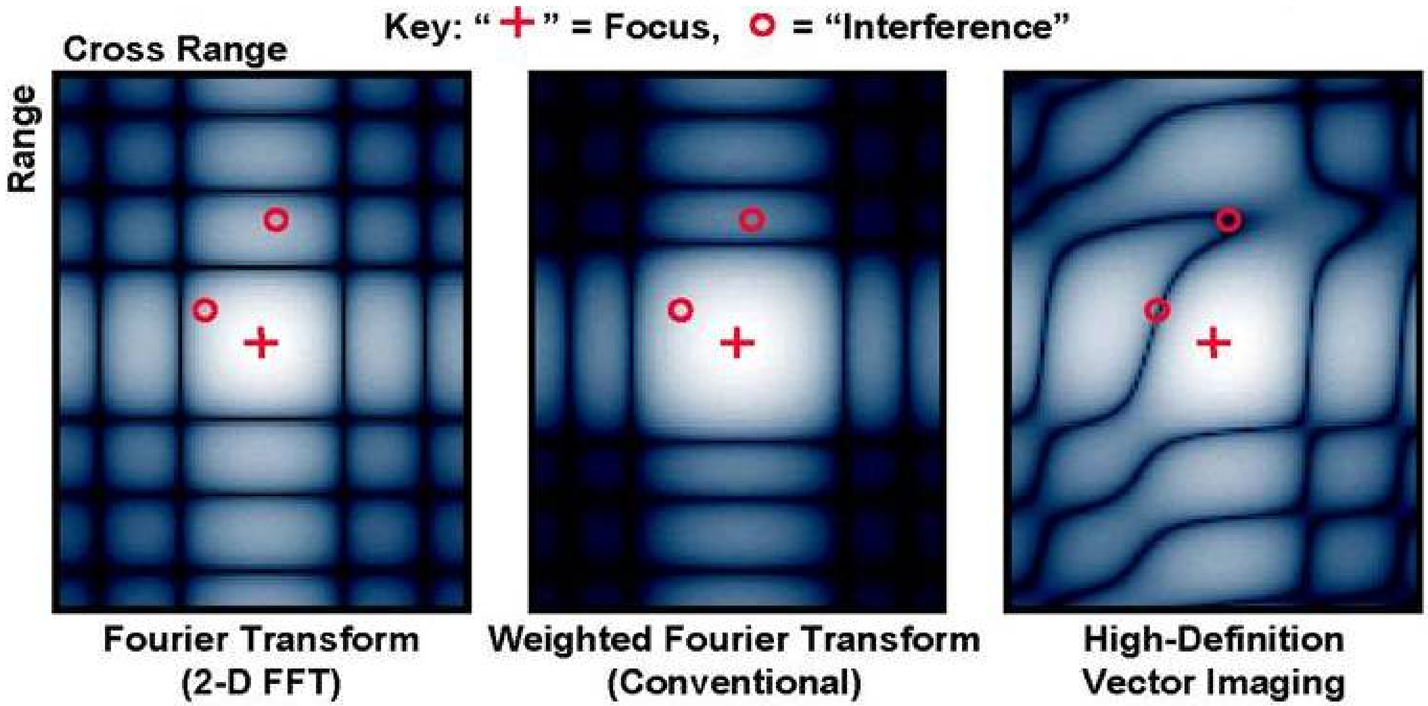
Controlling Sidelobes: An Inside Look

- **Problem: Estimate RCS in the presence of "Interference"**
- **Solution: Modify sidelobes to reject "interference"**

Spatial leakage patterns (for estimating RCS at "+")



See G. R. Benitz
Reference 8 for a much more detailed account

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Outline

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  - Sandia National laboratory
  - MIT Lincoln Laboratory
- Remote Sensing Applications
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Sandia National Laboratory K_U-Band Synthetic Aperture Radar

Sandia Twin Otter aircraft

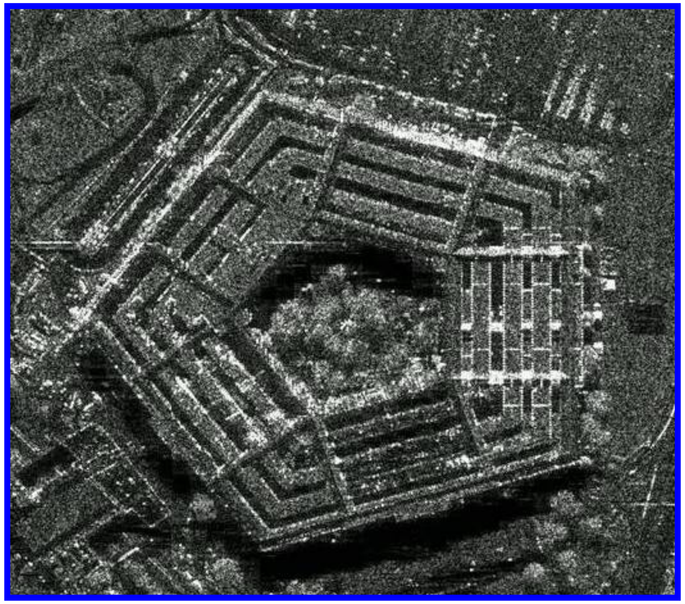
Sandia operates a Ku-Band (15 GHz) SAR

Carried by the Sandia Twin Otter aircraft.

Data is collected at ranges of 2 to 15 km

Processed into images in real-time.

Pentagon – 1 ft resolution



Washington DC Area 1 m resolution

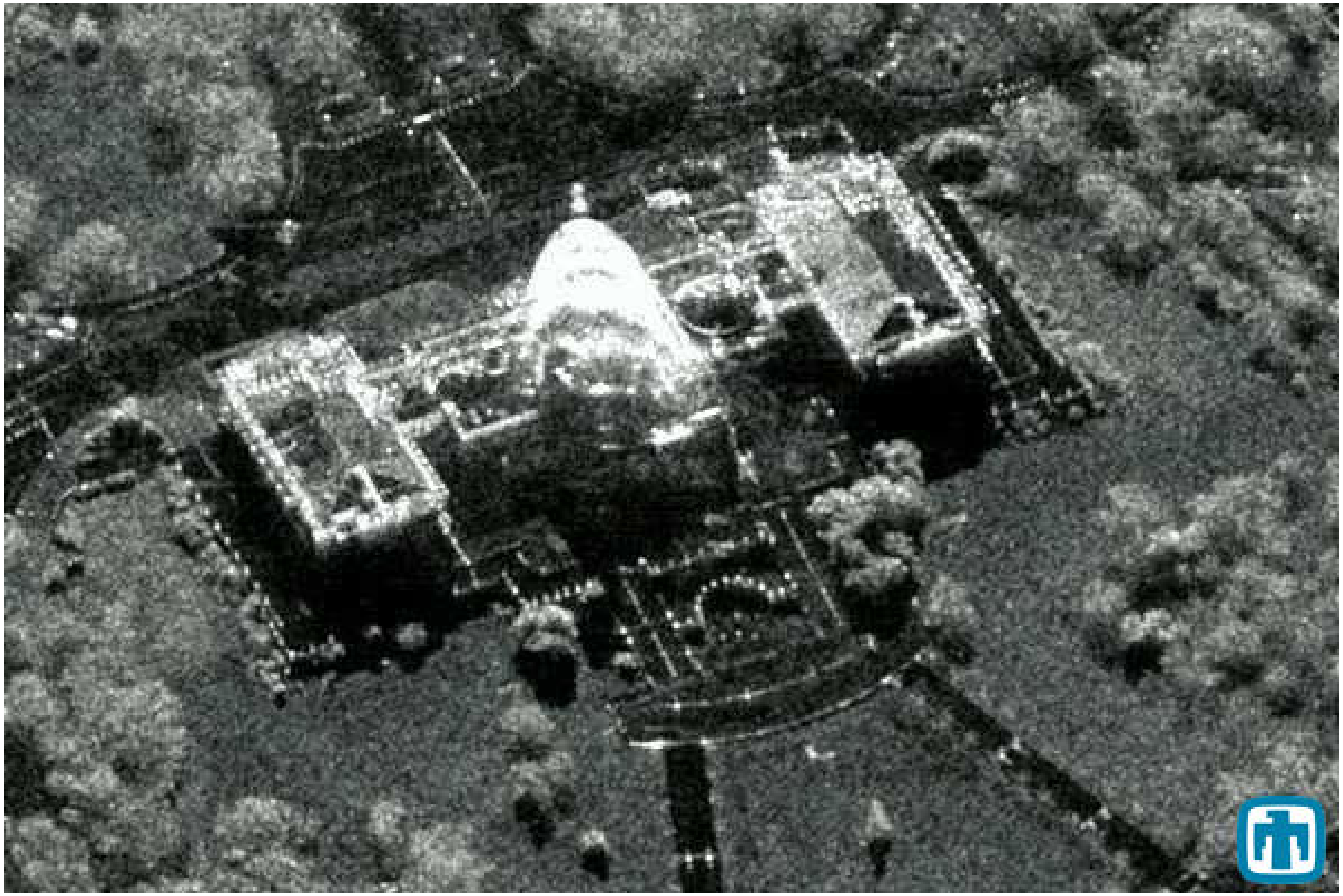
Images Courtesy of Sandia National Laboratories

Sandia K_U-Band SAR Image

U.S. Capitol building, House office buildings, Library of Congress, and Supreme Court Building (1 meter resolution)

Images Courtesy of Sandia National Laboratories

Capitol Building – 1 meter Resolution



Images Courtesy of Sandia National Laboratories

Sandia mini SAR

Mini SAR System

- Frequency 16.8 GHz
- Resolution 4 in (minimum)
- Range
  - 10 km @ 4 in res
  - 15 km @ 1 ft res
  - 23 km @ 12 in res
- Transmit Power 60 watts
- SARMode Spotlight, Stripmap

Images Courtesy of Sandia National Laboratories

mini SAR Image
DC-3 & Helicopter Static Display - KAFB

4 inch resolution 3.3 km range

Images Courtesy of Sandia National Laboratories

Sandia Lynx SAR Radar

LYNX Antenna and Gimbal

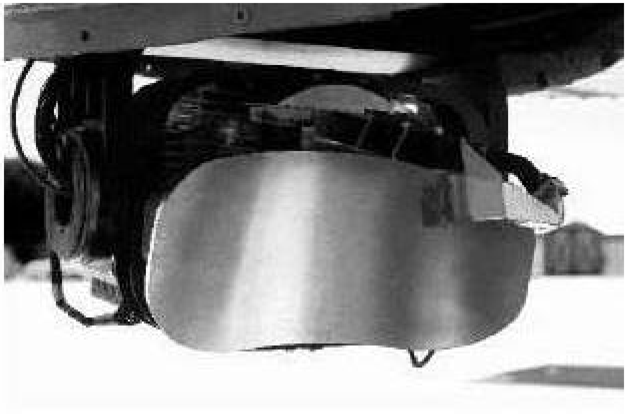


Image Courtesy of Sandia National Laboratories

LYNX Spotlight SAR Mode Parameters

- Resolution 0.1 m to 3.0
- Range 4 - 25 km
- 2 x (640 x 480) pixels
- View size 640 x 480 pixels
- Squint angle +/- 45 to 135 deg
  - 0.15 m resolution & coarser

