Principles of Radar

an introductory view

Chris Allen

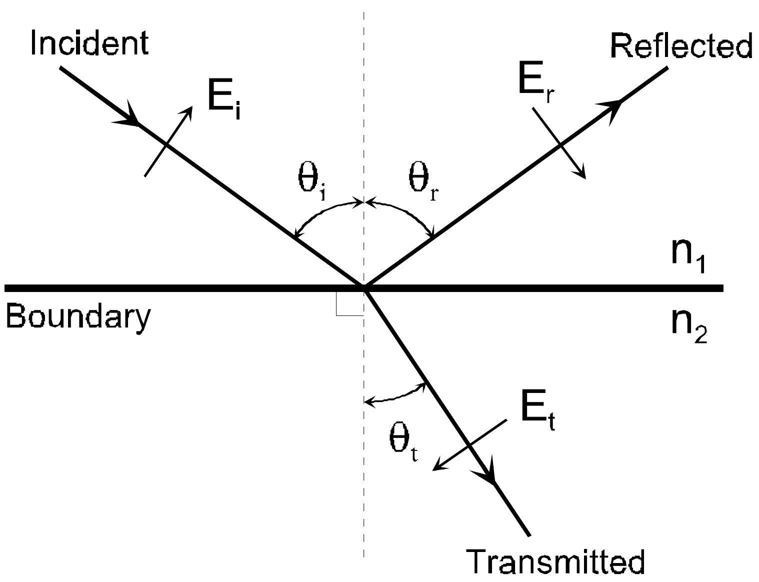
Basic concepts

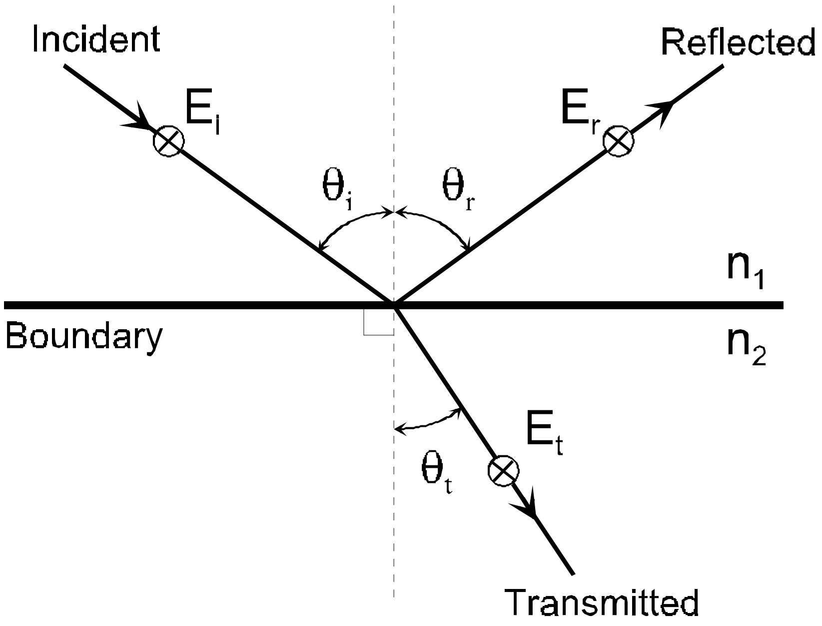
- EM signal transmission
- Signal reception
- Infer information about the 'target' by comparing received signal with transmitted signal

EM signals

- Frequency, wavelength, polarization, and speed of light
- signals propagate at speed of light,
  c = 3 × 10^8 m/s = 1 foot/ns [1 ns = 10^{-9} s]
  - speed of light is ~ 1,000,000 time faster than speed of sound in air

Reflection, refraction, attenuation, and scattering





Reflection, refraction, attenuation, and scattering

- Reflection and refraction depend on material's electrical and magnetic properties, geometry, surface characteristics
- Attenuation (signal strength reduction) caused by absorption (energy converted to heat) and scattering
- Scattering depends on material's electrical and magnetic properties and size of scatterer (relative to wavelength)
  (why the sky is blue)

Radar components

Timing and control

Waveform generator

Transmitter electronics

Transmit antenna

Receive antenna

Receive electronics

Data acquisition system

Digital signal processor

Ancillary sensors
  (e.g., GPS)

Data storage device

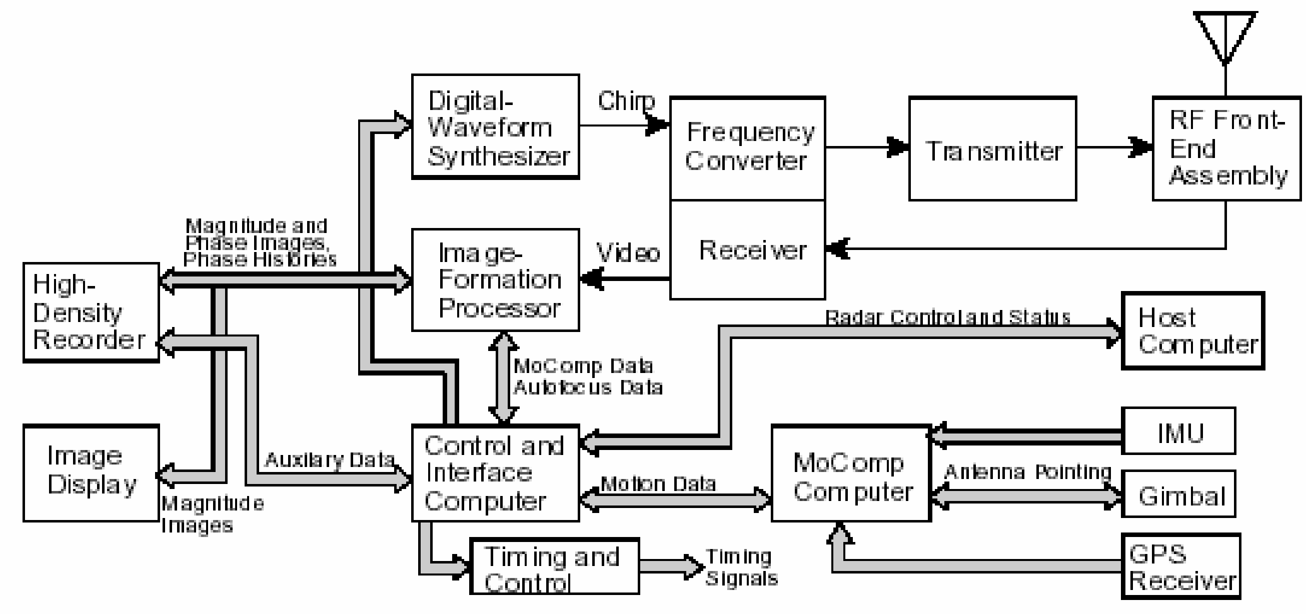


Figure 4. Simplified Block Diagram of the Twin-Otter SAR

Radar Range Equation

Received signal power (P_r) depends on:

- P_t: transmitted signal power
- G: antenna’s ability to focus power on target
- R: range to the target
- σ: target’s radar cross section
- A_e: antenna’s ability to capture echo signal

$$P_r = P_t \frac{G}{4\pi R^2} \sigma \frac{1}{4\pi R^2} A_e$$

which simplifies to

$$P_r = \frac{P_t G \sigma A_e}{(4\pi)^2 R^4}$$

What can be measured

Target range

Transmitted signal is time-gated sinusoid,

$$s(t) = A\cos(2\pi f_{TX} t + \phi_{TX}) \quad \text{for } 0 \le t \le \tau$$

(pulse duration is τ)

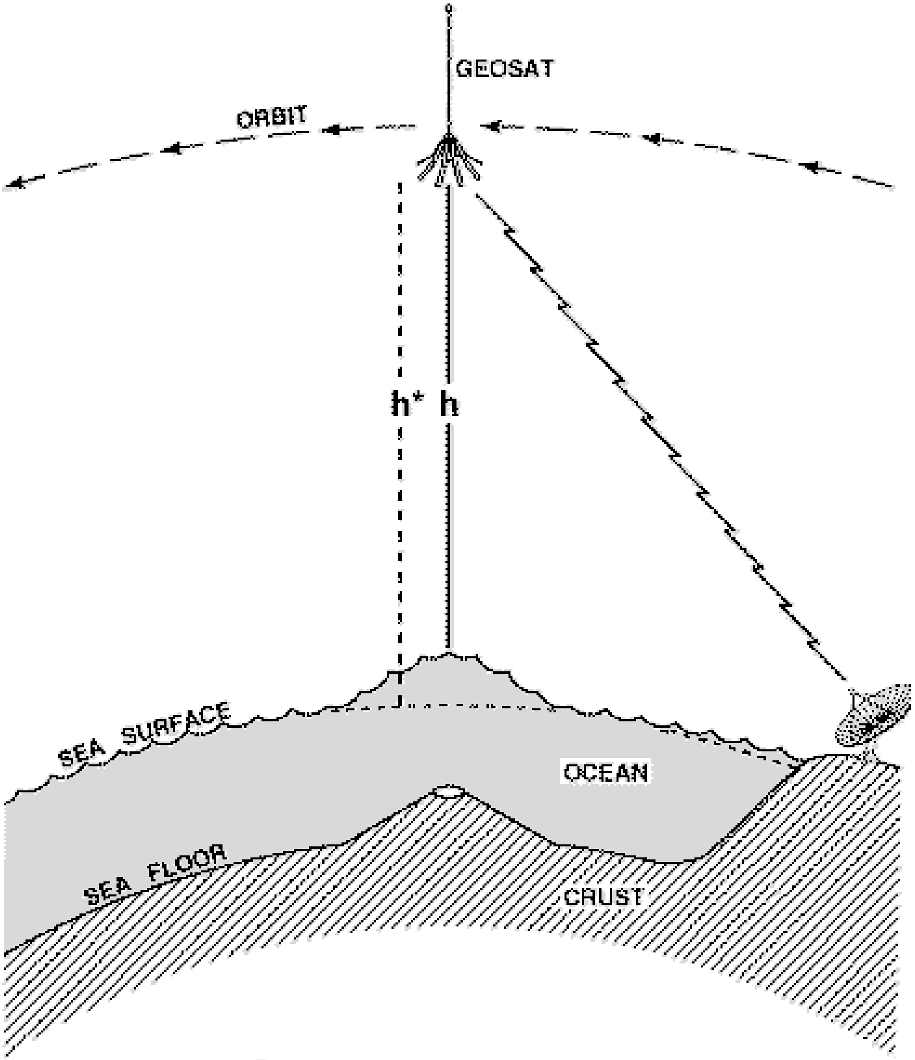
Received signal is

$$p(t) = B\cos[2\pi f_{TX}\, t + \phi_{TX} + \phi_{RX}] \quad \text{for } T \le t \le T + \tau$$

Round-trip travel time, $T = \dfrac{2R}{c}$ so $R = \dfrac{cT}{2}$

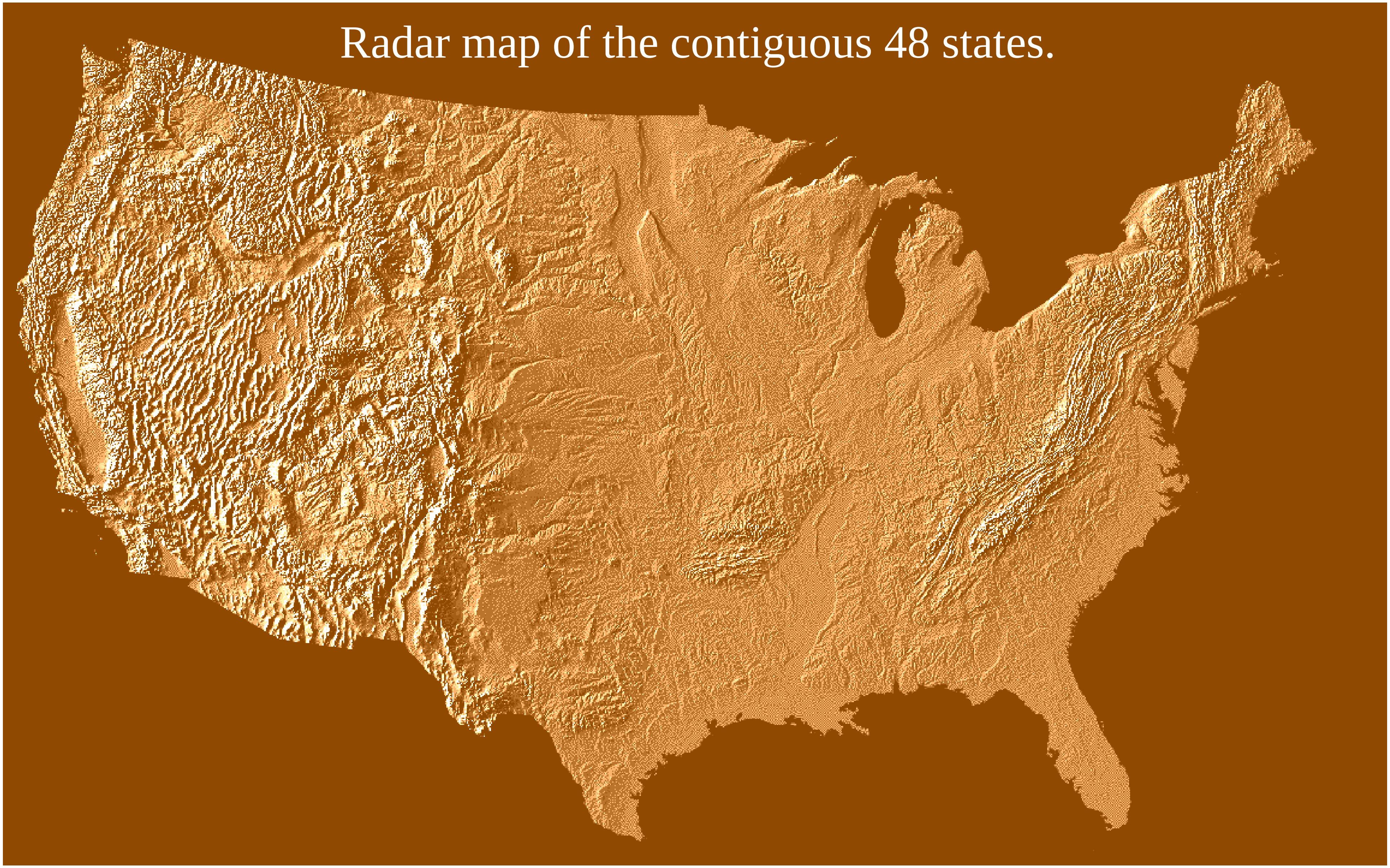
and we can measure time with great precision