LYNX Stripmap SAR Mode Parameters

- Resolution 0.3 m to 3.0
- Range 7 - 30 km
- Ground Swath
  - 2600 pixels
- View size 934 m
  - +/- (45 to 135 deg)
- Squint angle +/- (45 to 135 deg
  - At 0.3 m resolution; 45 deg depression

Courtesy of Sandia National Laboratories – see Reference 9

Sandia Lynx Image

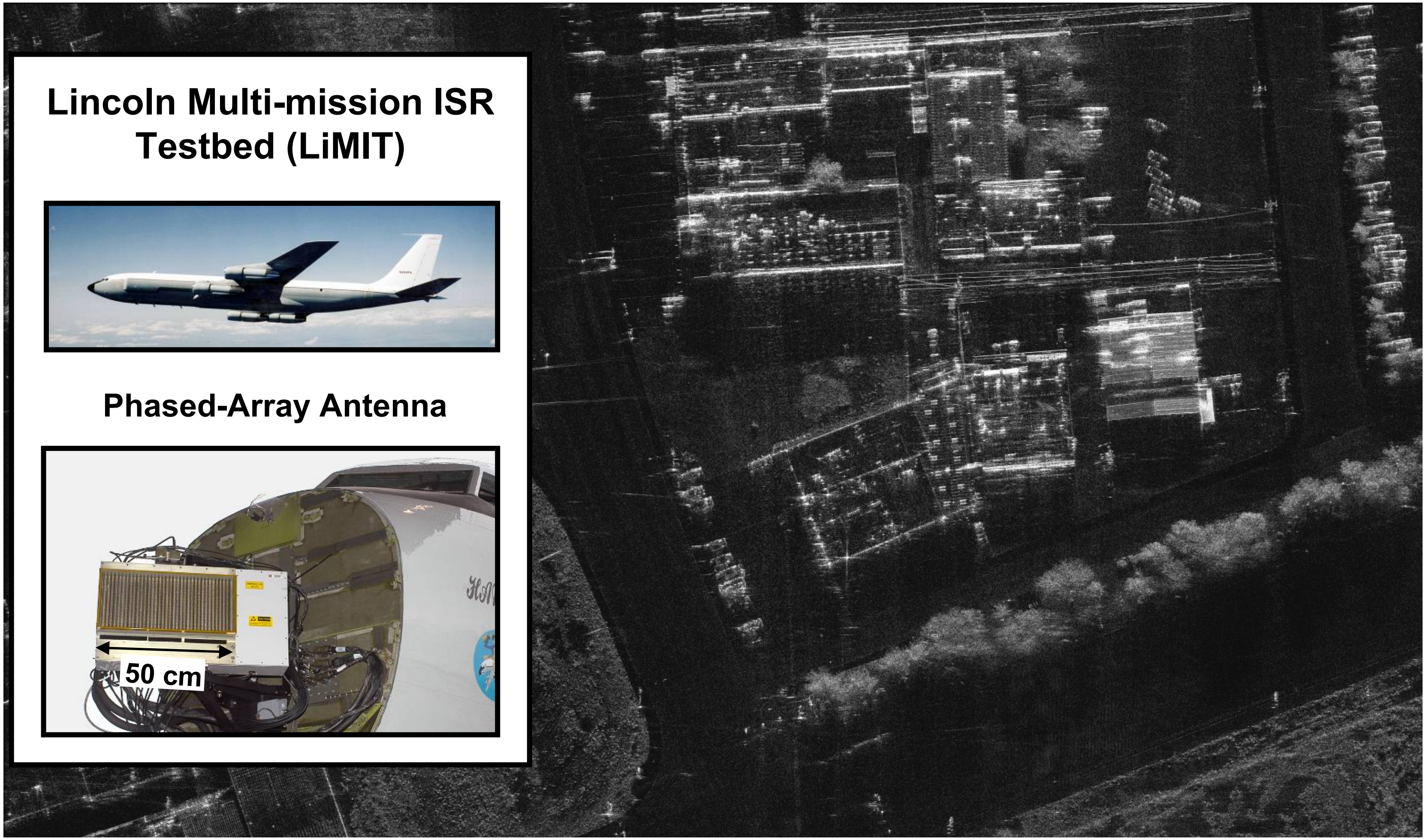
Courtesy
of
Sandia National Laboratories

Belen railroad bridge over Rio Grande river (1 ft resolution in spotlight mode)
see Reference 9

LiMIT Ultra-Wideband Frame Mode
2.5 in × 2.5 in Resolution (BW=3.0 GHz)

Sierra Vista, AZ, August 18, 2005

160 m Range cutout (400 m swath)



260 m Cross Range cutout (2 km swath)

Courtesy of MIT Lincoln Laboratory
Used with Permission

LiMIT Ultra-Wideband Frame Mode
2.5 in × 2.5 in Resolution (BW=3.0 GHz)

Sierra Vista, AZ, August 18, 2005

160 m Range cutout (400 m swath)

260 m Cross Range cutout (2 km swath)

Courtesy of MIT Lincoln Laboratory
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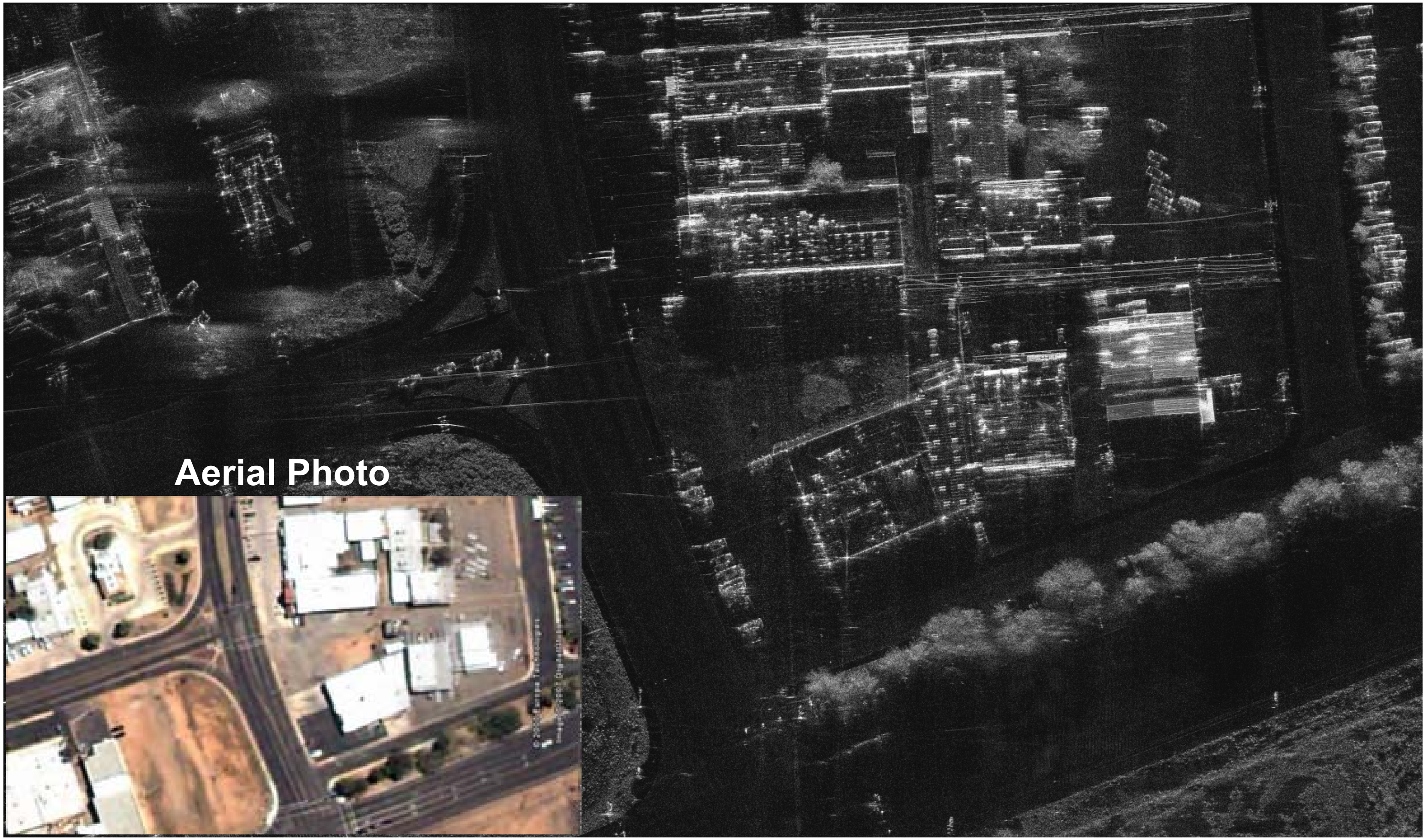
LiMIT Ultra-Wideband Frame Mode
2.5 in × 2.5 in Resolution (BW=3.0 GHz)

Sierra Vista, AZ, August 18, 2005

160 m Range cutout (400 m swath)



260 m Cross Range cutout (2 km swath)

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List of Space Probe SAR Systems

Mission	Country	Planet	Year	SAR
Venera 15/16	Russia	Venus	1983-1984	Wavelength = 8 cm
Magellan	USA	Venus	1990-1994	Wavelength=12.6 cm, 125m x 75m pixels
Cassini	USA	Titan	2004	Resolution (0.35 – 1.7 km)
Chandrayaan 1	India	Moon	2008	Mini RF SAR 12 cm
Lunar Reconnaissance Orbiter (LRO)	USA	Moon	2008	Mini RF SAR 12 cm and 4 cm

Partial List of Earth Viewing SAR Satellites

Satellite with SAR	Country	Launch Date	Resolution (m)	Band	Polarization
Seasat	USA	1978	25	L	HH
SIR A:B	USA	1981; 84	40;~25	L	HH
SIR C	USA	1994; 94	~30	L&C: X	Various to Quad HH
ERS-1	ESA	1991	25	C	VV
J-ERS-1	Japan	1992	30	L	HH
RADARSAT-1	Canada	1995	8, 25, 50, 100	C	HH
ERS-2	ESA	1995	25	C	VV
ENVISAT	ESA	2002	10, 30, 150, 1000		HH or VV, dual
TerraSAR-X	Germany	2007	1, 3, 15	X	Various
RADARSAT-2	Canada	2007	1, 3, 25, 100	C	Various
COSMO	Italy	2007	1, 3, 25, 100	X	Various to Quad
TecSAT	Israel	2007	1-8	X	Multi-Polarimetric
SAR-Lupe	Germany	2007	0.12, +	X	Multimode
HJ-1-C	China	2007	1, +	S	Multimode
RISAT	India	2008	1-50	C	Various to

Seasat

First US Satellite with SAR Capability (1978)

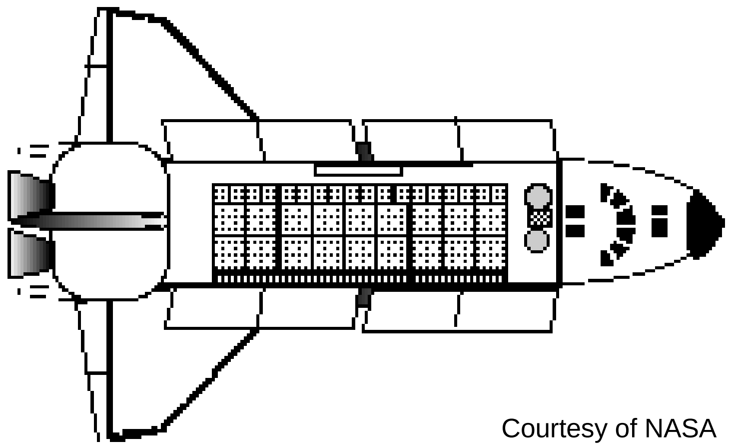
L-Band

Courtesy of NASA/JPL

Waves off Alaska's southern coastline near Yakutat (note the glaciers on land).

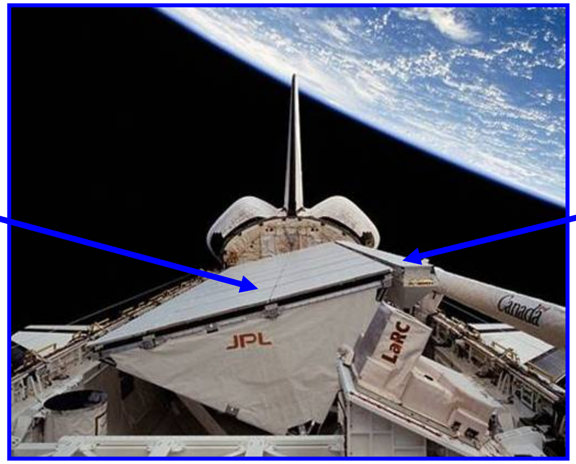
Courtesy of NASA/JPL

SIR (Shuttle Imaging Radar Series)



Courtesy of NASA

Shuttle Cargo Bay with SIR-C/X-SAR



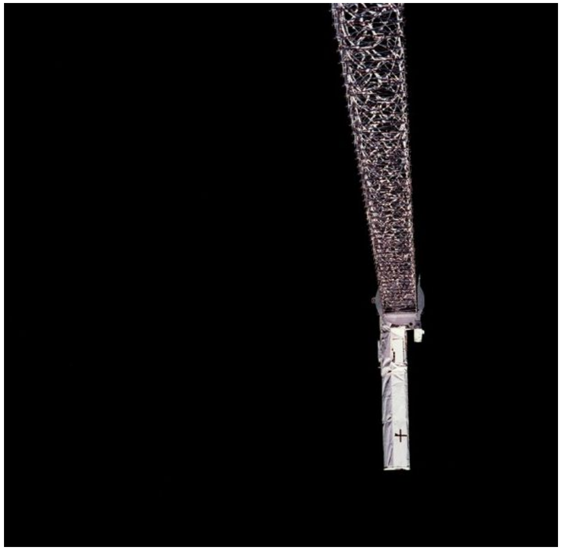
Courtesy of NASA

- The Shuttle Imaging Radar (SIR-C/X-SAR) is part of NASA's Mission to Planet Earth.
- The SAR radars illuminate Earth allowing detailed observations at any time, regardless of weather or sunlight conditions.
- SIR-C/X-SAR uses three microwave wavelengths: L-band (24 cm), C-band (6 cm) and X-band (3 cm).
- The multi-frequency data will be used by the international scientific community to better understand the global environment and how it is changing.
- SIR-C was developed by NASA's Jet Propulsion Laboratory. X-SAR was developed by the Dornier and Alenia Spazio companies for the German space agency, Deutsche Agentur fuer Raumfahrtangelegenheiten (DARA), and the Italian space agency, Agenzia Spaziale Italiana (ASI)

The Shuttle Radar Topography Mission (SRTM)

Artist's View of Shuttle with Extended Boom & 2nd set of Antennas

Photograph of 60 ft Boom & 2nd set of Antennas

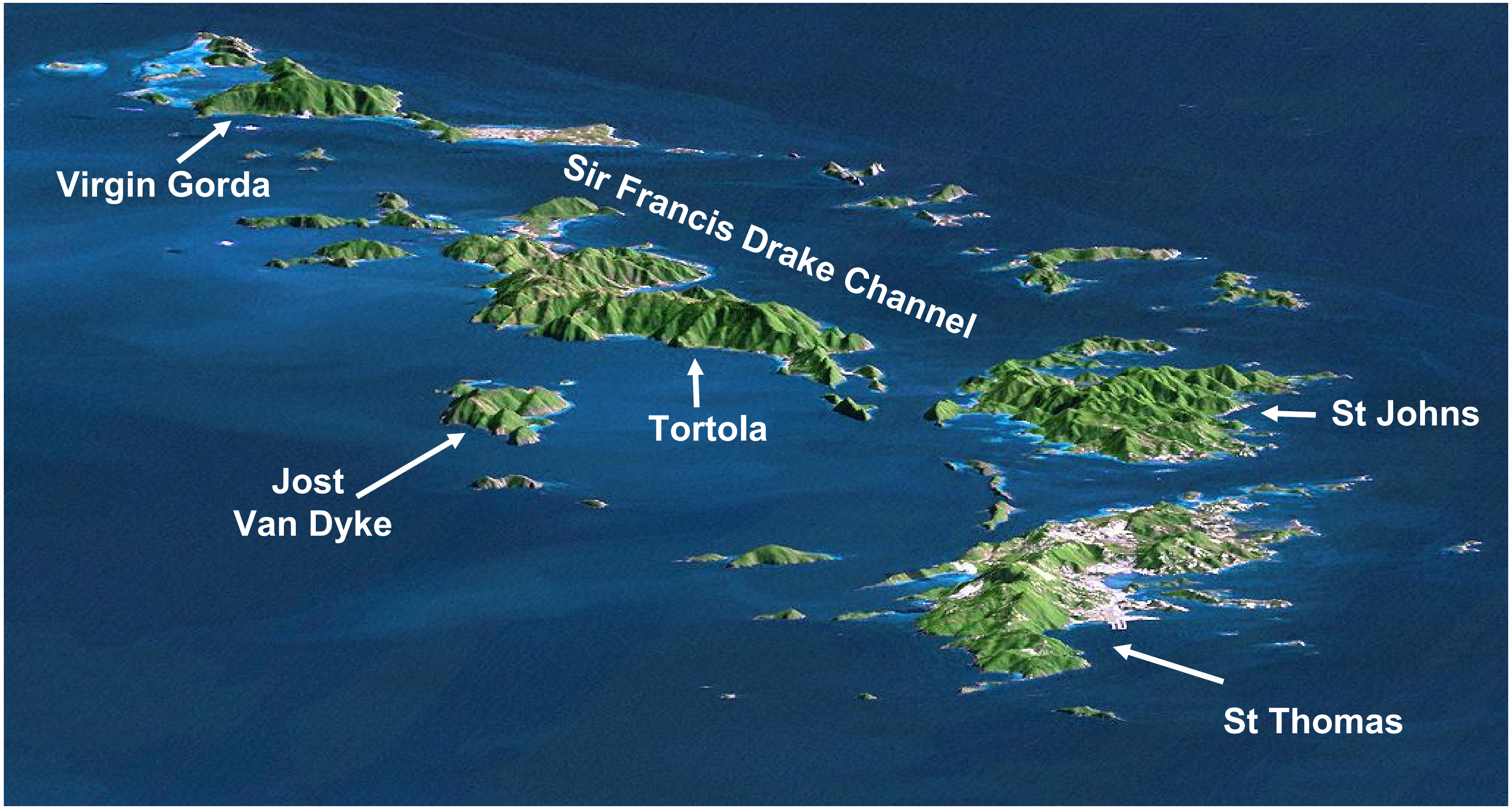


Images Courtesy of NASA

- **The Shuttle Imaging Radar (SIR-C/X-SAR) synthetic aperture radar yields two-dimensional images that are resolved in range and in azimuth The radars operate at C- and X-Band.**
- **For the SRTM mission the L-Band radar was not used; and a 60 ft. boom was extended out from the main SIR radars, so that two different ground reflections at C and X-Band could be received, from the transmitted pulses, on a single pass of the shuttle.**
- **The range difference between two radar images is measured. Each radar antenna images the surface from a slightly different vantage point.**
- **The phase difference between each image point will then simply be the path difference between the two measurements of the point; the height of a given point may be calculated**

SRTM SAR Image of Virgin Islands

East-looking view of the U.S. and British Virgin Islands, in the NE Caribbean Sea.

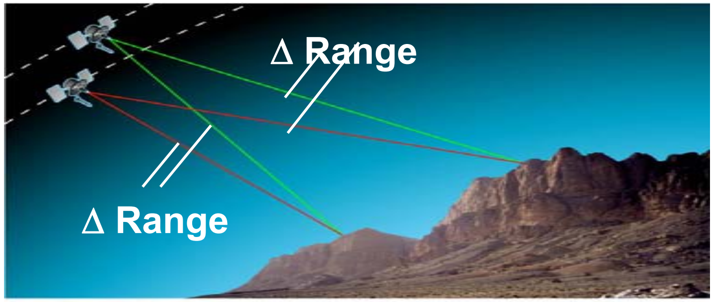


Courtesy of
NASA
JPL
NIMA

For this view, a Landsat image was draped over elevation data from the SRTM Mission

Coral reefs fringe the islands in many locations and appear as very light shades of blue.
Tropical vegetation appears green, and developed areas appear in shades of brown & white.