Target Range - Altimeter



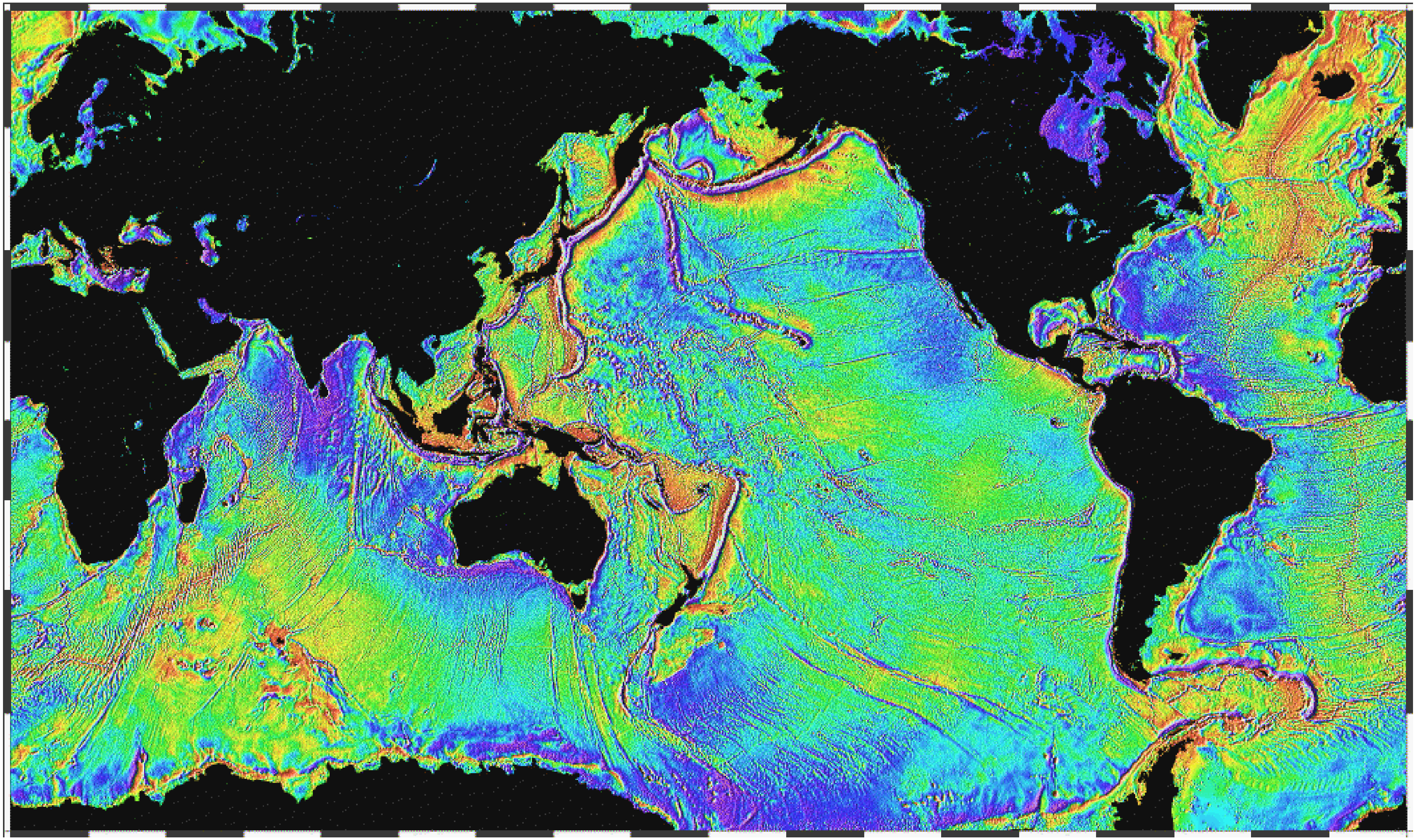
Altimeter concept.

Altimeter data



Radar map of the contiguous 48 states.

Altimeter data



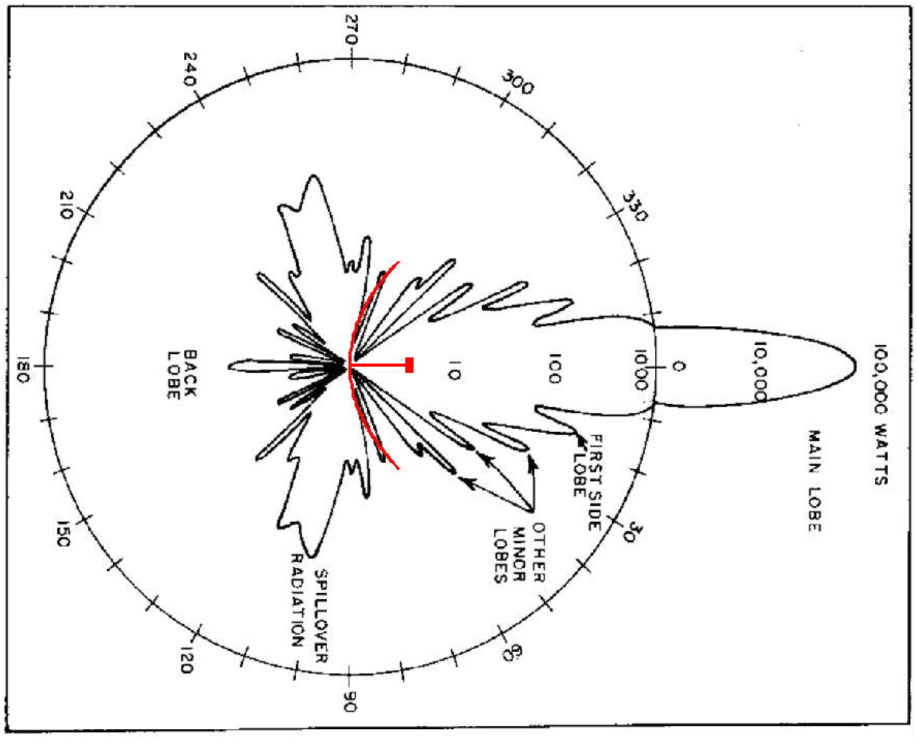
Global topographic map of ocean surface produced with satellite altimeter.

What can be measured

Spatial extent of target

Antenna directs radar signal in narrow beam, rotating antenna enables radar to scene in a circular fashion

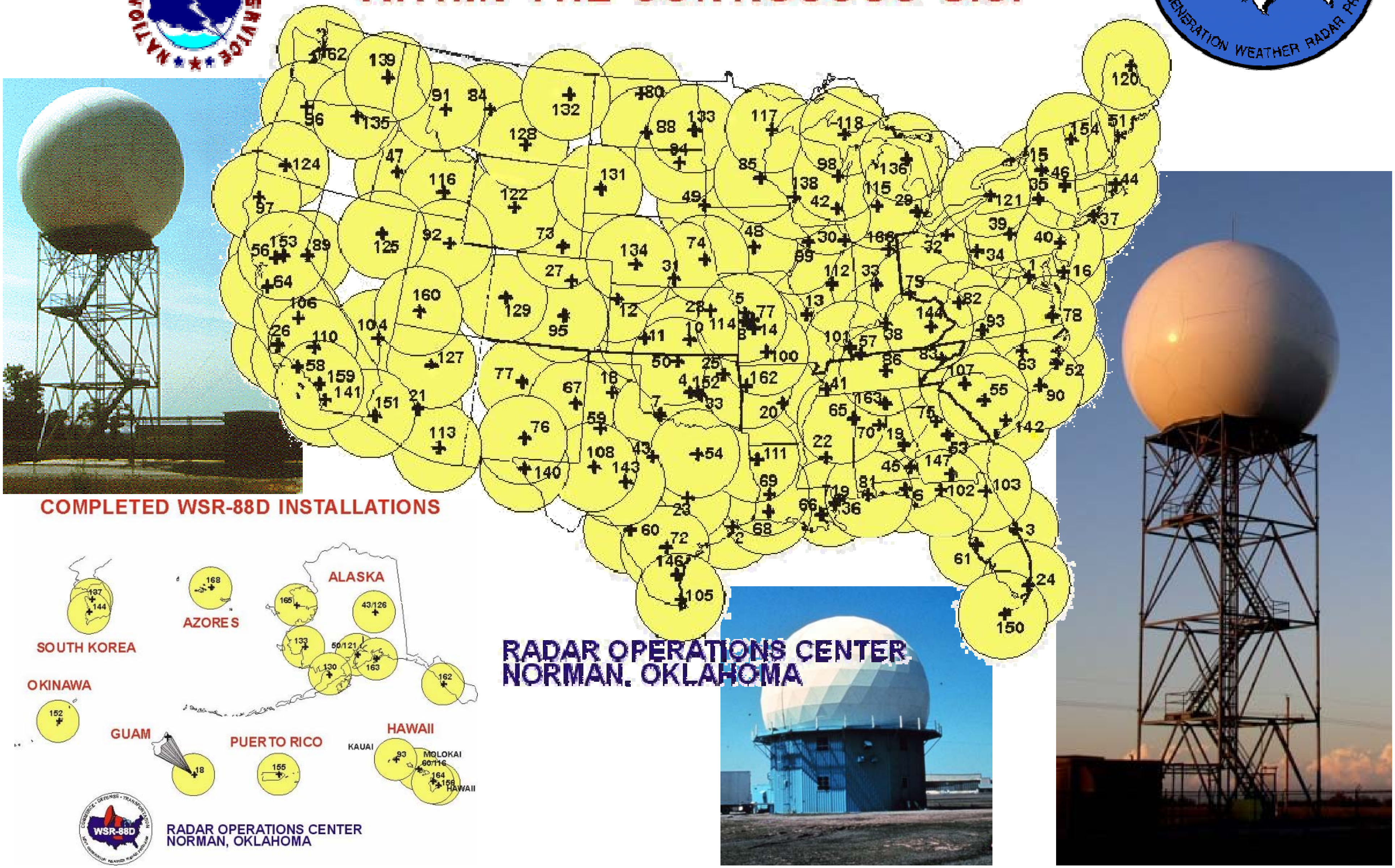
Radar antenna.



Radiation pattern of radar antenna.

NEXRAD Radar (WSR-88D)

COMPLETED WSR-88D INSTALLATIONS WITHIN THE CONTIGUOUS U.S.

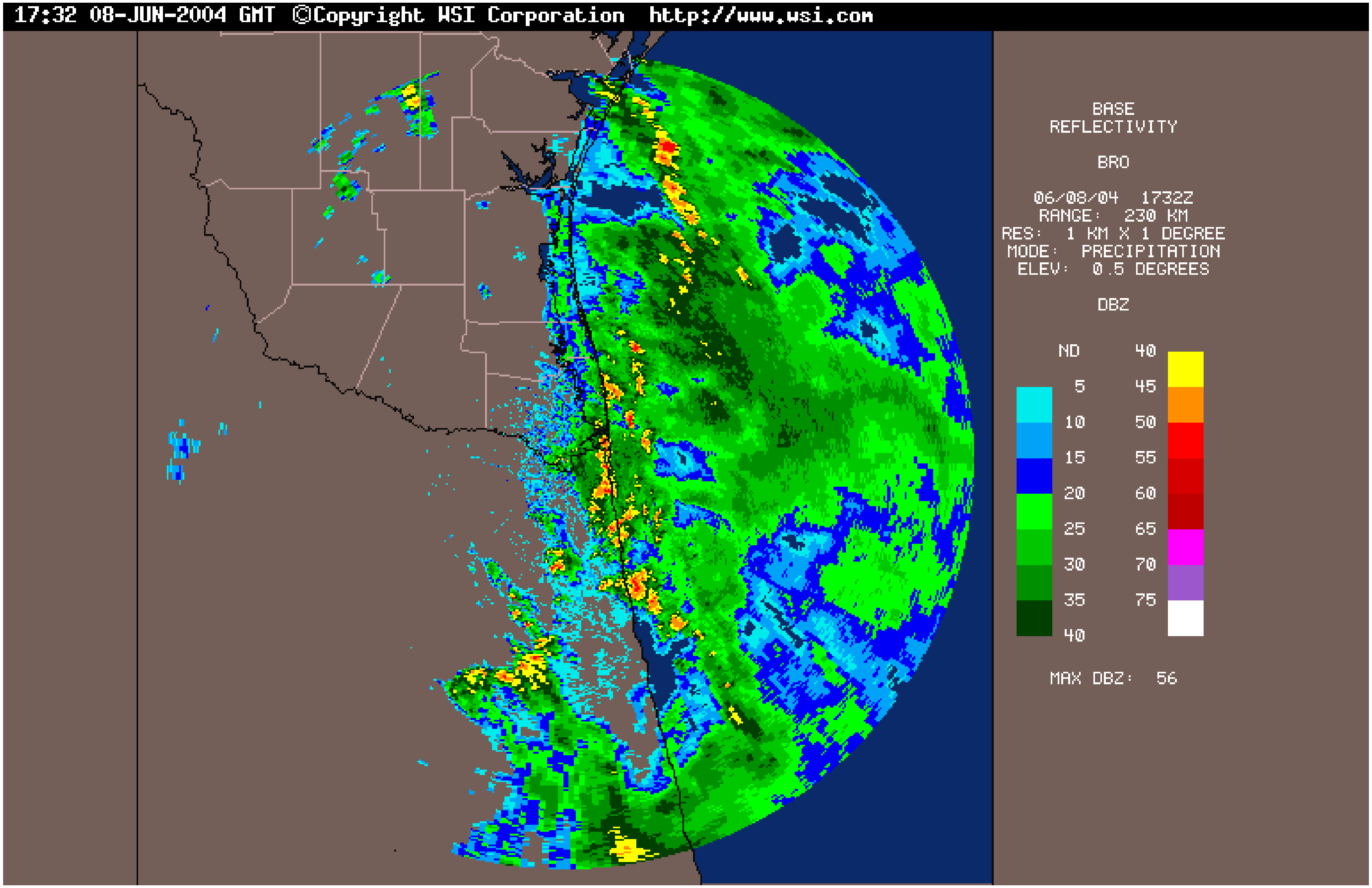


COMPLETED WSR-88D INSTALLATIONS

RADAR OPERATIONS CENTER
NORMAN, OKLAHOMA

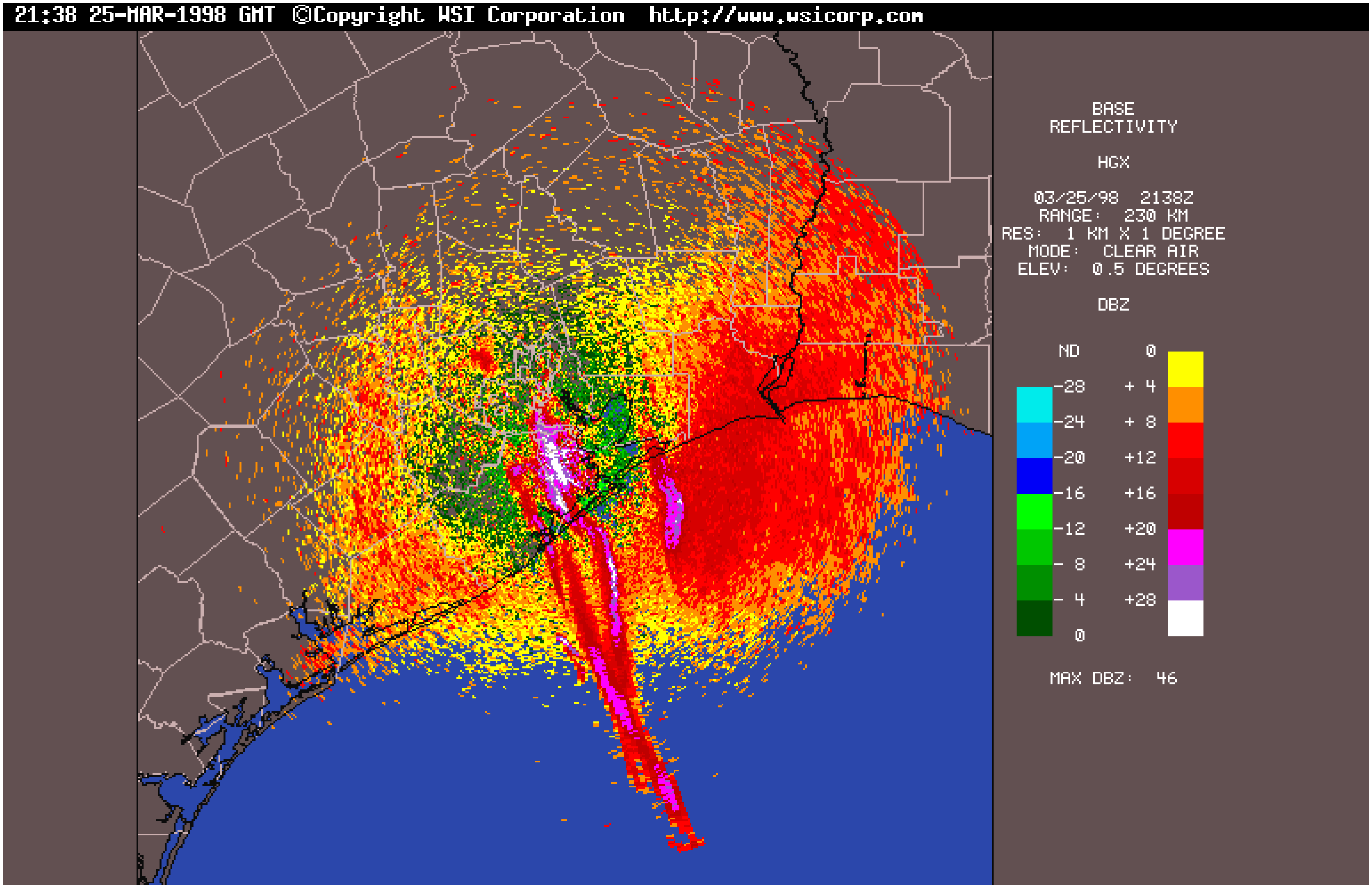
RADAR OPERATIONS CENTER
NORMAN, OKLAHOMA

Spatial extent of target



Rain off the coast of Brownsville, Texas.