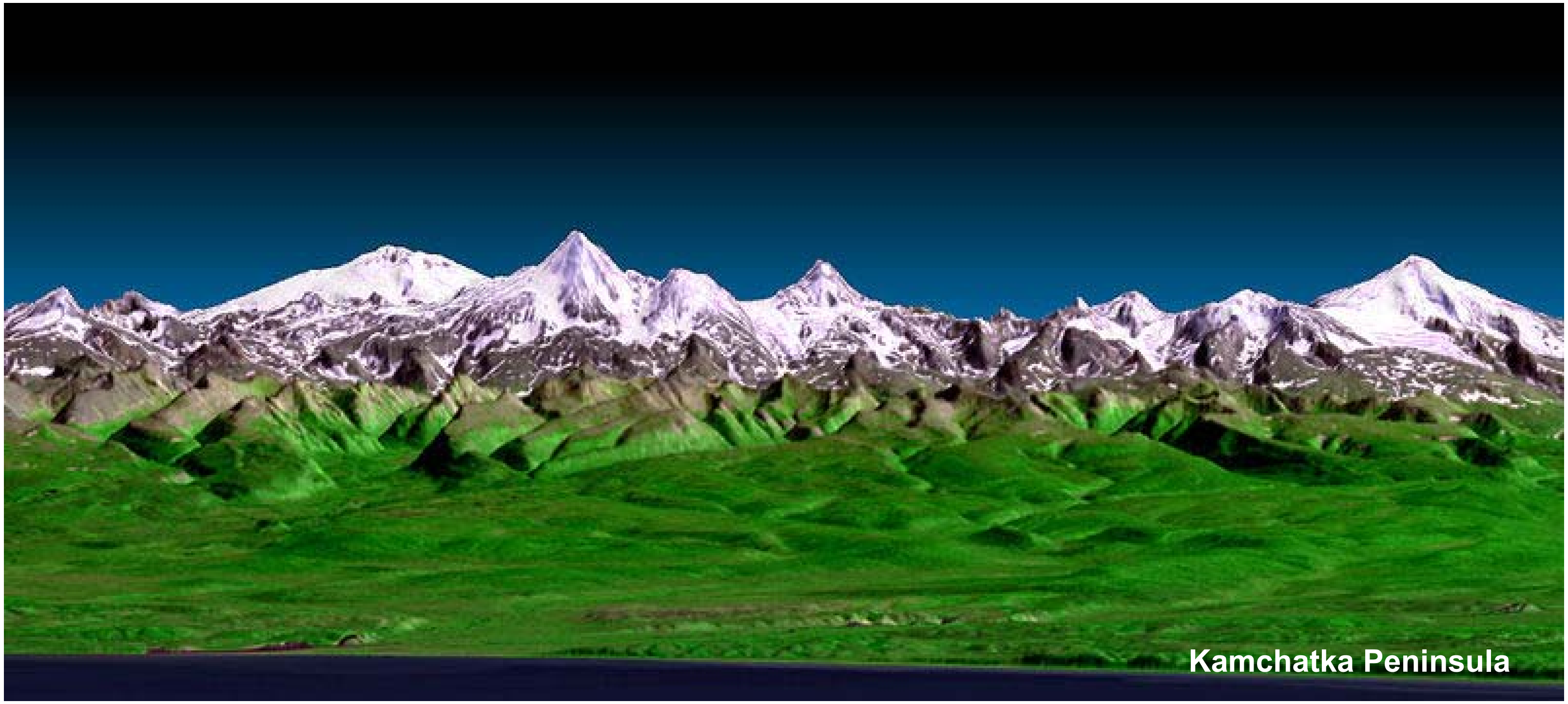
SRTM Interferometric SAR Image



Height ∝ ΔRange

Coherent registration of images provides ΔRange via phase offset

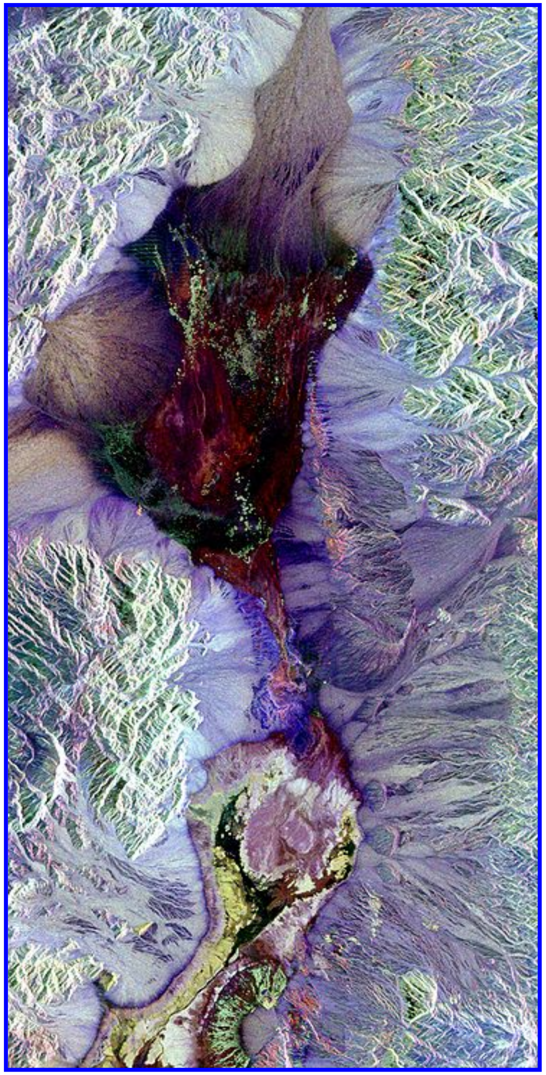
Courtesy of NASA



Optical imagery draped over IFSAR-generated Digital Elevation Model (from SRTM)

SIR (C/X) Band SAR Image

SAR Image of Death Valley, CA



Courtesy of NASA

This SAR radar image shows the area of Death Valley, California and the different surface types in the area. Radar is sensitive to surface roughness with rough areas showing up brighter than smooth areas, which appear dark.

This is seen in the contrast between the bright mountains that surround the dark, smooth basins and valleys of Death Valley.

Elevations in the valley range from 70 meters below sea level, the lowest in the United States, to more than 3,300 meters above sea level. Scientists are using these radar data to help answer a number of different questions about Earth's geology.

Colors in the image represent different radar channels as follows: red =L-Band horizontally polarized transmitted, horizontally polarized received (LHH); green =L-Band horizontally transmitted, vertically received (LHV) and blue = C-Band (HV).

SIR (C/X) Band SAR Image

SAR Image of Active Volcano near Kyushu, Japan

The active volcano Sakura-Jima on the island of Kyushu, Japan is shown in the center of this radar image.

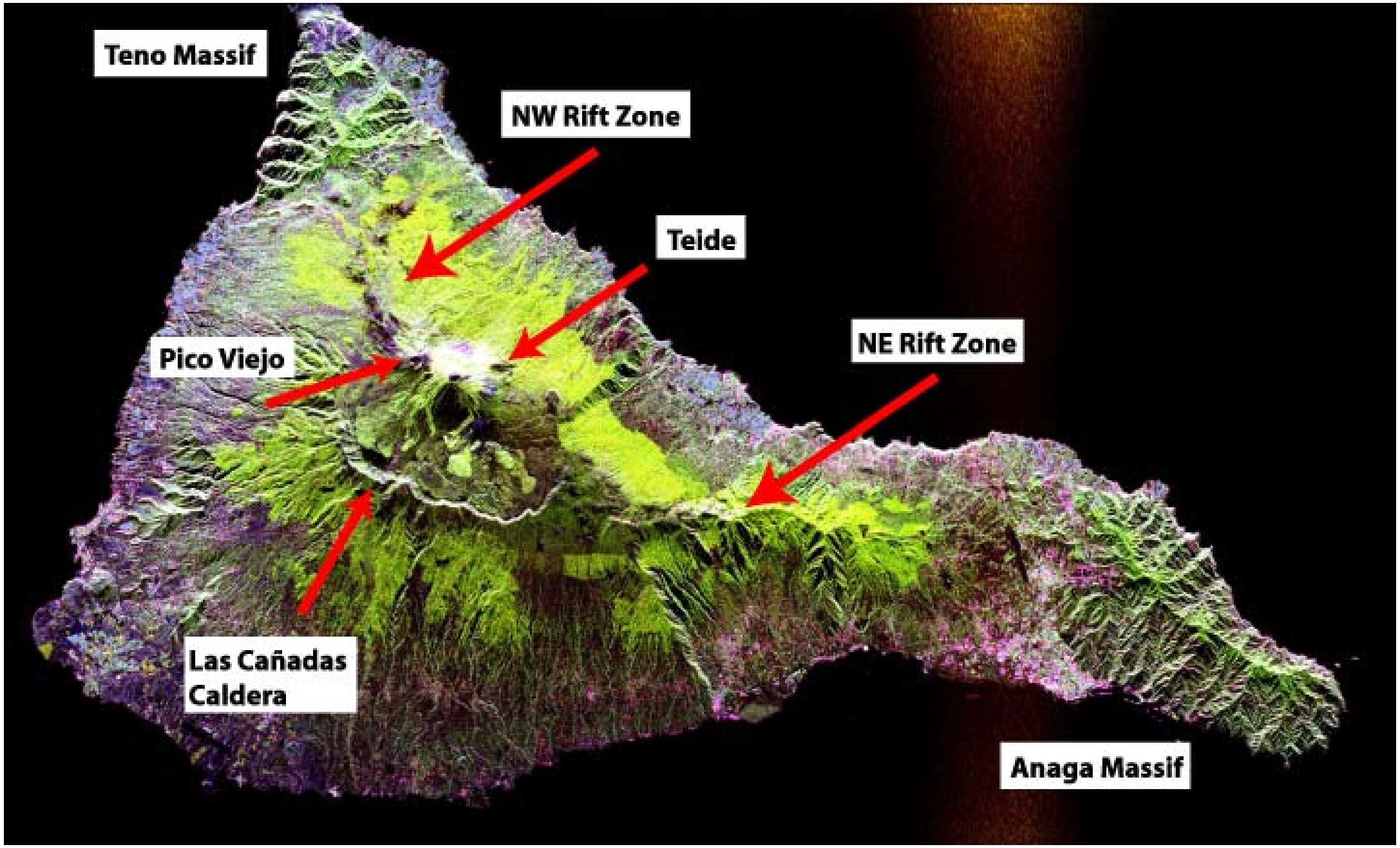
The volcano occupies the peninsula in the center of Kagoshima Bay, which was formed by the explosion and collapse of an ancient predecessor of today's volcano.

The volcano has been in near continuous eruption since 1955.