Spatial extent of target



A flock of birds traveling north into south Texas from the Gulf of Mexico.

What can be measured

Relative radial velocity of target

Received signal phase, ϕ_{RX}, is range dependent, $\phi_{RX} = 2\pi \frac{2R}{\lambda}$

where λ is the signal wavelength, $\lambda = c/f_{TX}$

If the range to the target changes, the received signal phase will change with time producing a Doppler shift, f_D, where

$$f_D = \frac{\Delta\phi_{RX}}{\Delta t}$$

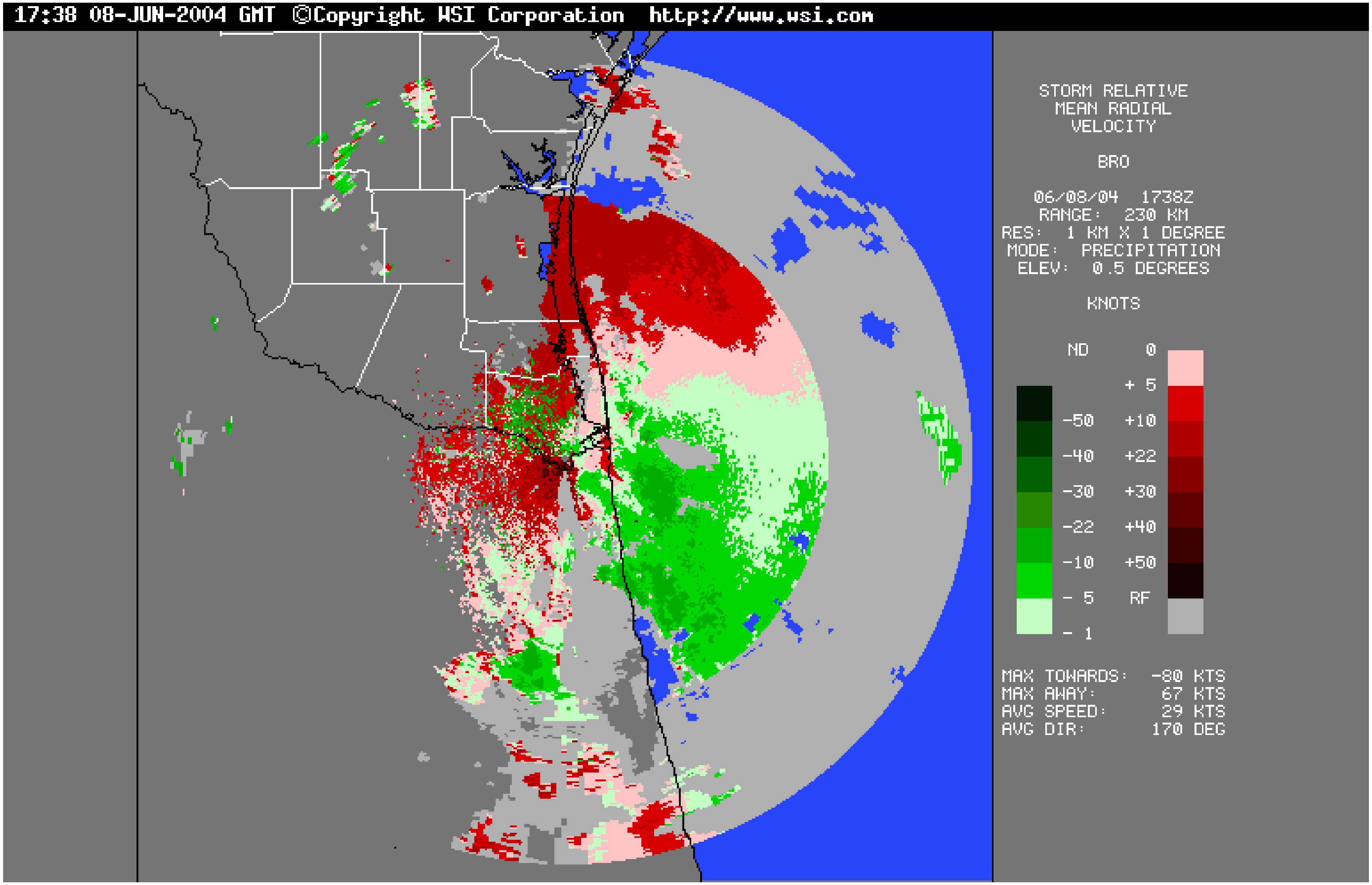
which can be shown to be

$$f_D = \frac{2v}{\lambda}\cos\theta$$

where θ is the angle between the velocity vector and the radar's range vector. The received signal is

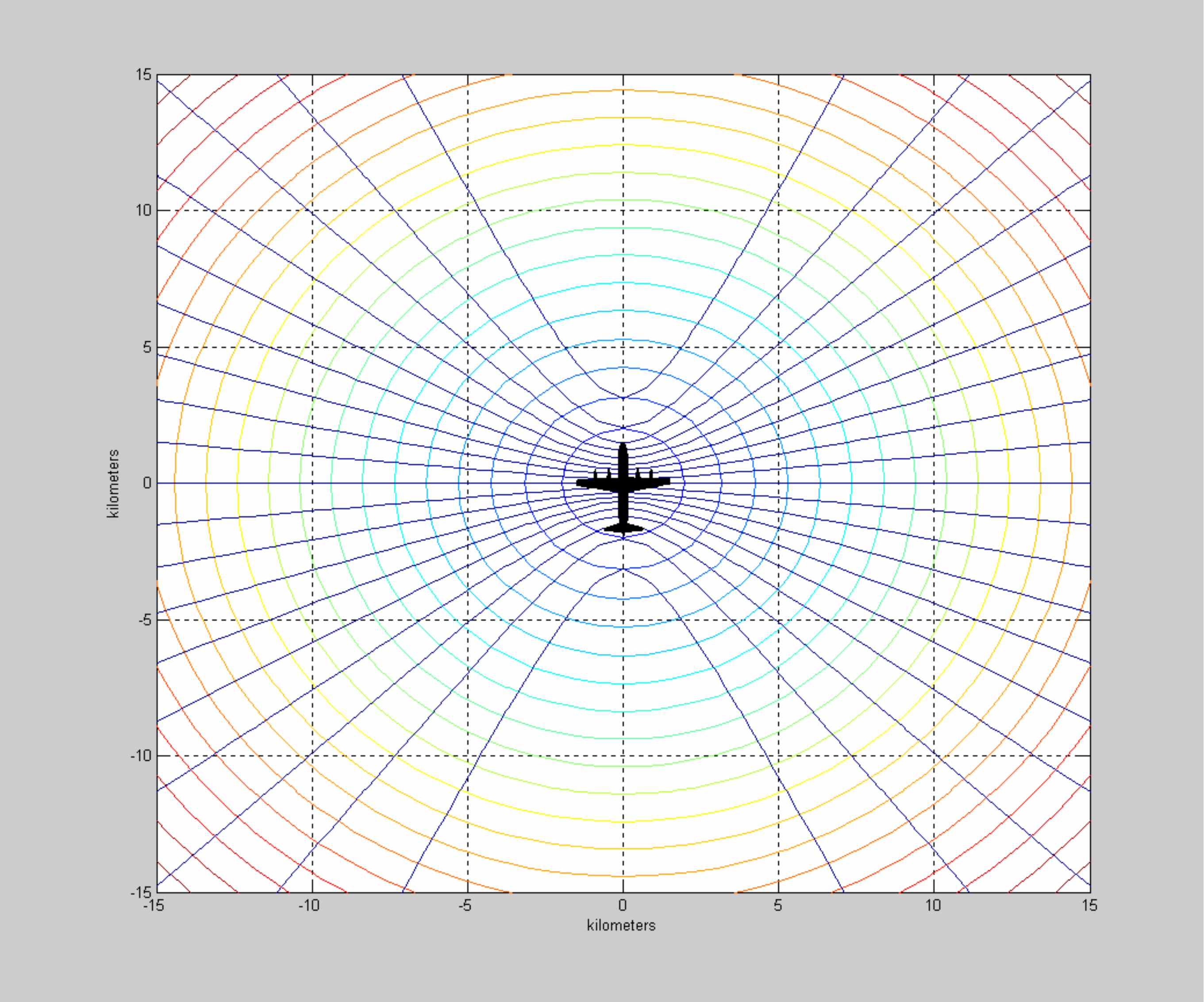
$$p(t) = B\cos\left[2\pi(f_{TX} + f_D)t + \phi_{TX}\right] \qquad \text{for } T \le t \le T + \tau$$

Relative radial velocity of target



Radial velocity of precipitation near Brownsville, Texas.

Relative radial velocity of target

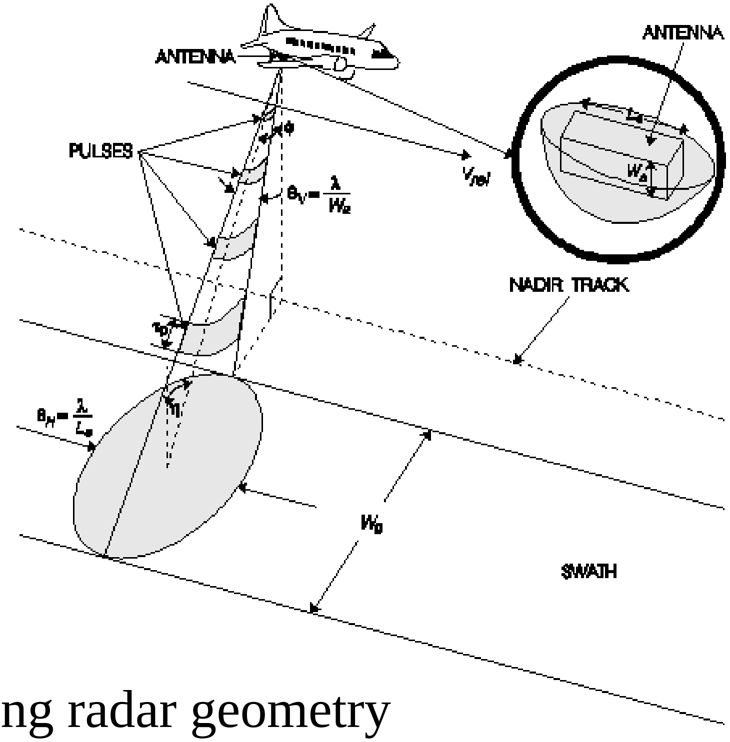


Isorange and isodoppler lines for aircraft flying north at 10 m/s at a 1500-m altitude.
$\Delta R = 2$ m, $\Delta V = 0.002$ m/s, $\Delta f_D = 0.13$ Hz @ $f = 10$ GHz, $\lambda = 3$ cm

What can be measured

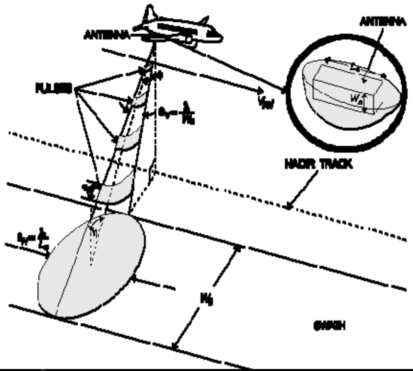
Target reflectivity

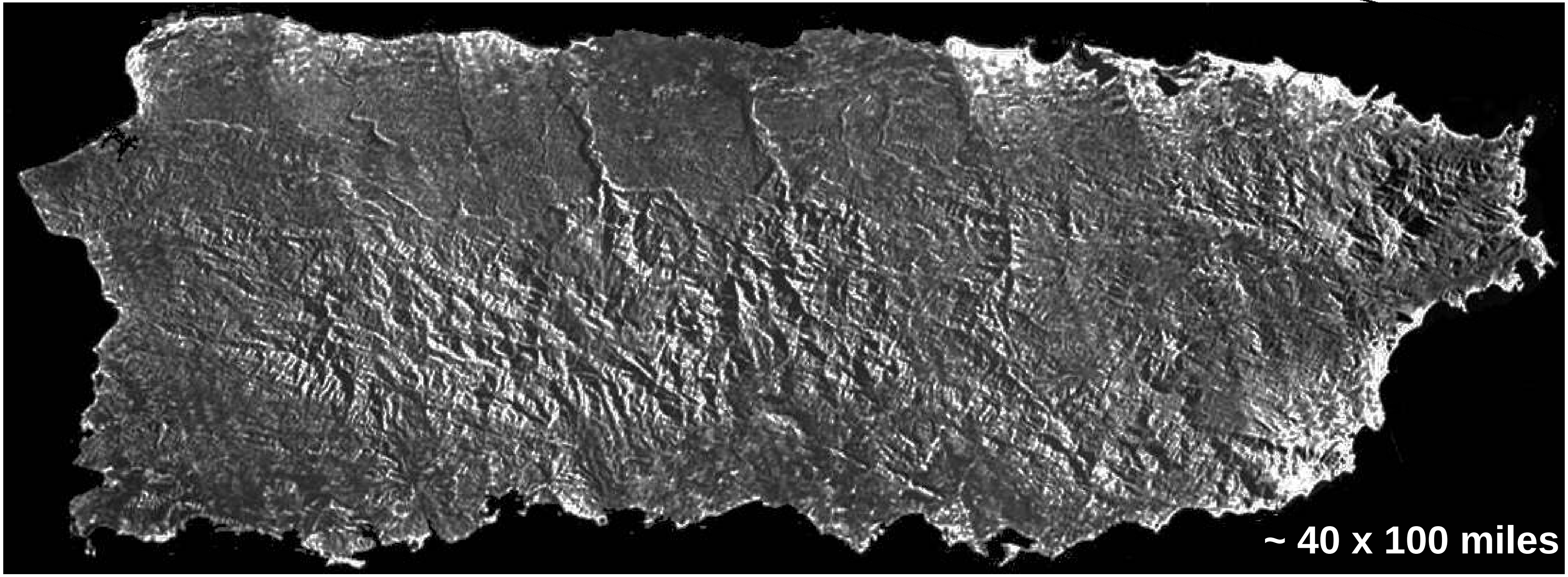
Backscatter depends on material properties, local geometry (e.g., slope), surface roughness. By combining the ability to discriminate based on range and velocity (Doppler), images of radar backscatter can be formed.



Imaging radar geometry

Real-aperture, side-looking airborne radar (SLAR) image of Puerto Rico



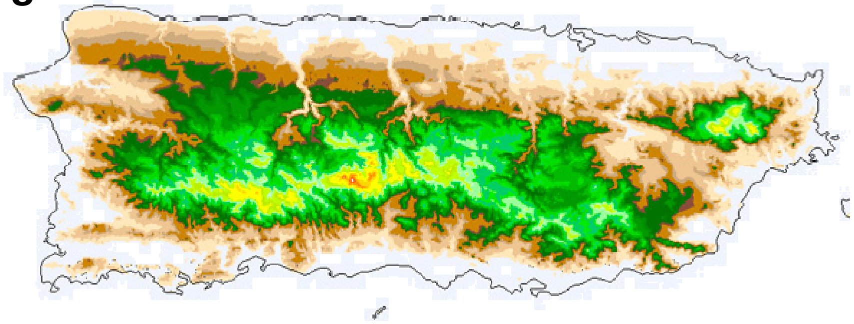


Mosaicked image composed of 48-km (30-mile) wide strip map images

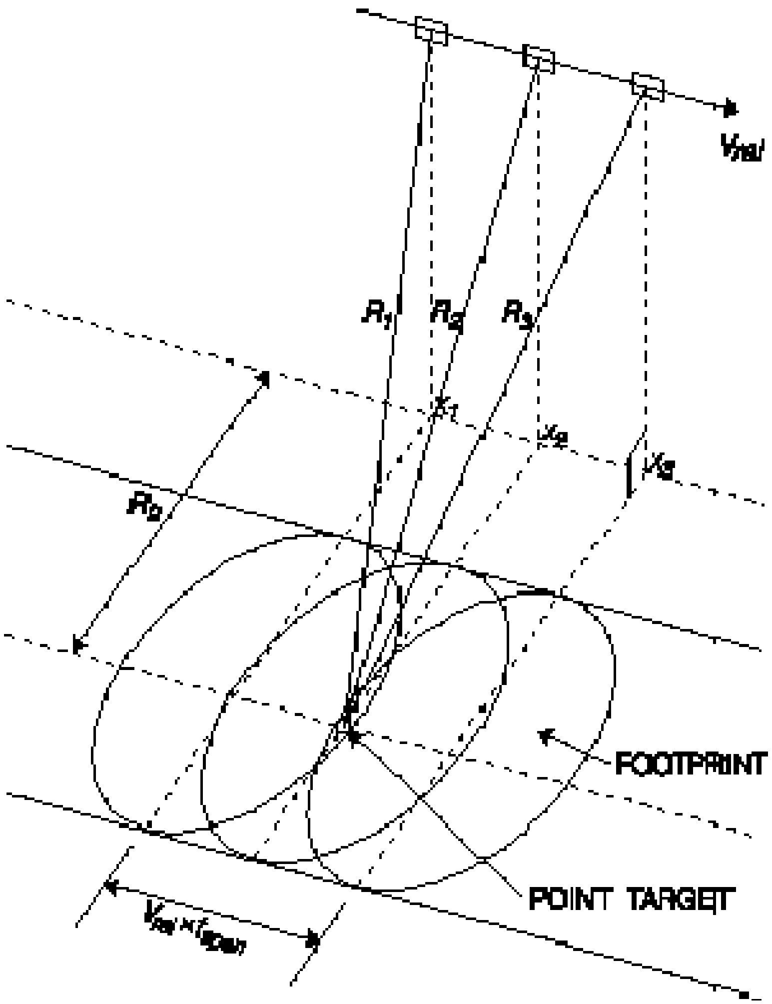
<u>Radar parameters</u>

modified Motorola APS-94D system
X-band (3-cm wavelength)
altitude: 8,230 m (above mean sea level)
azimuth resolution: 10 to 15 m

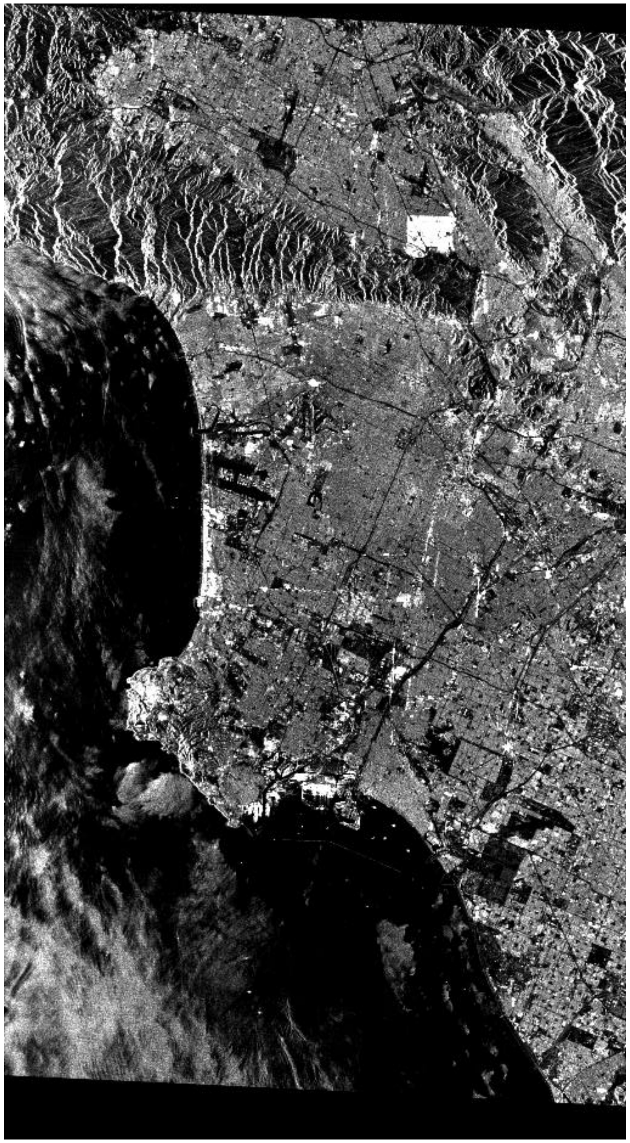
Digital Elevation Model of Puerto Rico



Target reflectivity



Synthetic-aperture radar (SAR) geometry



SAR image of Los Angeles, CA area.

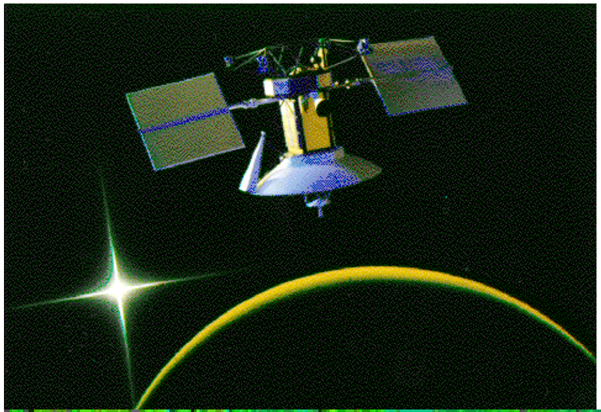
SAR image of Gibraltar

Nonlinear internal waves propagating eastwards and oil slicks can be seen.

ERS-1 Synthetic Aperture Radar

f: 5.3 GHz
ant: 10 m x 1 m
$\Delta x = \Delta y = 30$ m
orbit: 780 km

P_{TX}: 4.8 kW
B: 15.5 MHz
f_s: 19 MSa/s
D_R: 105 Mb/s



SAR imagery of Venus

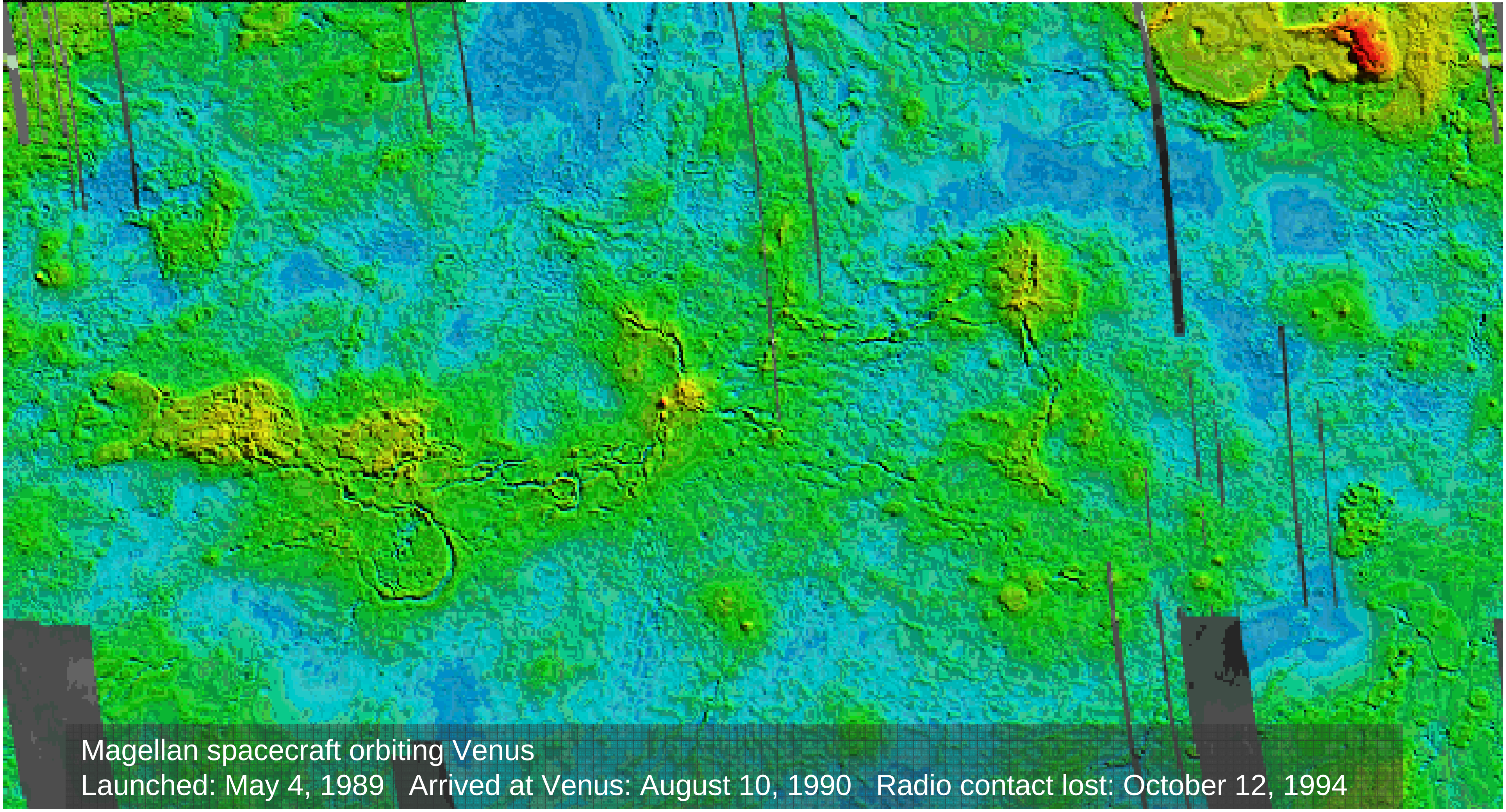
Magellan SAR parameters

Frequency: 2.385 GHz, Bandwidth: 2.26 MHz

Pulse duration: 26.5 μs

Antenna : 3.5-m dish

Resolution (Δx, Δy): 120 m, 120 m

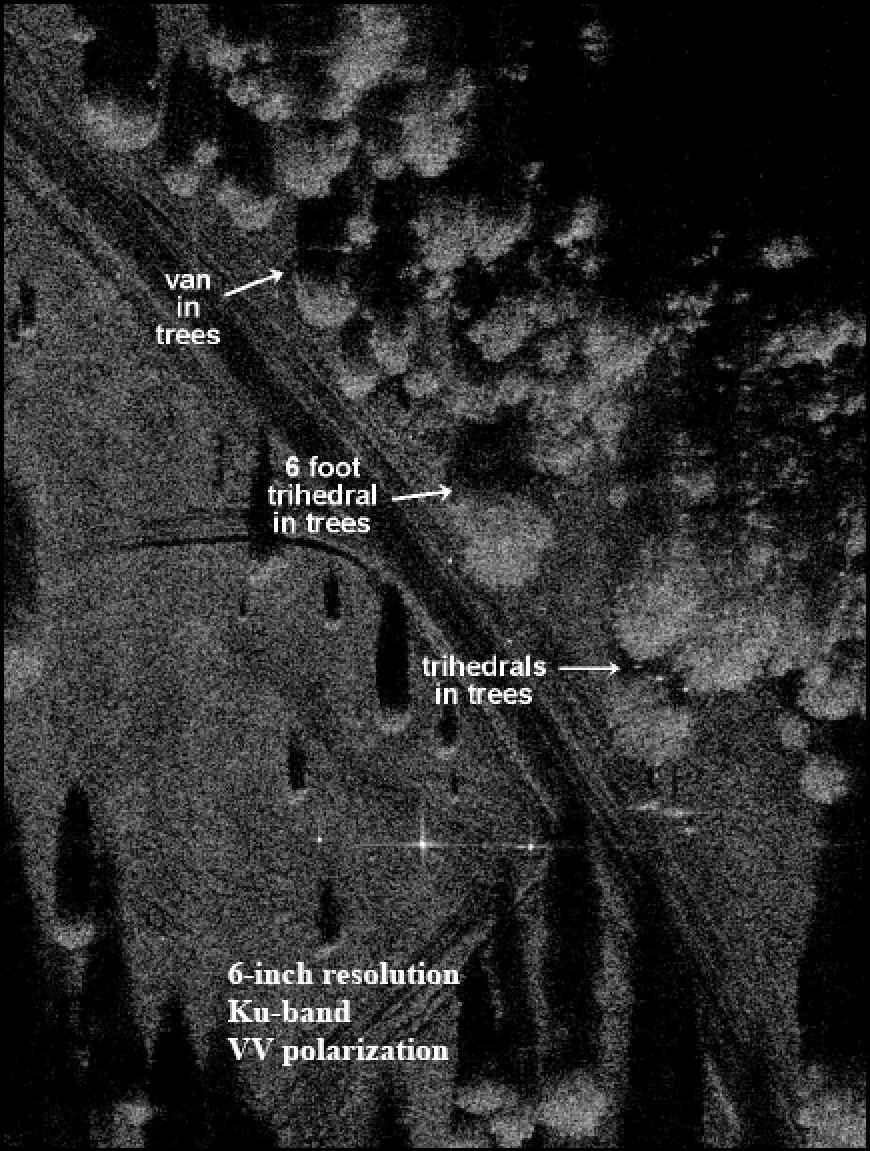


Magellan spacecraft orbiting Venus
Launched: May 4, 1989 Arrived at Venus: August 10, 1990 Radio contact lost: October 12, 1994