Courtesy of NASA/JPL-Caltech

SIR (C/X) Band SAR Image

Shuttle Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) onboard the space shuttle Endeavour



SAR radar image shows the Teide volcano on the island of Tenerife in the Canary Islands

(Colors are assigned to different frequencies and polarizations of the radar system)

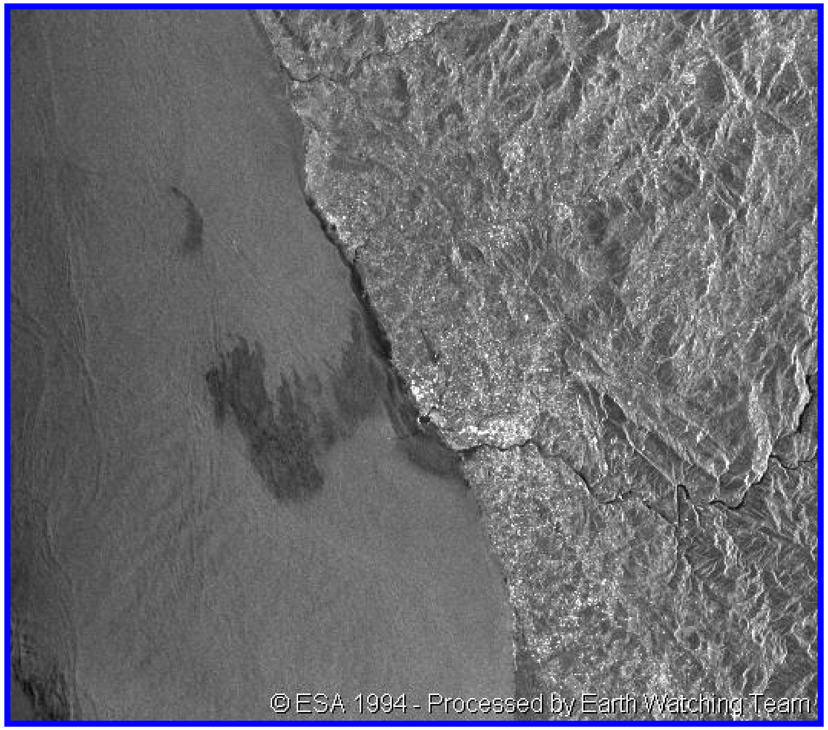
Courtesy of NASA

ERS-1 and ERS-2

Full Size Mode of ERS-2
With C-Band SAR

Courtesy of poppy

ERS-1 SAR Image
Of Oil Spill off the coast of Portugal



Courtesy of ESA

ERS = (European Remote-Sensing Satellite)

ERS-1 Images

Ellesmere Island, Canada

Courtesy of ESA

Malaspina Glacier in Alaska

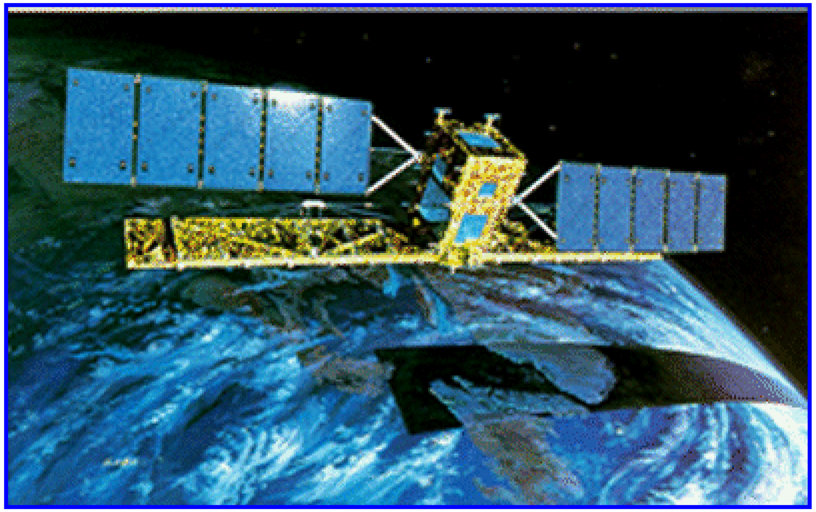
Courtesy of ESA

Alfred Ernest Ice Shelf on Ellesmere Island. March 1, 1992. The ice shelf is the dark gray area between mountains. Sea ice is seen at the top of the image next to the shelf, which is a glacier that extends beyond land.

The Malaspina Glacier in Alaska was captured by the ERS-1 SAR on July 18, 1992.The glacier has a dark core surrounded by radiating bright lines. The open ocean is at the top of the image. A ship (a dot) and its dark wake can be barely seen also in the upper right

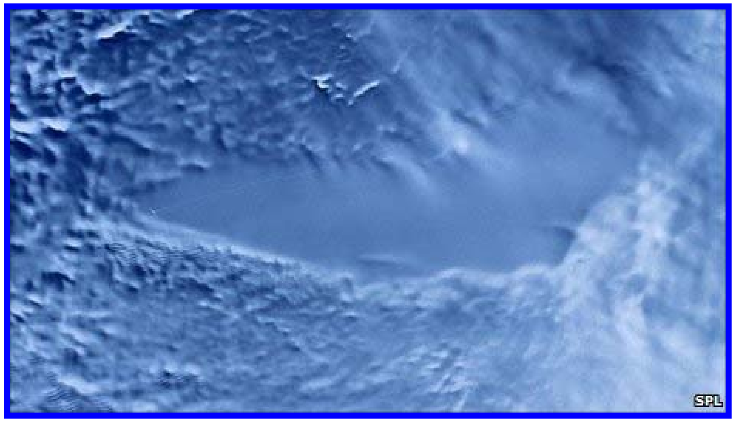
RADARSAT-1

Advanced Earth Observation Satellite developed by the Canadian Space Agency (CSA)



Courtesy of NASA

RADARSAT SAR image of Lake Vostok, Antartica.

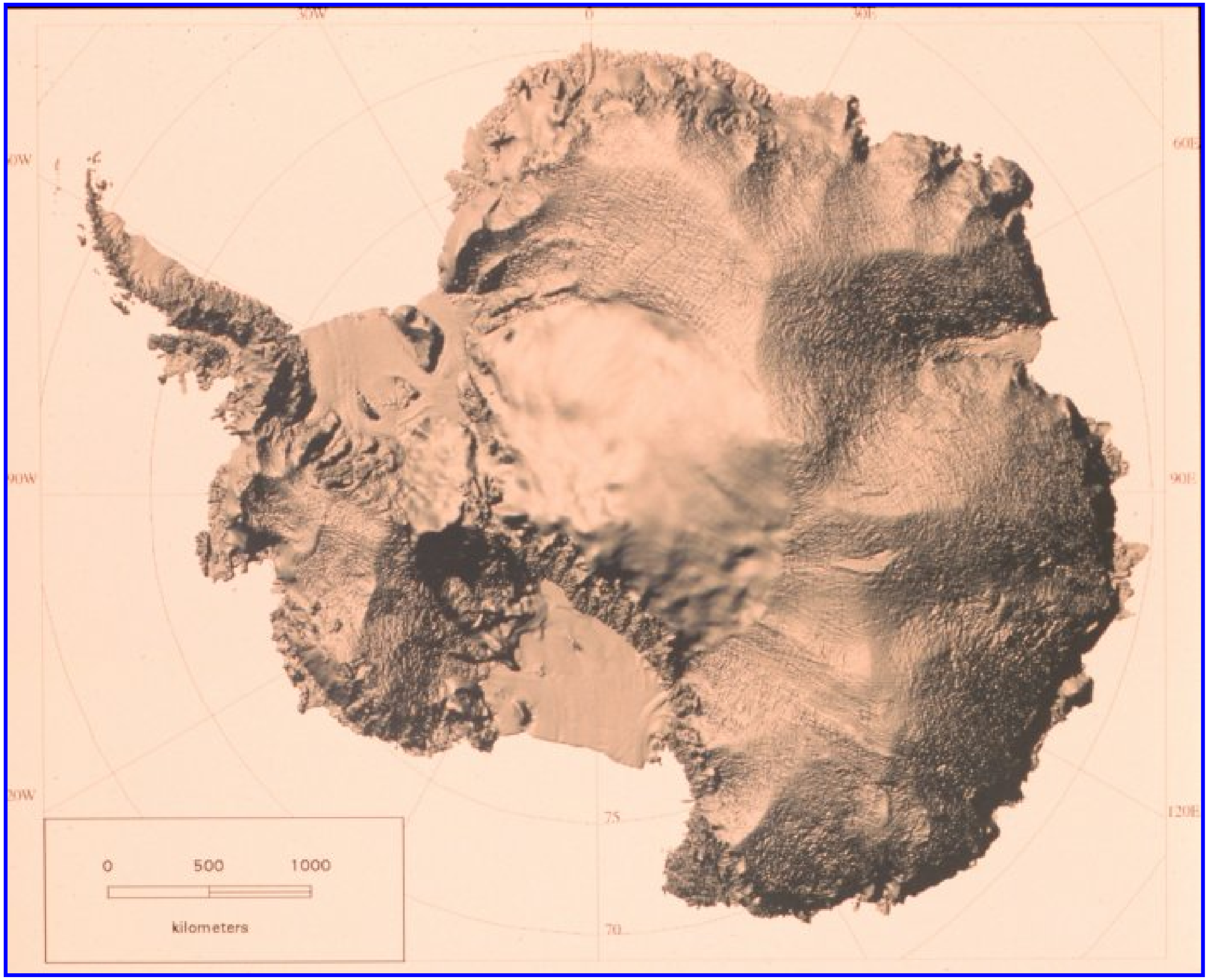


Courtesy of NASA

RADARSAT Missions

- **Sea-ice monitoring**
  - **Daily ice charts**
- **Extensive cartography; flood mapping and disaster monitoring in general**
- **Glacier monitoring**
- **Forest cover mapping**
- **Oil spill detection**
- **Assessment of the likelihood of mineral, oil and gas deposits**
- **Urban planning**
- **Crop production forecasts;**
- **Coastal surveillance (erosion)**
- **Surface deformation detection (seismology, volcanology).**

RADARSAT-1 Image of Antarctica



Courtesy of NOAA

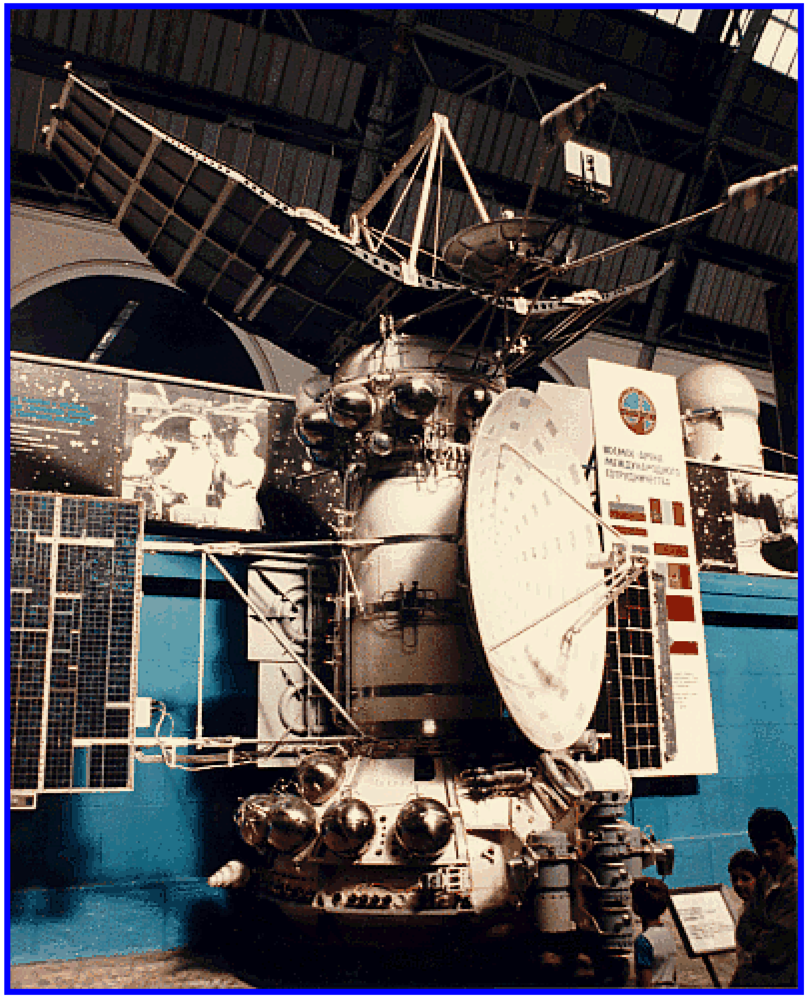
Shaded relief map of Antarctica developed from RADARSAT Synthetic Aperture Radar data
RADARSAT is a Canadian remote sensing satellite

List of Space Probe SAR Systems

Mission	Country	Planet	Year	SAR
Venera 15/16	Russia	Venus	1983-1984	Wavelength = 8 cm
Magellan	USA	Venus	1990-1994	Wavelength=12.6 cm, 125m x 75m pixels
Cassini	USA	Titan	2004	Resolution (0.35 – 1.7 km)
Chandrayaan 1	India	Moon	2008	Mini RF SAR 12 cm
Lunar Reconnaissance Orbiter (LRO)	USA	Moon	2008	Mini RF SAR 12 cm and 4 cm

Venera

Photograph of Venera 15 / 16



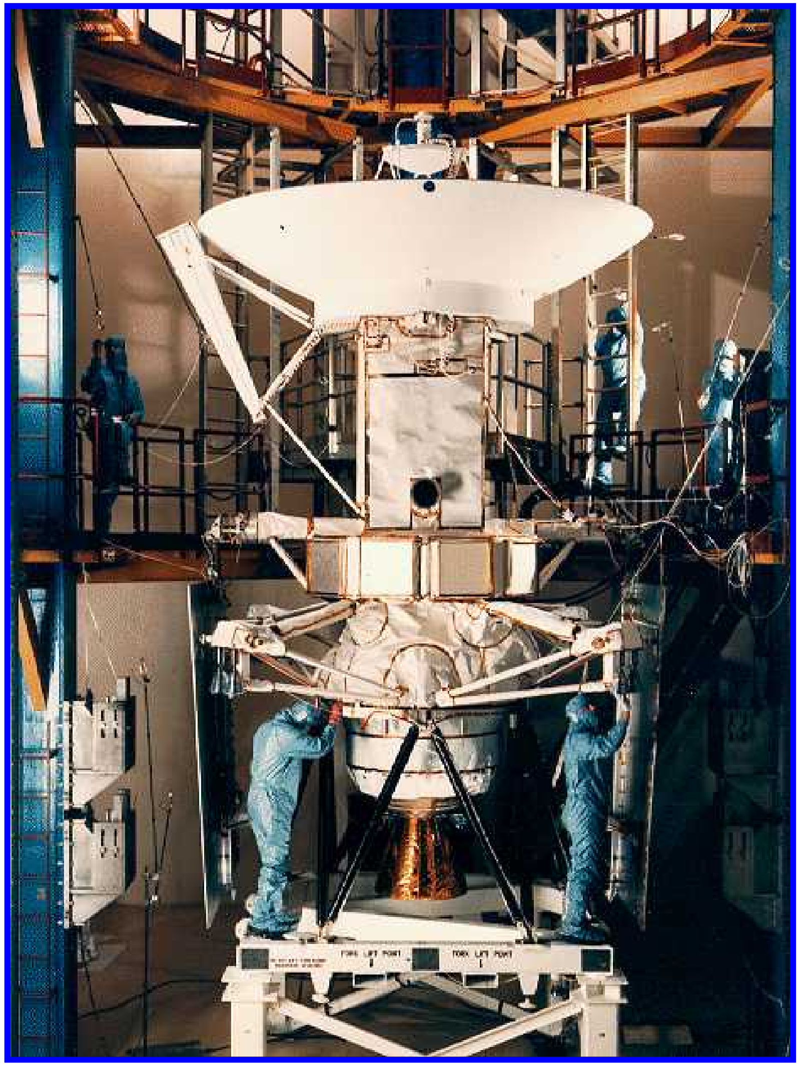
Courtesy of NASA

- **Venera 15 and 16 were launched from Russia in June 1983 and both arrived in Oct 1983**
- **Both contained SAR systems to image the Northern hemisphere down to 30 degrees**
- **SAR Resolution 1-2 km**
- **Both missions were successful although no images are able to be presented on this site**
- **Images may be seen at the website below**

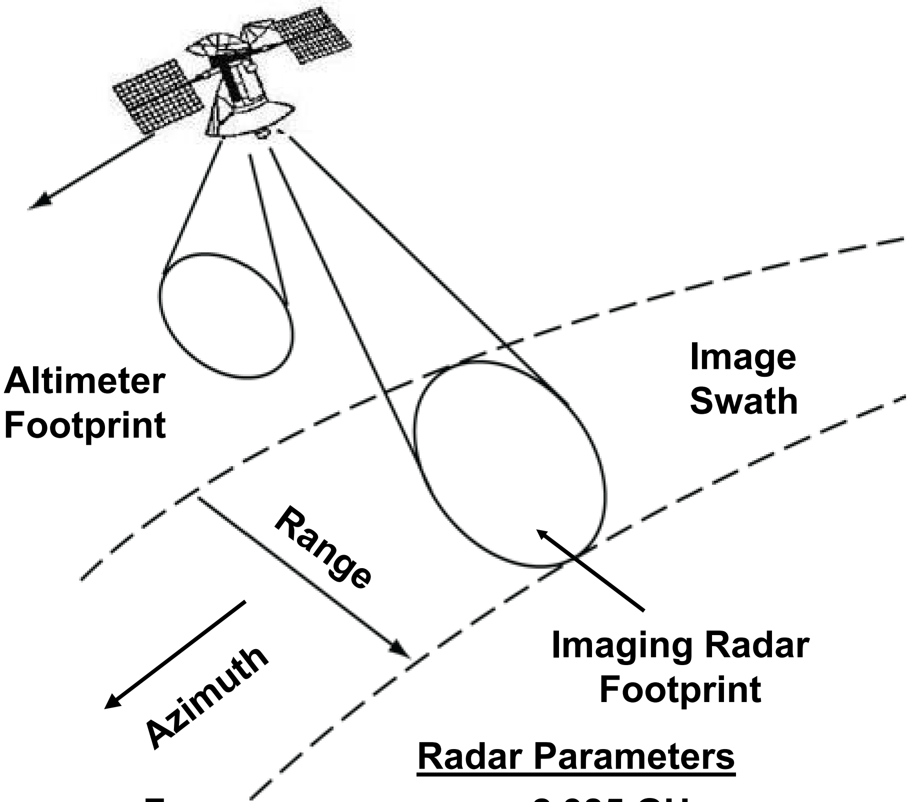
http://www.mentallandscape.com/C_CatalogVenus.htm

Synthetic Aperture Radar on Magellan Mission to Venus

Spacecraft before Launch



Courtesy of NASA



Radar Parameters

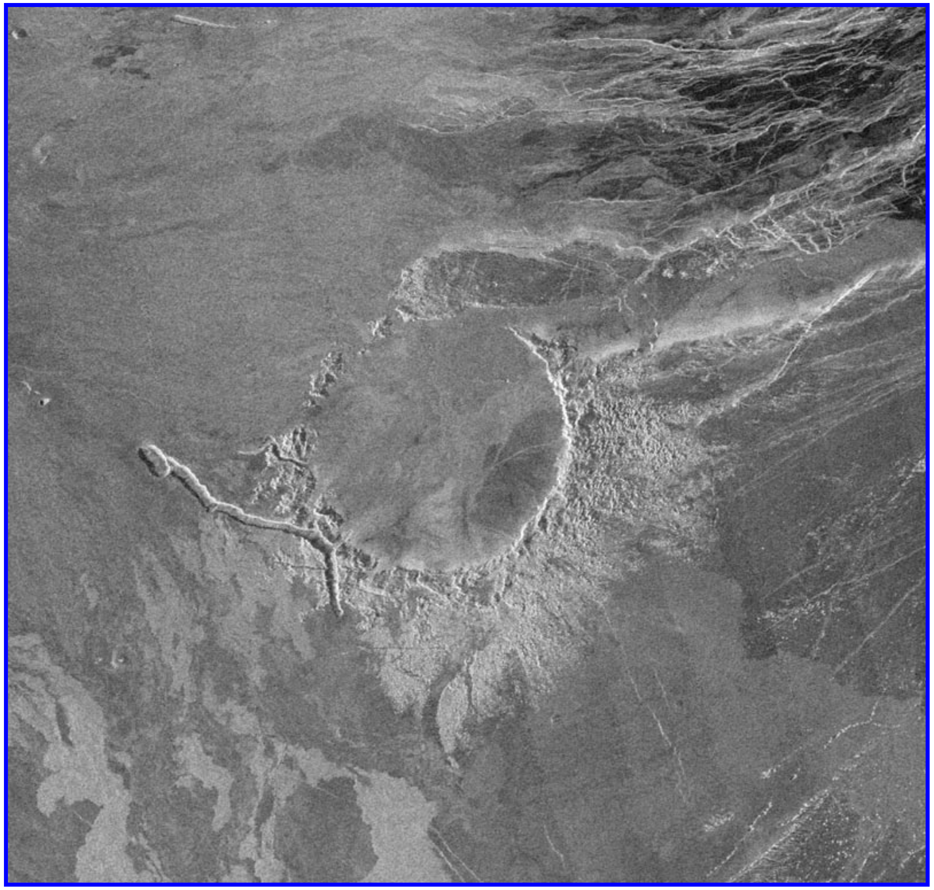
Frequency	2.385 GHz
Peak Power	325 watts
Antenna Diameter	3.7 m
Pulse Length	26.5 microseconds
PRF	4400 - 5800 Hz
Resolution	
Range	~150 m
Cross Range	~150 m