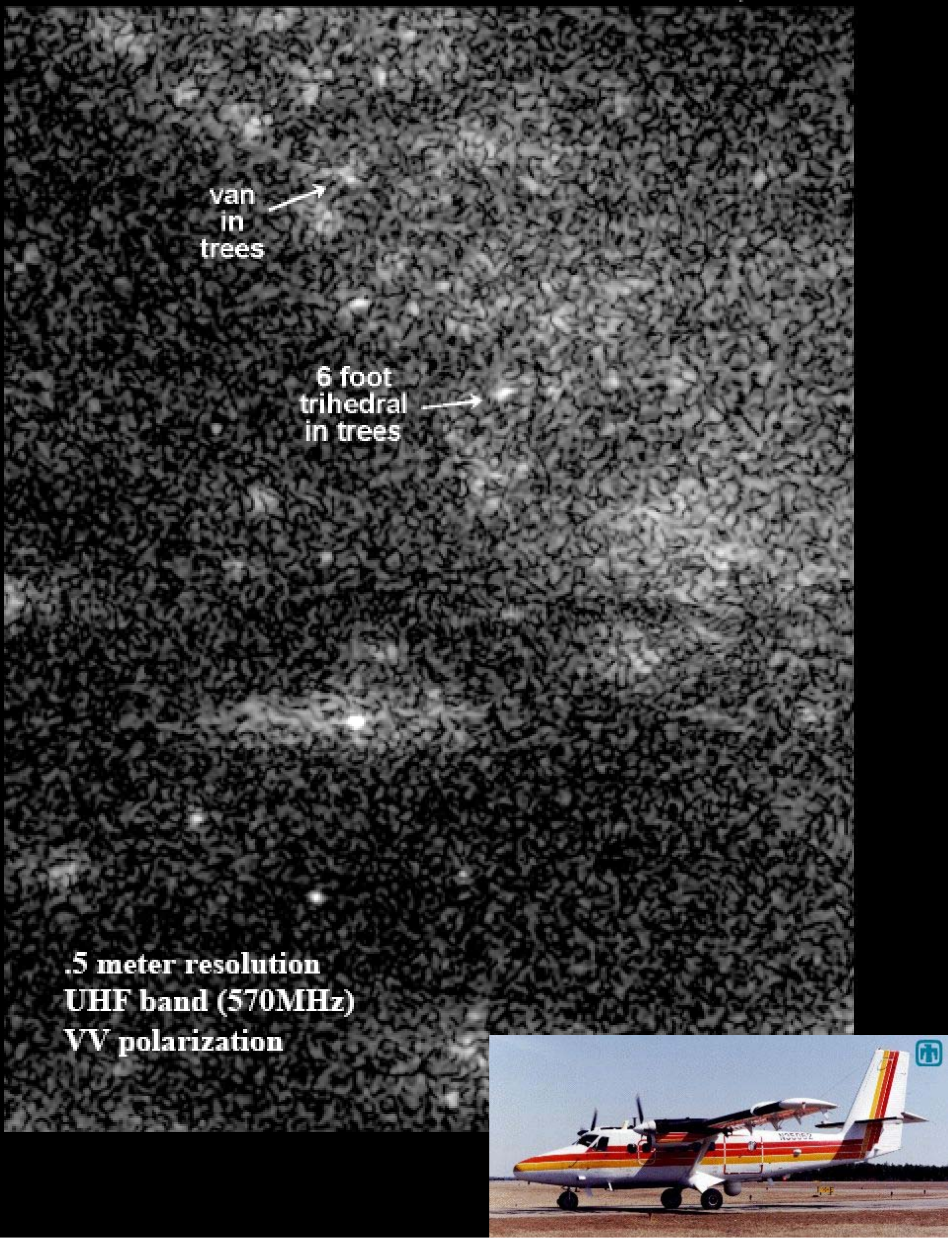
Ka-band, 4” resolution
Helicopter and plane static display

Sandia National Laboratories

Frequency Comparison – Ku vs. UHF

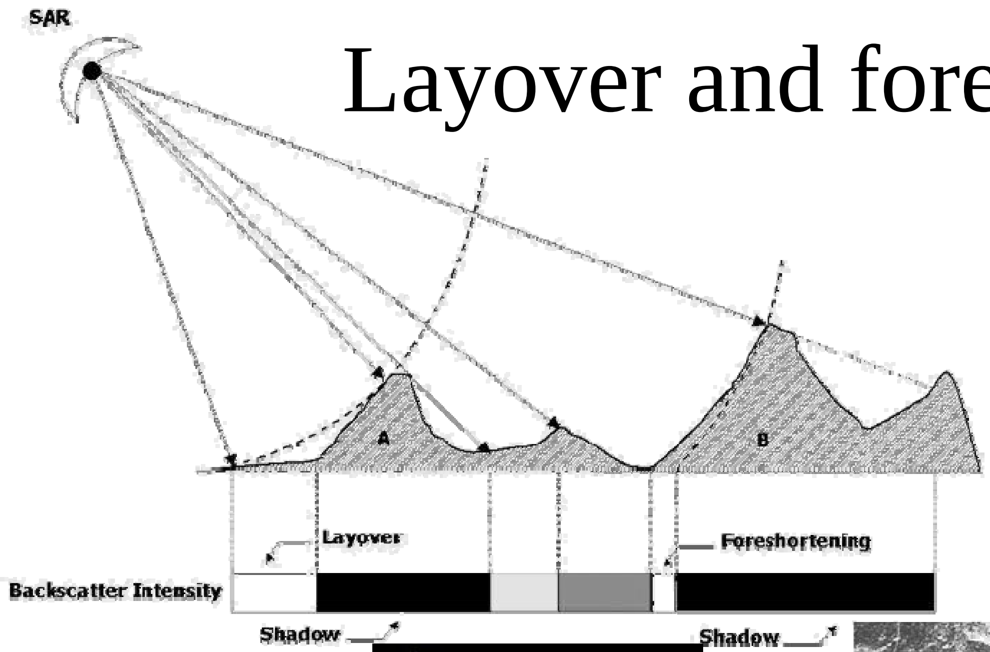


6-inch resolution
Ku-band
VV polarization



.5 meter resolution
UHF band (570MHz)
VV polarization

Layover and foreshortening distortion



<u>SEASAT Synthetic Aperture Radar</u>

Launched: June 28, 1978
Died: October 10, 1978
orbit: 800 km
f: 1.3 GHz **P_{TX}: 1 kW**
τ: 33.8 μs **B: 19 MHz**
θ: 23 ± 3° **PRF: 1464 to 1647 Hz**
ant: 10.7 m x 2.2 m
Δx = 18 to 23 m **Δy = 23 m**

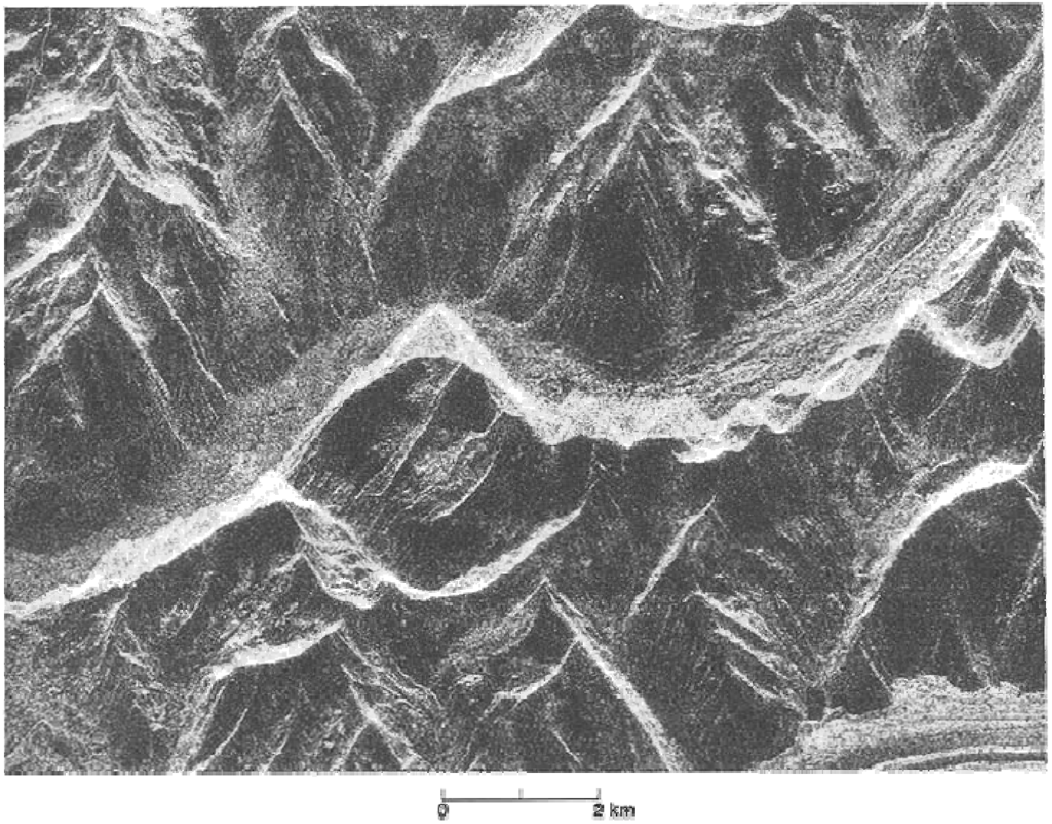


Figure 5-4. Example of radar image layover. Seasat image of the Alaska Range showing the top of a mountain imaged onto the glacier at its foot (center). Shadows are also present on many of the backslopes of these steep mountains. Illumination is from the top [from Ford et al., 1989].

SEASAT image of Ames, Iowa

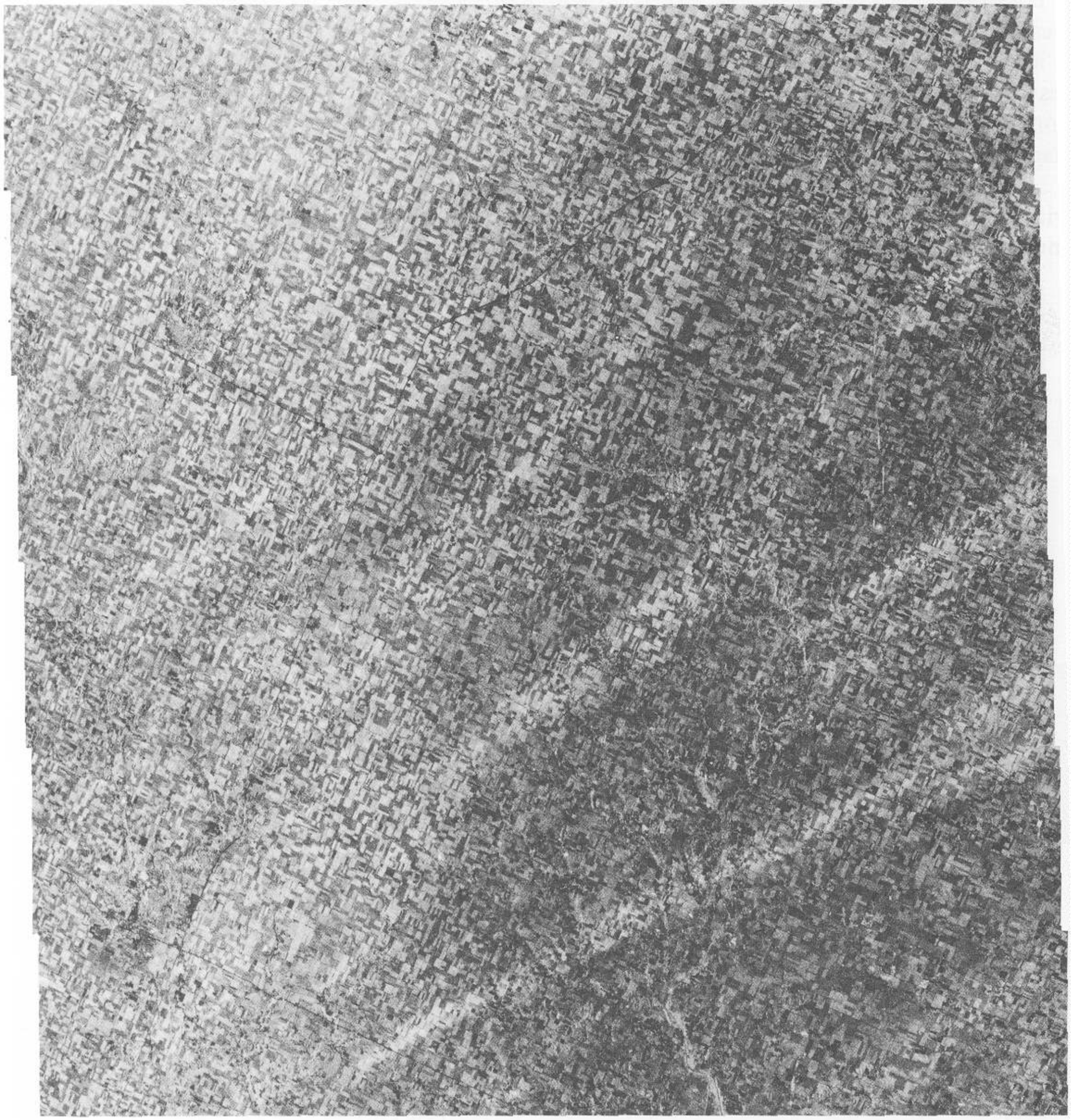
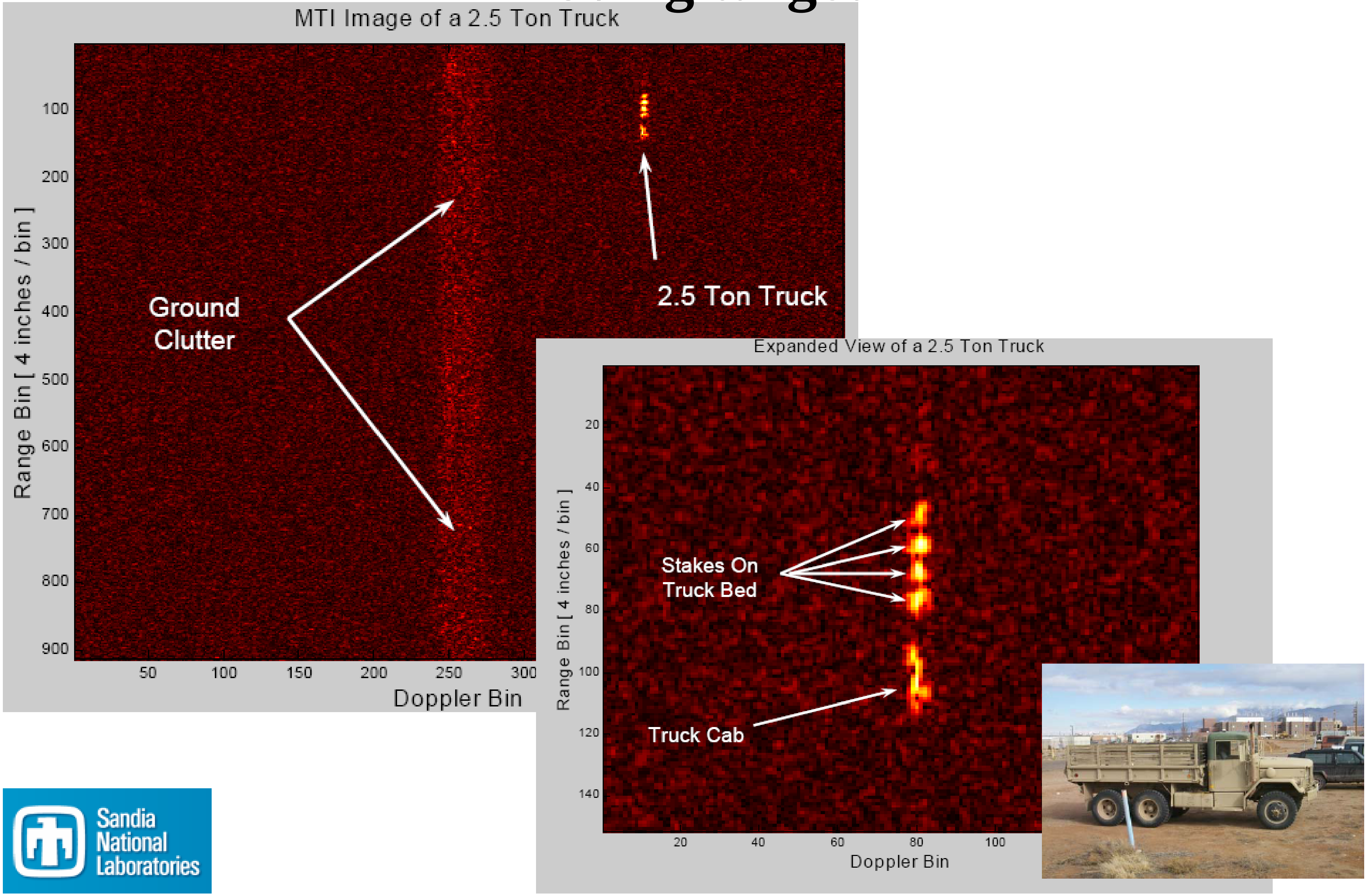