SAR Images of Venus with Magellan

SAR Image of Venus

Courtesy of NASA

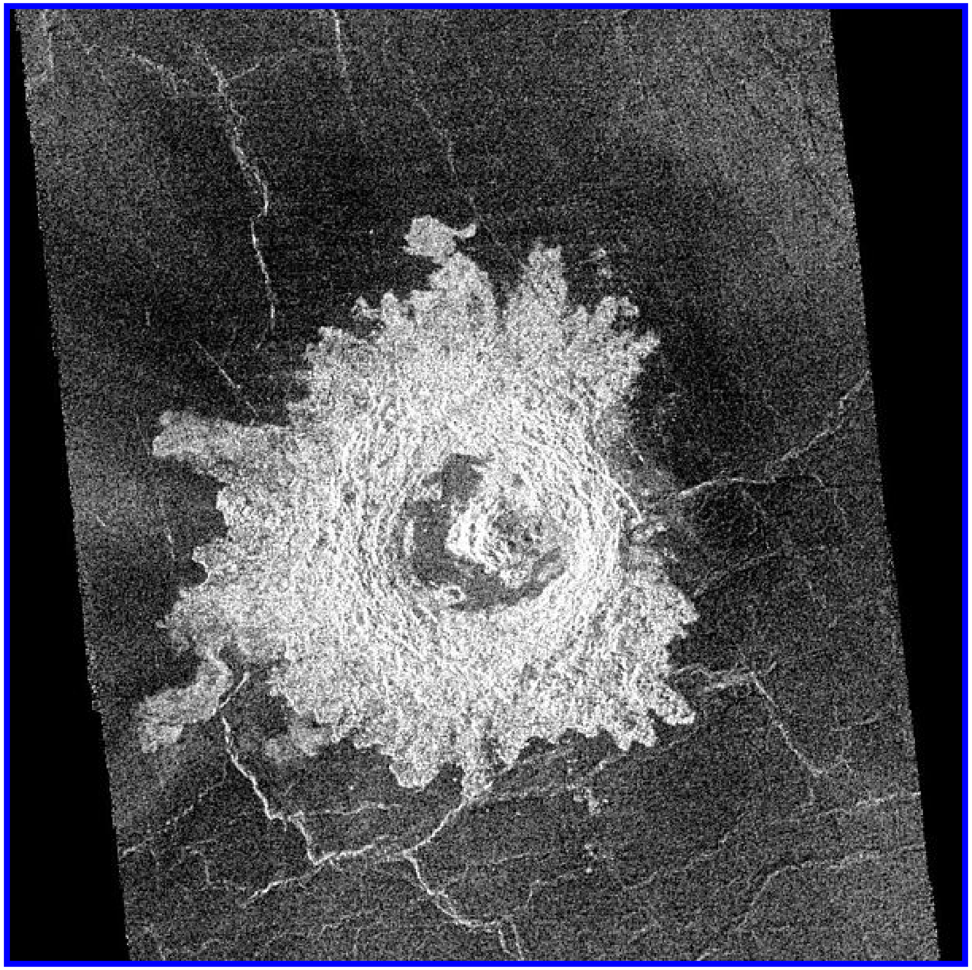
SAR Image of Alcott Crater on Venus



Courtesy of NASA

Magelllan SAR Image of Buck Crater

Buck Crater



Courtesy of NASA

This complex crater in the Navka region of Venus was mapped by Magellan.

The crater has a diameter of 22 km.

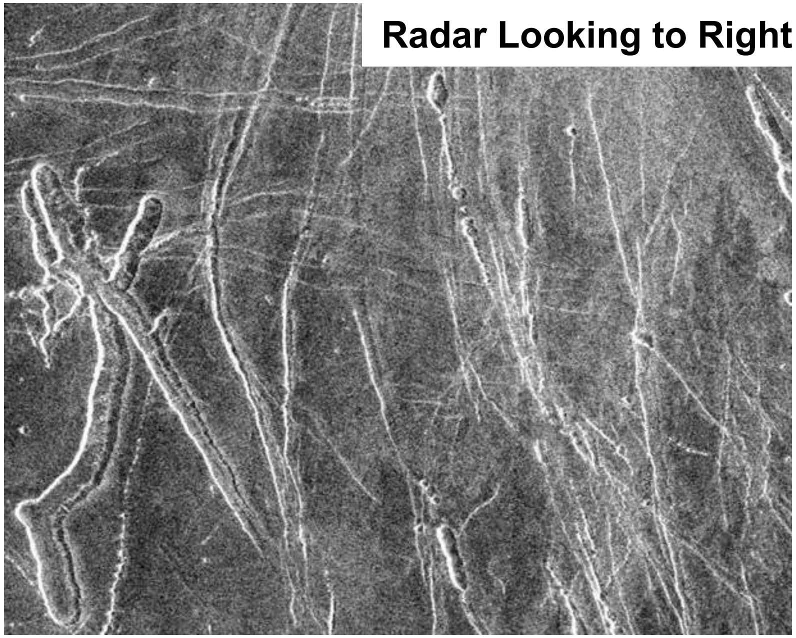
It has the terraced walls, flat radar-dark floor, and central peak that are characteristic of craters classified as 'complex.'

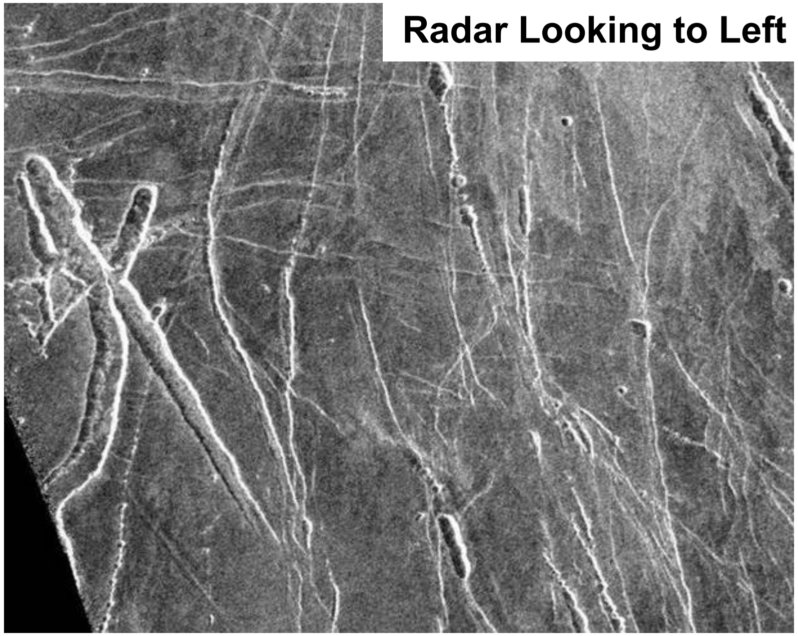
The central peak on its floor is unusually large.

Flow-like deposits extend beyond the limits of the coarser rim deposits on its west and southwest.

Buck, the proposed name for this crater honors Pearl S. Buck, American author (1892-1973).

Magellan SAR Images from Left and Right Aspects



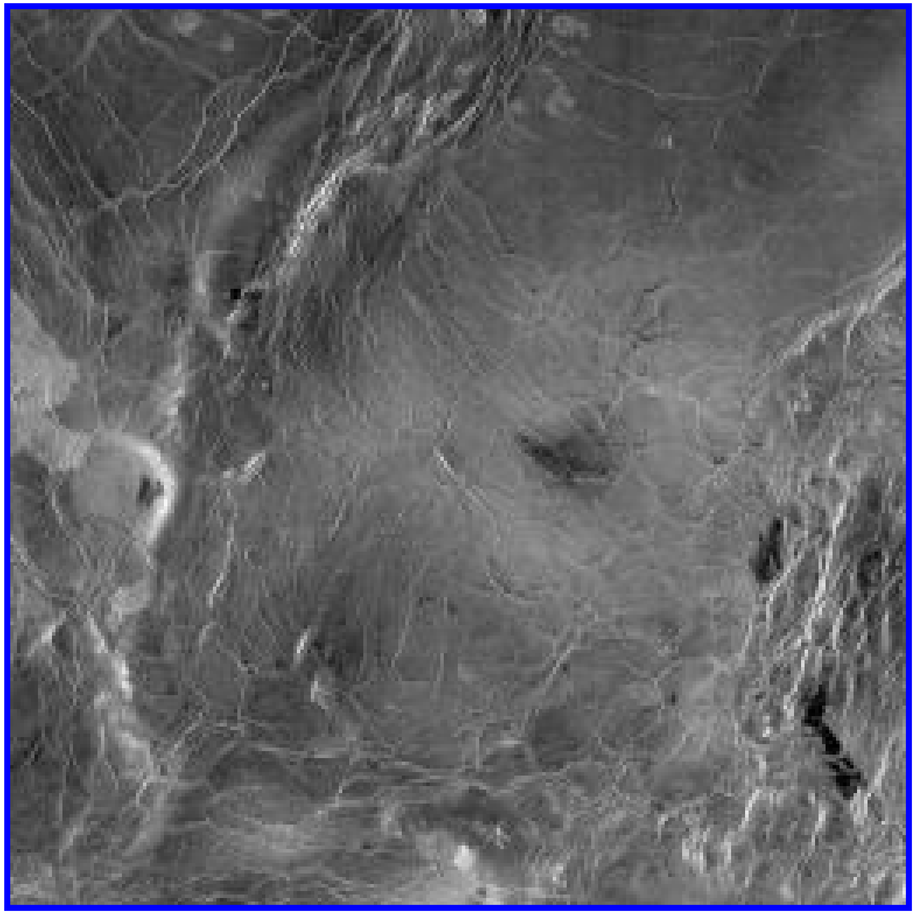


Both Images Courtesy of NASA

- **These two radar images are in the eastern Lavinia Region of Venus.**
  - **110 kilometers in length**
  - **130 kilometers in width**
  - **Full resolution mosaics of 14 orbits.**
- **Since the radar was looking from the right in the left image and from the right in the left image, the bright and dark sides for the trough are reversed between the two images.**
- **It is very useful to obtain right-looking and left-looking images of the same area because features may not be visible from the opposite look direction.**
- **Resolution of the Magellan data is about 120 meters (400 feet).**

SAR Image of 600 Kilometer Segment of Longest Channel on Venus

SAR Image of Longest Channel on Venus



Courtesy of NASA

Resolution of the Magellan data is ~120 meters.

This compressed resolution radar mosaic from Magellan shows a 600 kilometers (360 mile segment of the longest channel discovered on Venus to date. It is approximately 1.8 kilometers wide.

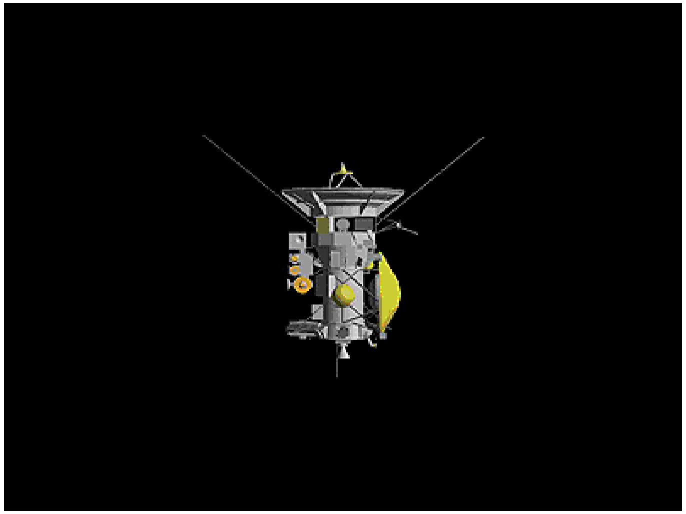
At 7,000 kilometers long, it is much longer than the Nile River, thus making it the longest known channel in the solar system.

The channel was initially discovered by the Soviet Venera 15-16 orbiters.

In some places they appear to have been formed by lava which may have melted or thermally eroded a path over the plains' surface. Most are 1 to 3 kilometers (0.6 to 2 miles) wide.

Cassini Space Probe to Saturn

Animated Video of Cassini Huygens Space Probe



Courtesy of NASA

Cassini Probe (During Pre-Flight Testing)

Courtesy of NASA

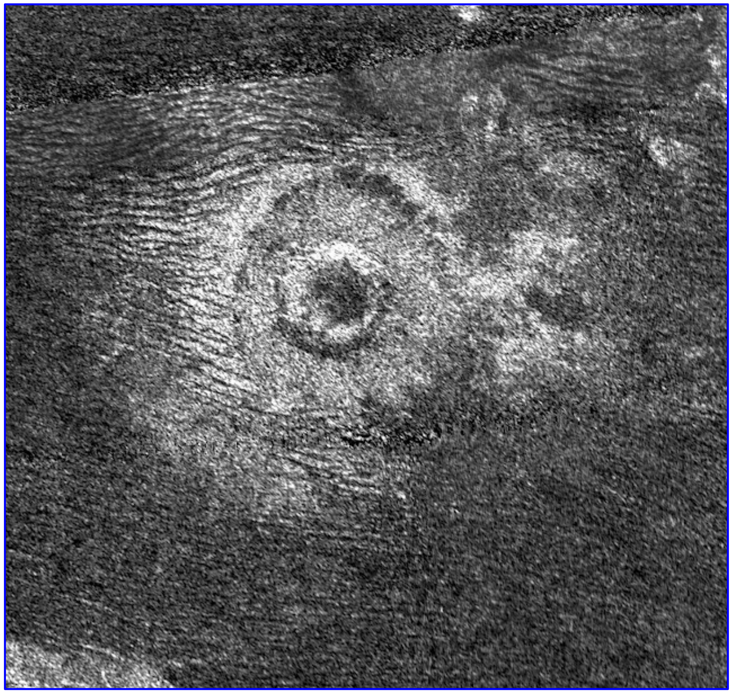
***Cassini–Huygens* is a flagship-class NASA-ESA-ASI spacecraft sent to the Saturn system.**

Launched in 1997, an atmospheric probe / lander for the moon Titan called *Huygens*, which surveyed and then landed on Titan in 2005.

***Cassini*'s instrumentation consists of a large suite of sensors, including a synthetic aperture radar for mapping the surface of Titan,**

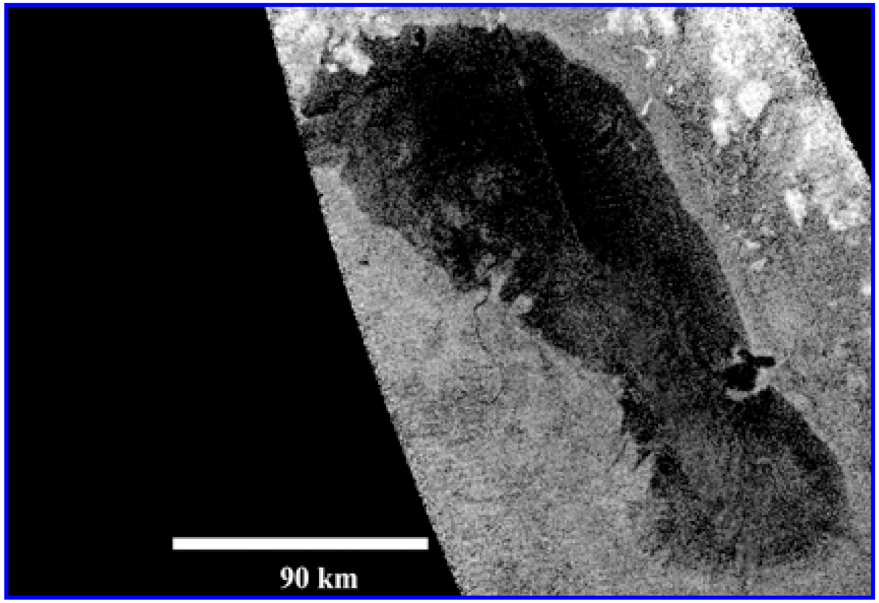
Cassini SAR Images of Titan, Saturn's Largest Moon

SAR Image of New Volcano Found on Titan



SAR Image of Largest Lake of Titan

This image of Ontario Lacus, the largest lake on the southern hemisphere of Saturn's moon Titan, was obtained by NASA's Cassini spacecraft



Both Images - Courtesy of NASA/JPL-Caltech

- **Impact craters are rare on Titan, so it was exciting when Cassini's Titan SAR Radar Mapper imaged (June 2011) a rare 8th impact crater is about 25 miles in diameter.**
- **The new volcano is surrounded by a continuous blanket of ejecta (material thrown out from the crater) that extends roughly 10 to 12 miles.**
- **Saturn's other moons have many thousands of craters, while Titan has very few, because it's dense atmosphere burns up the smaller impacting bodies before they can reach the surface.**
- **The SAR image has a resolution of about 350 meters per pixel.**

Chandrayaan 1

- Chandrayaan-1 was India's first unmanned lunar probe. It was launched in October 2008, and operated until August 2009

- Mini-SAR is the active SAR system to search for lunar polar ice. The instrument transmitted right polarized radiation with a frequency of 2.5 GHz and monitored scattered left and right polarized radiation.

- The Fresnel reflectivity and the circular polarization ratio (CPR) are the key parameters deduced from these measurements. Ice shows the Coherent Backscatter Opposition Effect, which results in an enhancement of reflections and CPR, so that water content of the Moon's polar regions can be estimated.

- The experiments to find lunar polar ice have not been successful.

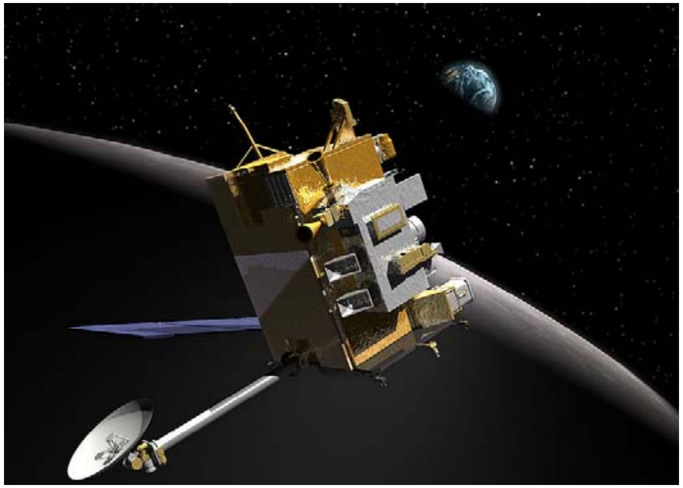
Lunar Reconnaissance Orbiter (LRO)

- The Miniature Radio-Frequency instrument (Mini-RF) is a synthetic aperture radar (SAR) instrument on the Lunar Reconnaissance Orbiter (LRO), which is currently in orbit around the Moon. It has a resolution of 30 m/pixel and two wavelength bands, a primary band at 12.6 cm and a secondary band at 4.2 cm

- On 21 August 2009, the spacecraft, along with the Chandrayaan-1 orbiter, attempted to perform a bistatic radar experiment to detect the presence of water ice on the lunar surface. The attempt was a failure; it turned out the Chandrayaan-1 radar was not pointed at the Moon during the experiment.

- In January, 2011, after completion of Mini-RF's primary mission objectives, NASA announced that Mini-RF had suffered a critical failure and was no longer collecting useful scientific data.

Lunar Reconnaissance Orbiter



Courtesy of NASA

Summary

- **Synthetic Aperture Radar has been and is an incredibly useful technology for**
  - **Military endeavors**
  - **Environmental monitoring**

- **A SAR achieves cross range resolution by utilizing the change in the platform position with respect to the target**
  - **Resolution improves with collection time**
  - **With focused SAR processing resolution is not a function of range**
    - **Unlike typical optical approaches**

- **Image formation and exploitation requires**
  - **Intensive, coherent processing**
  - **Precise motion measurement and compensation**
  - **Automation or more analysts**
    - **Volume of data exceeds capacity of analysts**

- 1. An aircraft is flying at a velocity of 300 knots and an altitude of 3 km. It is equipped with an X-band (frequency=9200 MHz, and 1 m dish antenna). The SAR antenna is pointing sideways (perpendicular to the line of flight) with its boresight at a depression angle of 37.5 degrees to the ground.

  - What is the swarth widthof the SAR footproint on the ground?
  - What is the antenna footprint on the ground (cross track and along track)?
  - What is the distance from the center of the SAR beam's footprint on the ground to the aircraft ground track?
  - What is the cross range and range resolution for the radar when not operated in a SAR mode?

Homework Problems (2 of 2)

- **1. Continued : An aircraft is flying at a velocity of 300 knots and an altitude of 3 km. It is equipped with an X-band (frequency=9200 MHz, and 1 m dish antenna). The SAR antenna is pointing sideways (perpendicular to the line of flight) with its boresight at a depression angle of 37.5 degrees to the ground.(same as previous page)**
  - **What are the minimum PRFs of the radar?**
  - **Choose a PRF within these limits and a reasonable integration time. What is the cross range and range resolution of the SAR when operated in a focused mode?**
  - **Assume a 200 m high SAR shadow is observed for an object located at the center of the swath. What is the height of the object?**

- **2. Derive the equation for the height of a SAR shadow for round earth?**

By "RMOD Radar Systems"

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Acknowledgements

- Dr Gerald Benitz, MIT Lincoln Laboratory
- Dr Eli Brookner, Raytheon Co.

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