Figure 5-6. Ames, Iowa, with bright streaks due to rain-soaked ground

Fine resolution range imaging of a ground moving target



Sandia National Laboratories

Examples of SAR Imagery

Washington, D.C. mall area

Aerial photo, 8-m resolution (USGS)

SAR image, 1-m resolution (Sandia National Laboratory)

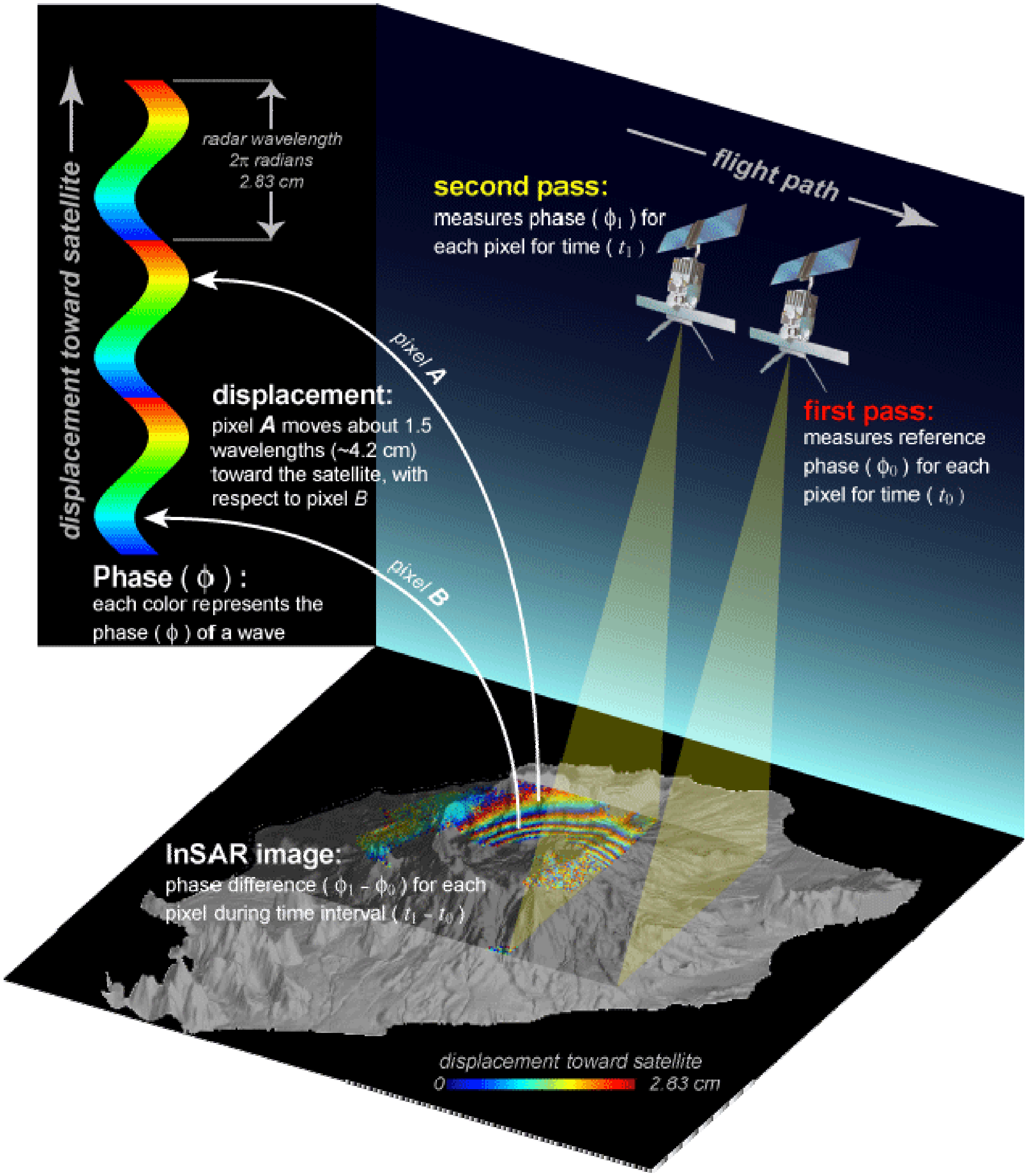
Examples of SAR Imagery

Capitol building, Washington, D.C.

Aerial photo, 1-m resolution (USGS)

SAR image, 1-m resolution (Sandia National Laboratory)

Multipass interferometry



Multipass interferometry. Same or similar SAR systems image common region at different times. Differences can be attributed to elevation (relief) or horizontal displacements.
Third observation needed to isolate elevation effects from displacement effects.

Digital elevation mapping with InSAR

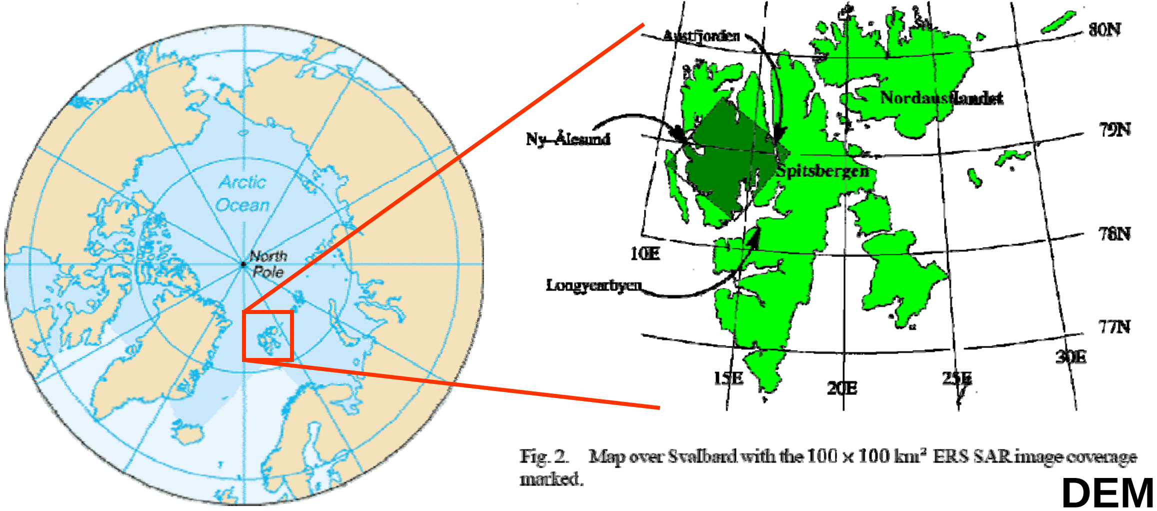
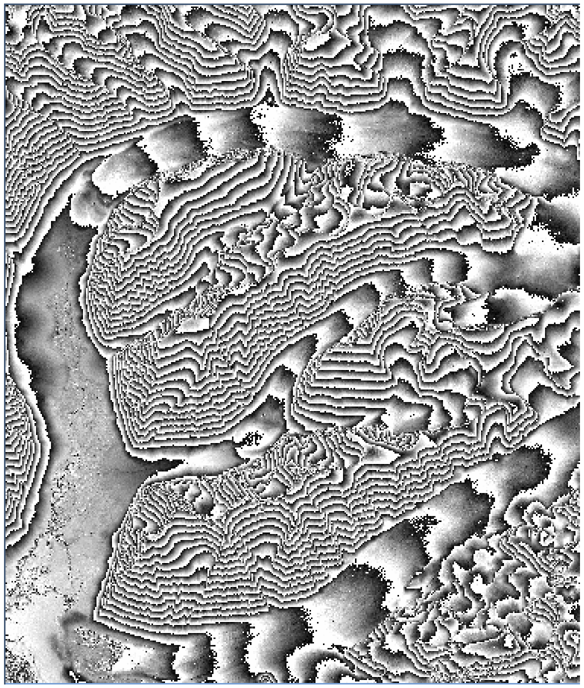


Fig. 2. Map over Svalbard with the 100 × 100 km² ERS SAR image coverage marked.

Interferogram



Digital elevation map (DEM)

DEM draped with SAR amplitude data

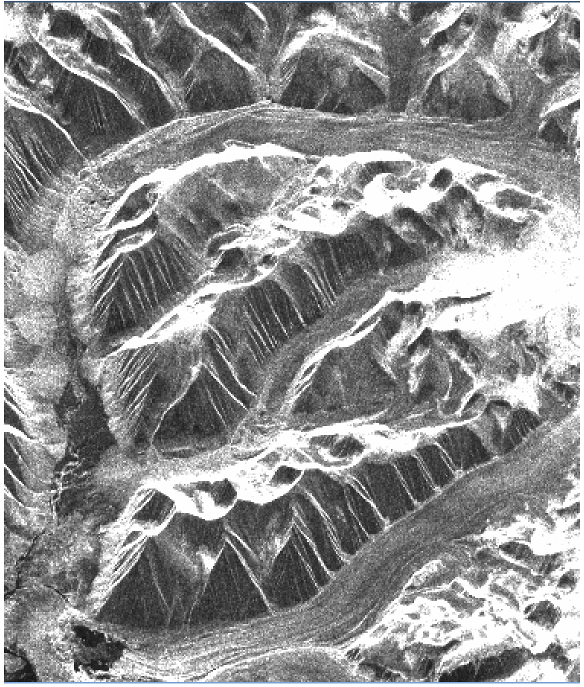
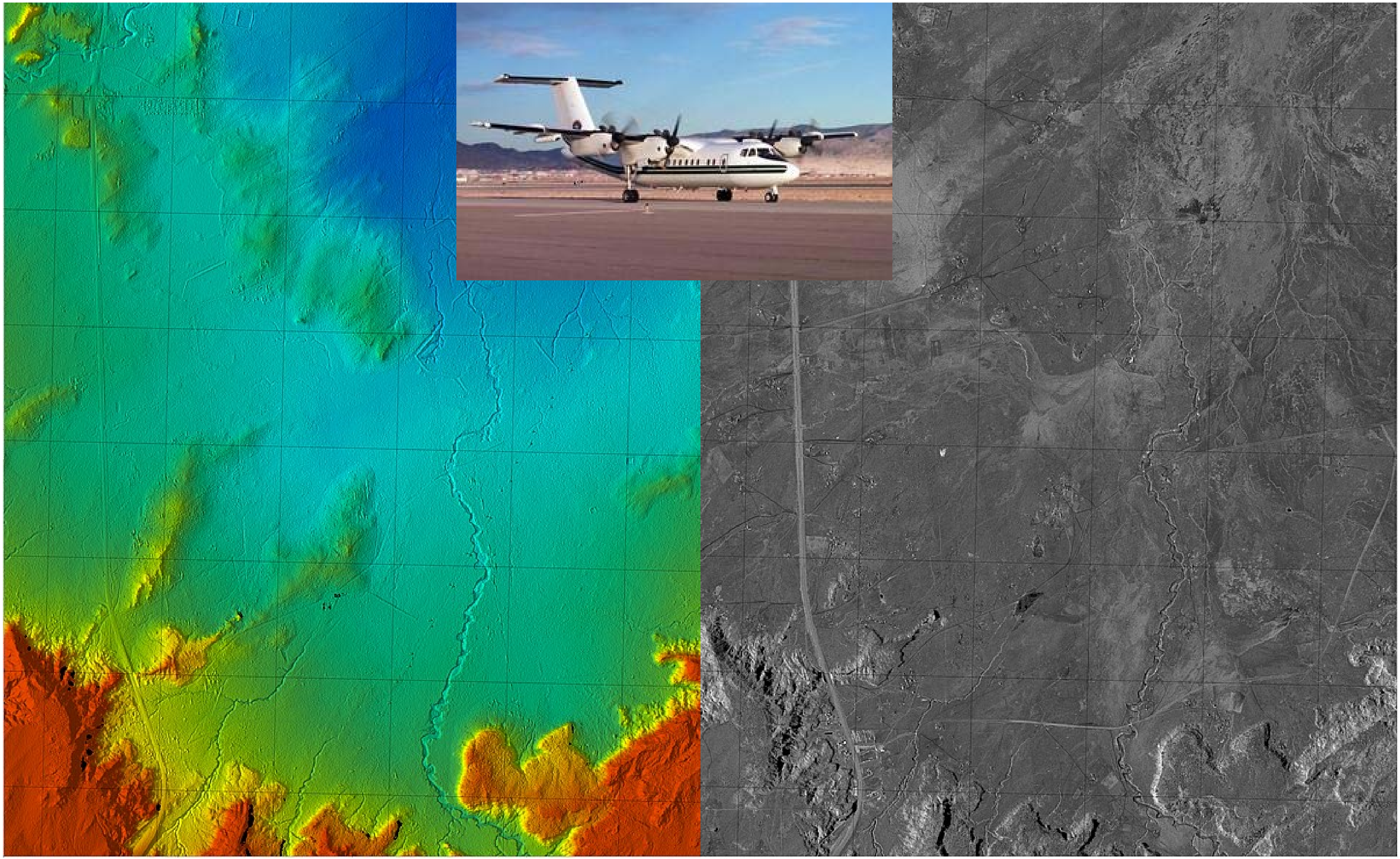


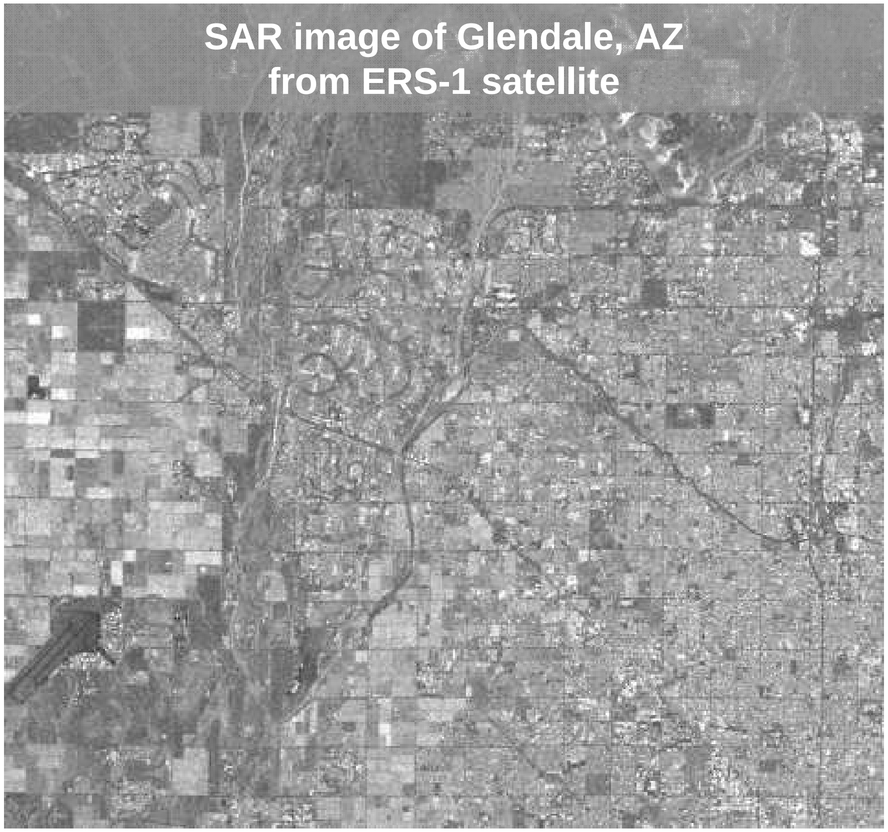
Image covers 18.1 km in azimuth, 26.8 km in range. The azimuth direction is horizontal.

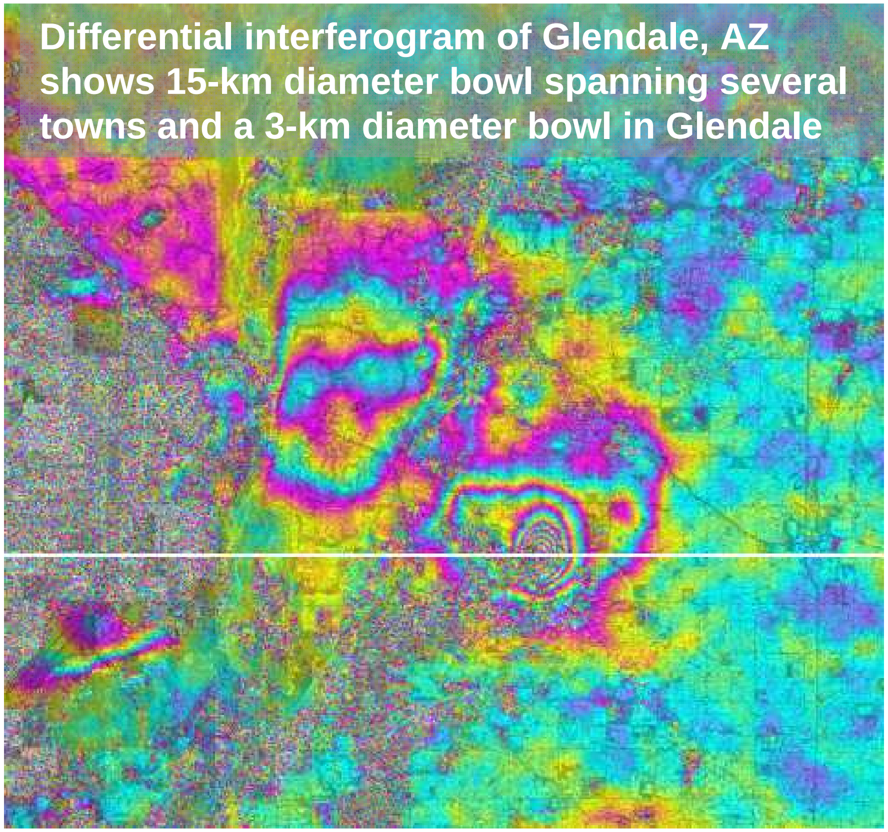


DTED Level IV Digital Elevation Model - Twin Lakes, NM

Orthorectified SAR Image - Twin Lakes, NM

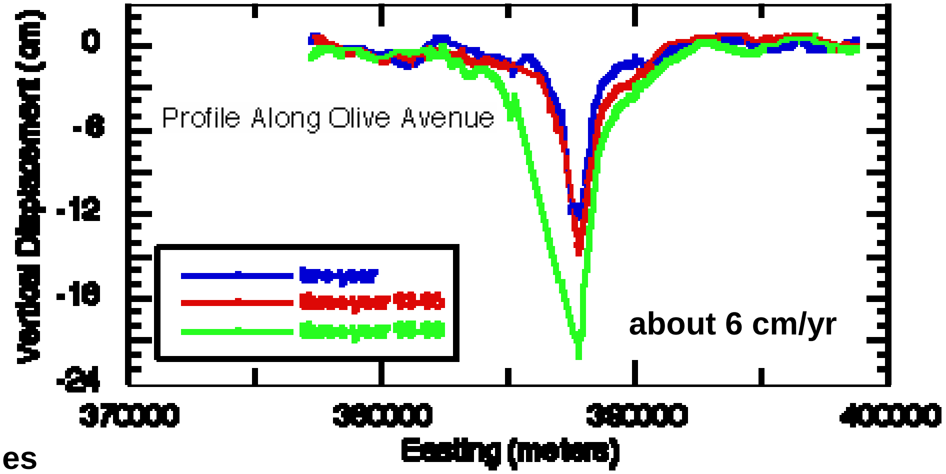
Subsidence measurement


SAR image of Glendale, AZ
from ERS-1 satellite


Differential interferogram of Glendale, AZ
shows 15-km diameter bowl spanning several
towns and a 3-km diameter bowl in Glendale

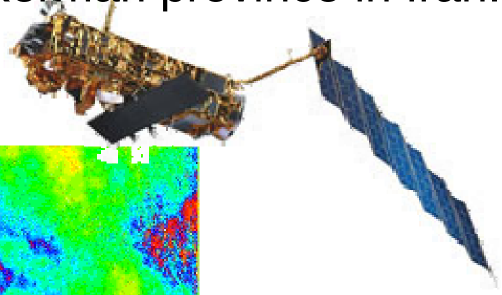
ERS-1
f: 5.3 GHz
P_{TX}: 4.8 kW
ant: 10 m x 1 m
B: 15.5 MHz
f_s: 19 MSa/s
orbit: 780 km
D_R: 105 Mb/s

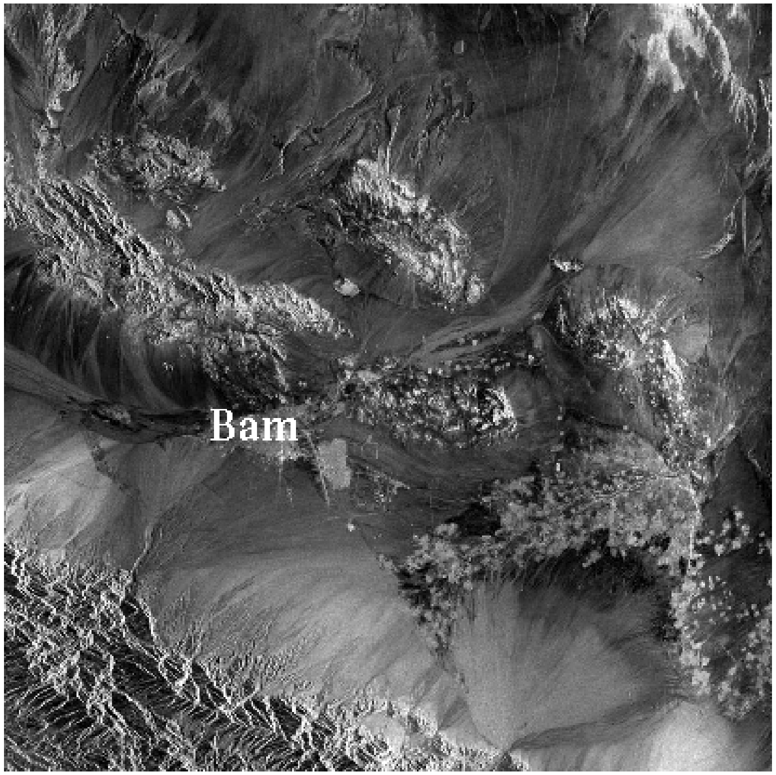

Damage associated with subsidence at 71st and Olive Avenues



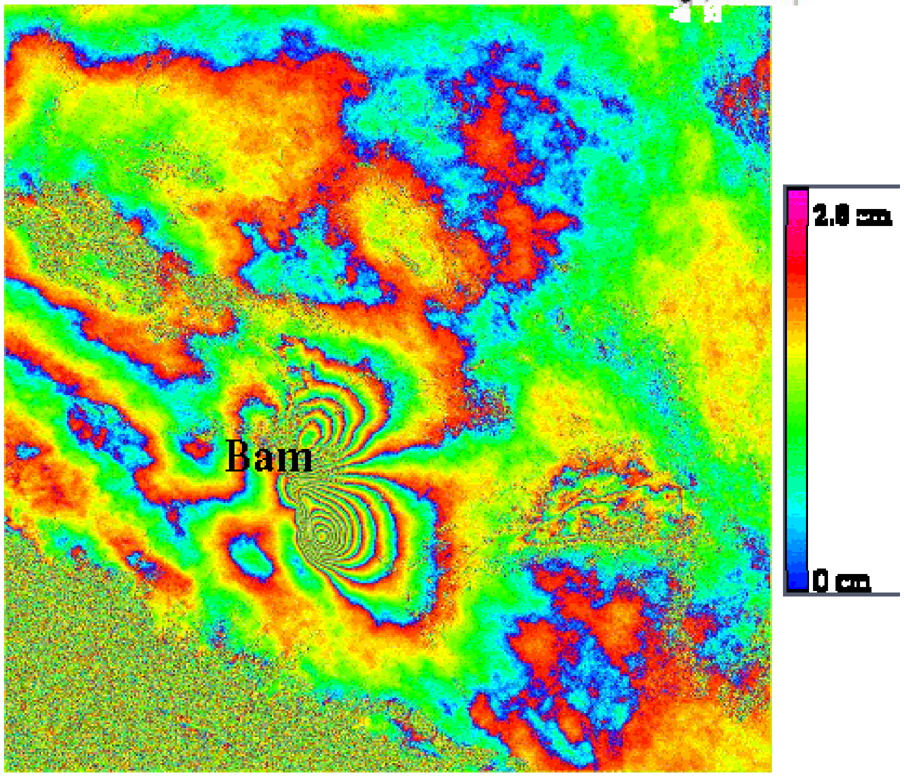
Earthquake displacements

On December 26, 2003 a magnitude 6.6 earthquake struck the Kerman province in Iran.





radar intensity image



differential interferogram

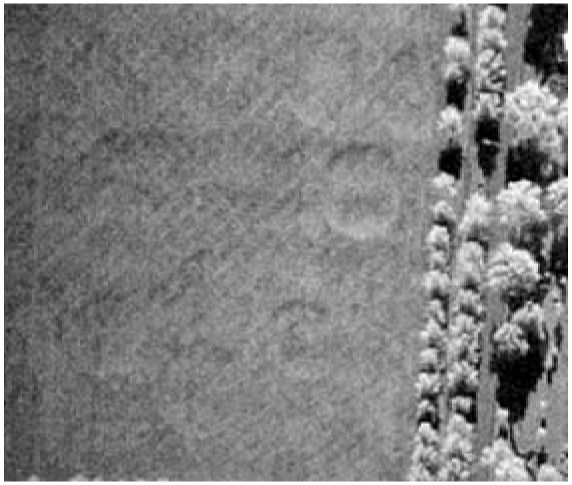
Multipass ENVISAT SAR data sets from June 11, 2003, December 3, 2003 and January 7, 2004.
The maximum relative movement change in LOS is about 48 cm and located near the city Bam.

ENVISAT SAR launched March 1, 2002

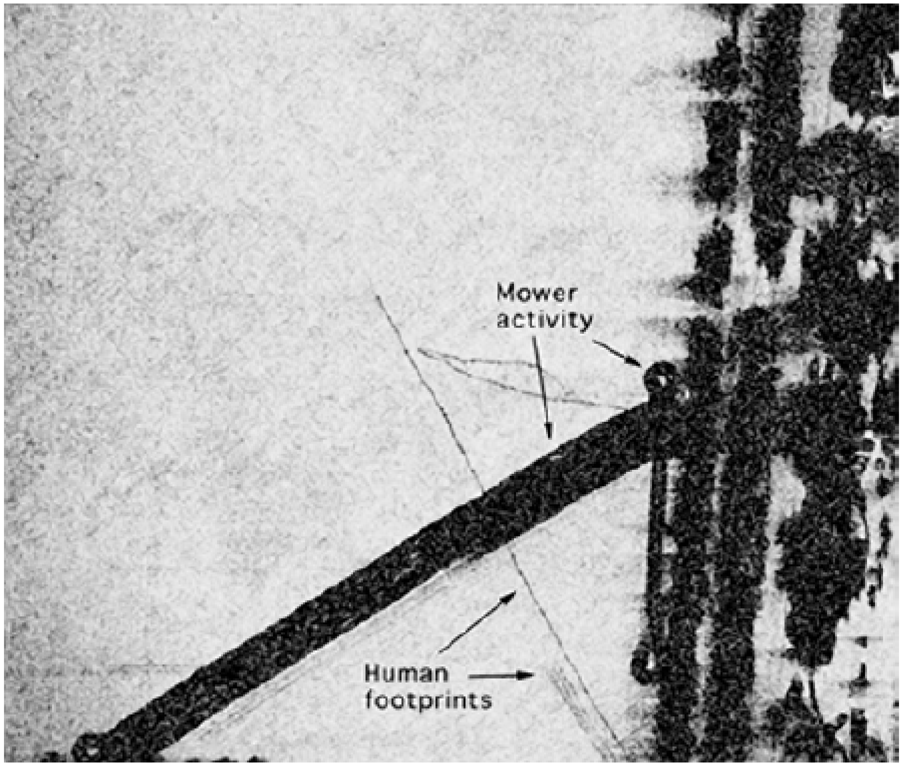
f: 5.331 GHz orbit: 800 km antenna: 10 m x 1.3 m $\Delta x = \Delta y = 28$ m

320 T/R modules @ 38.7 dBm each: 2300 W

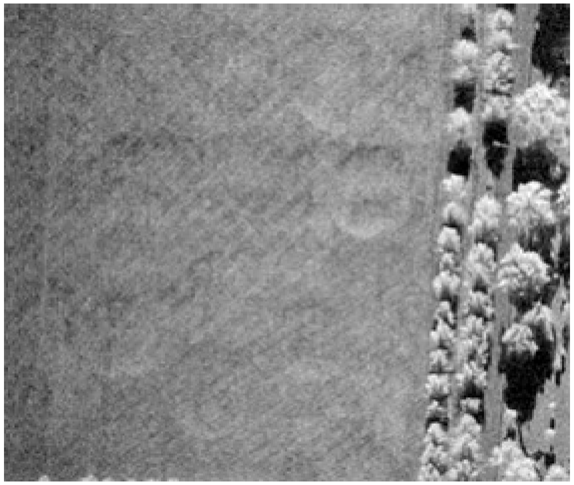
InSAR Coherent Change Detection



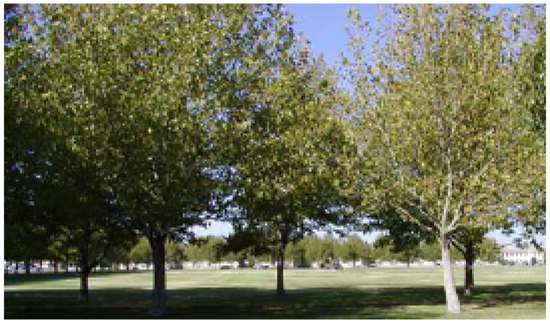
Reference SAR Image: Grassy Field



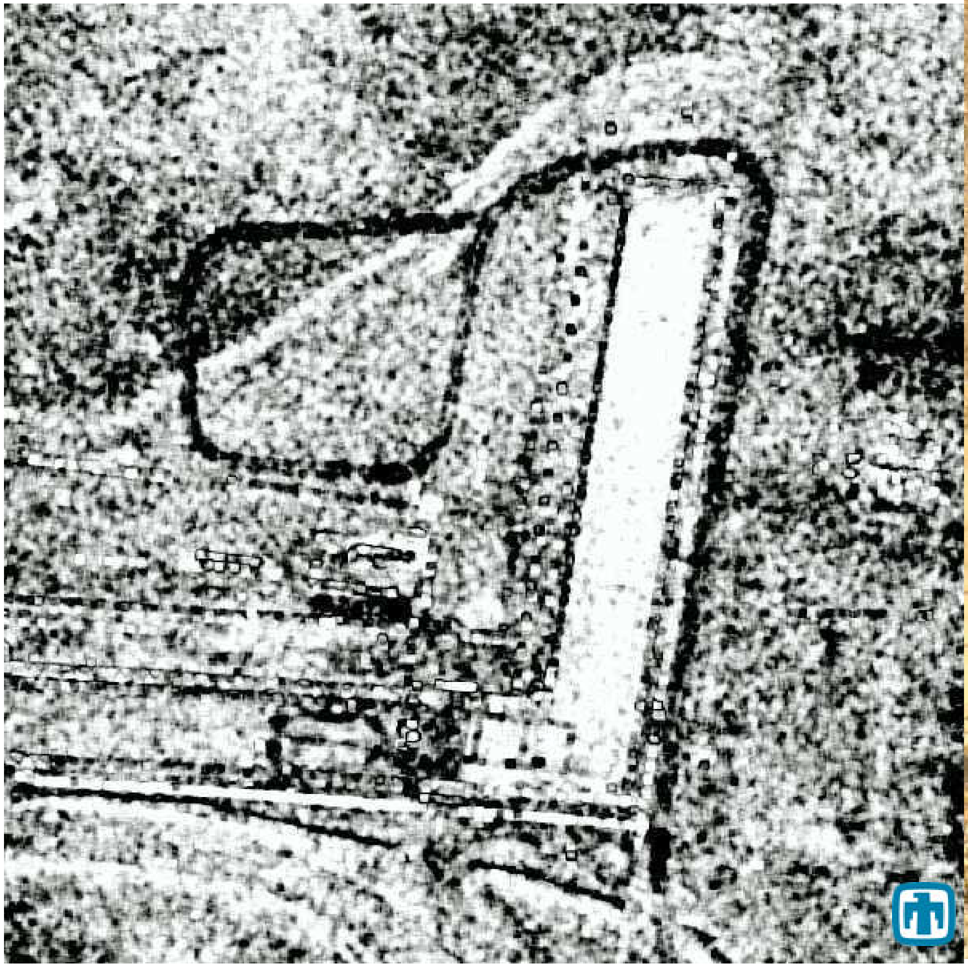
CCD Image – Changes denoted by dark areas

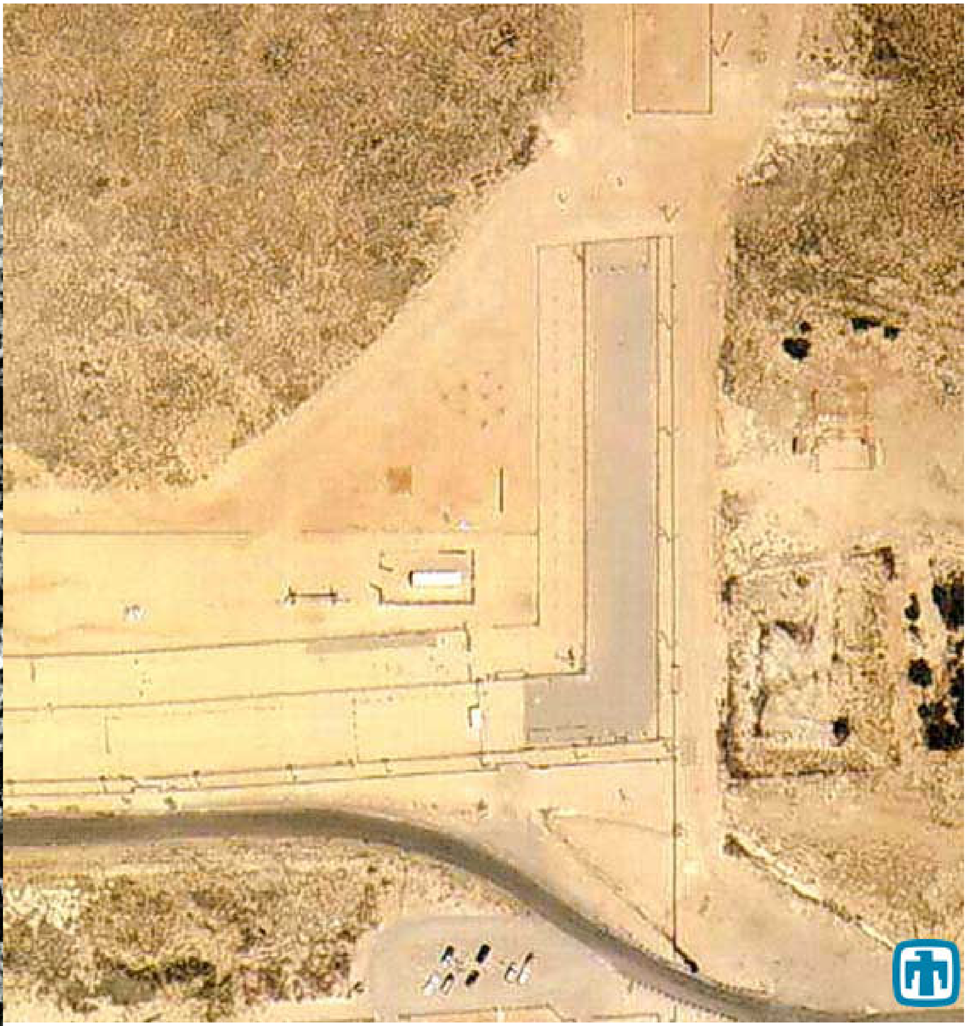


Current SAR Image: Grassy Field

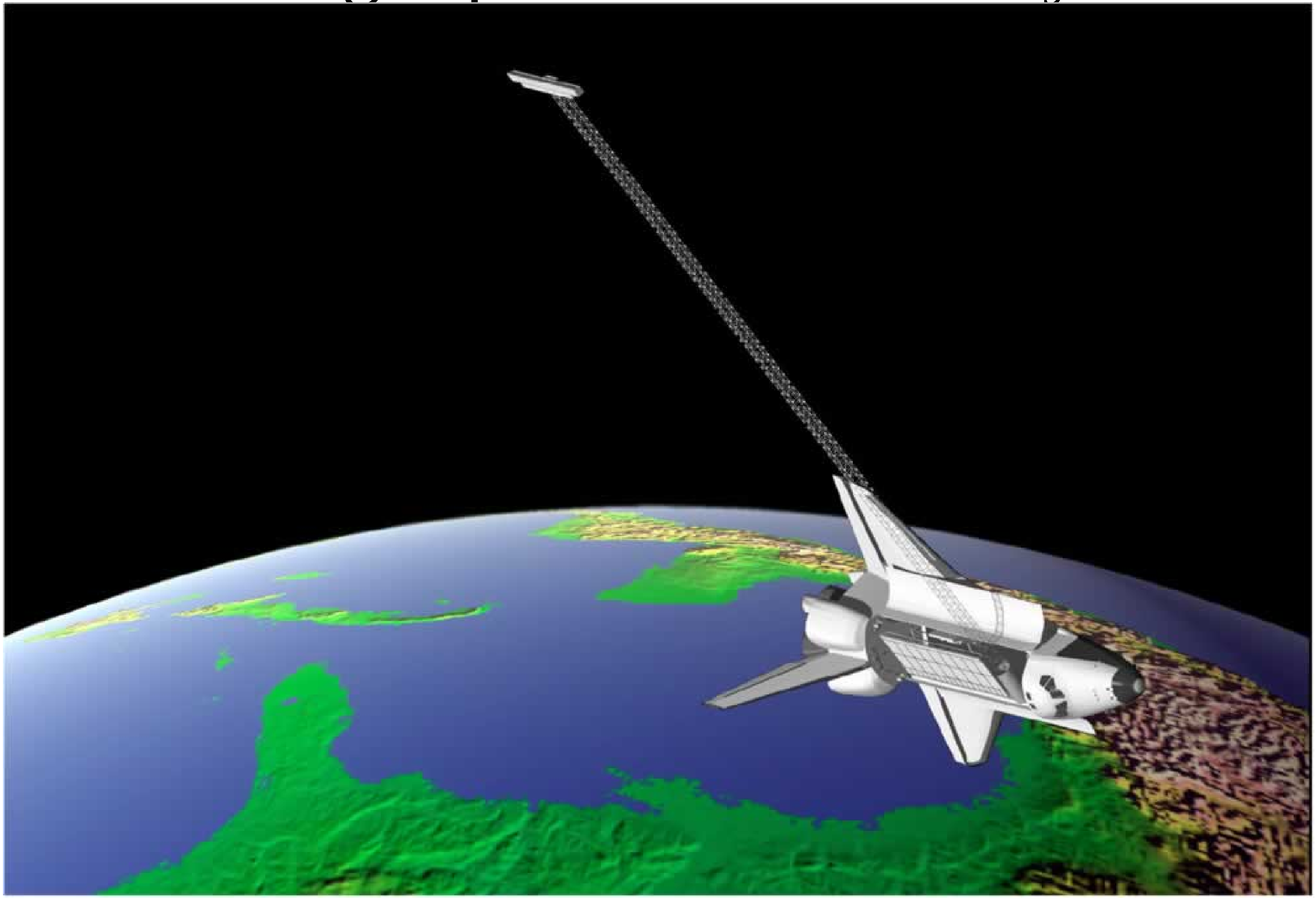


InSAR Coherent Change Detection



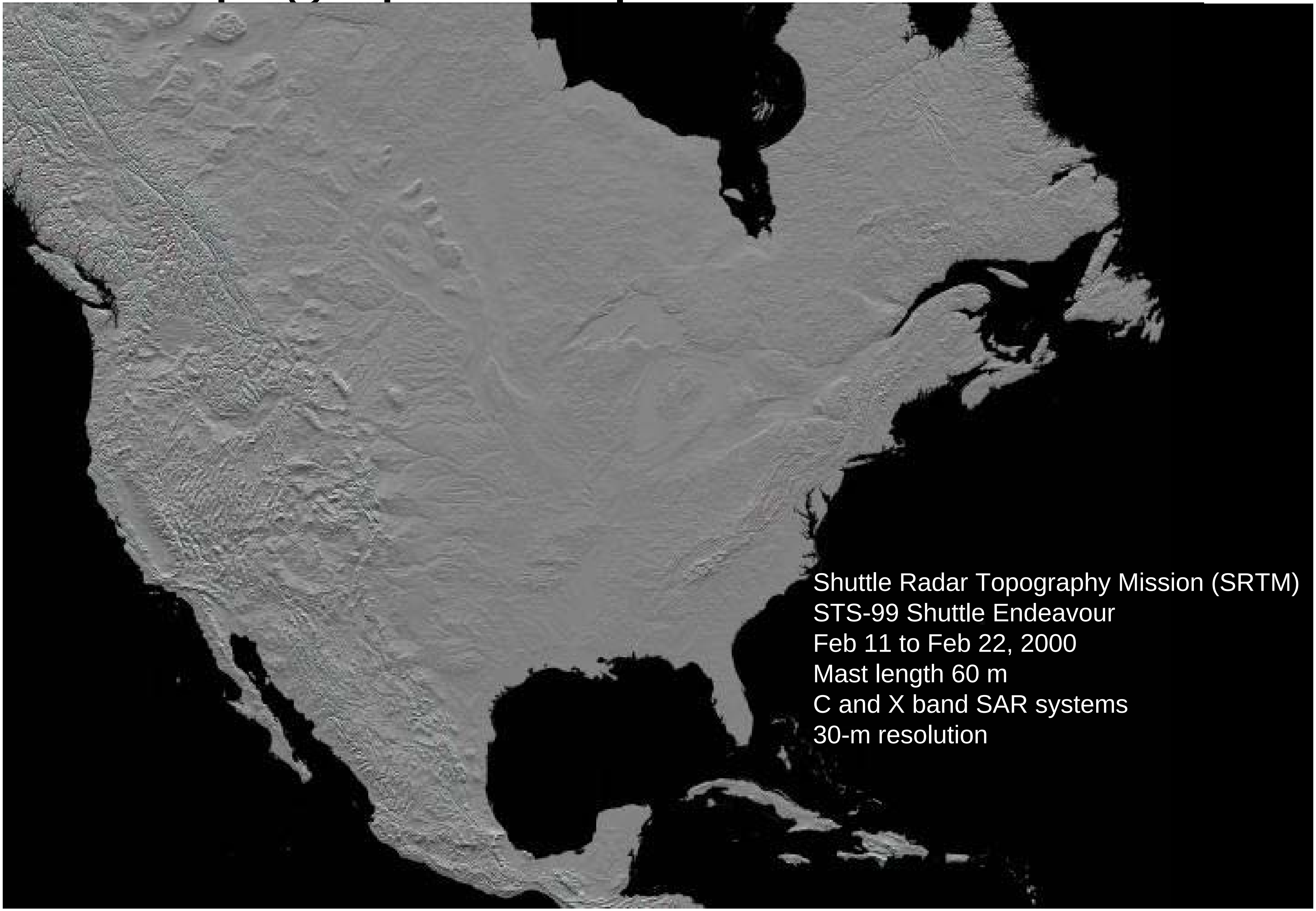


Single-pass interferometry



Single-pass interferometry. Two antennas offset by known baseline.

Topographic map of North America

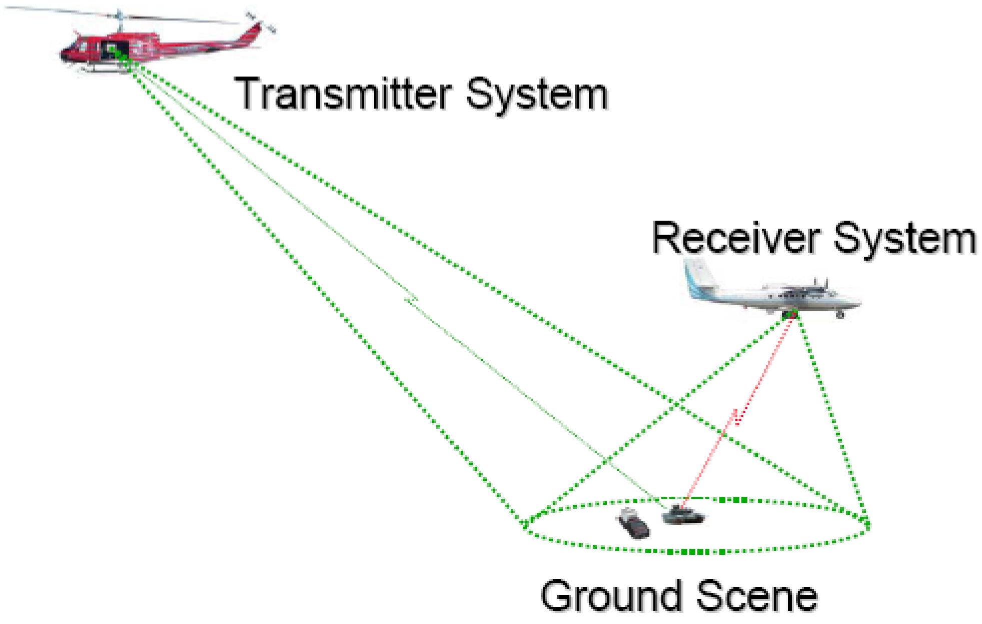


Shuttle Radar Topography Mission (SRTM)
STS-99 Shuttle Endeavour
Feb 11 to Feb 22, 2000
Mast length 60 m
C and X band SAR systems
30-m resolution

Bi-static SAR

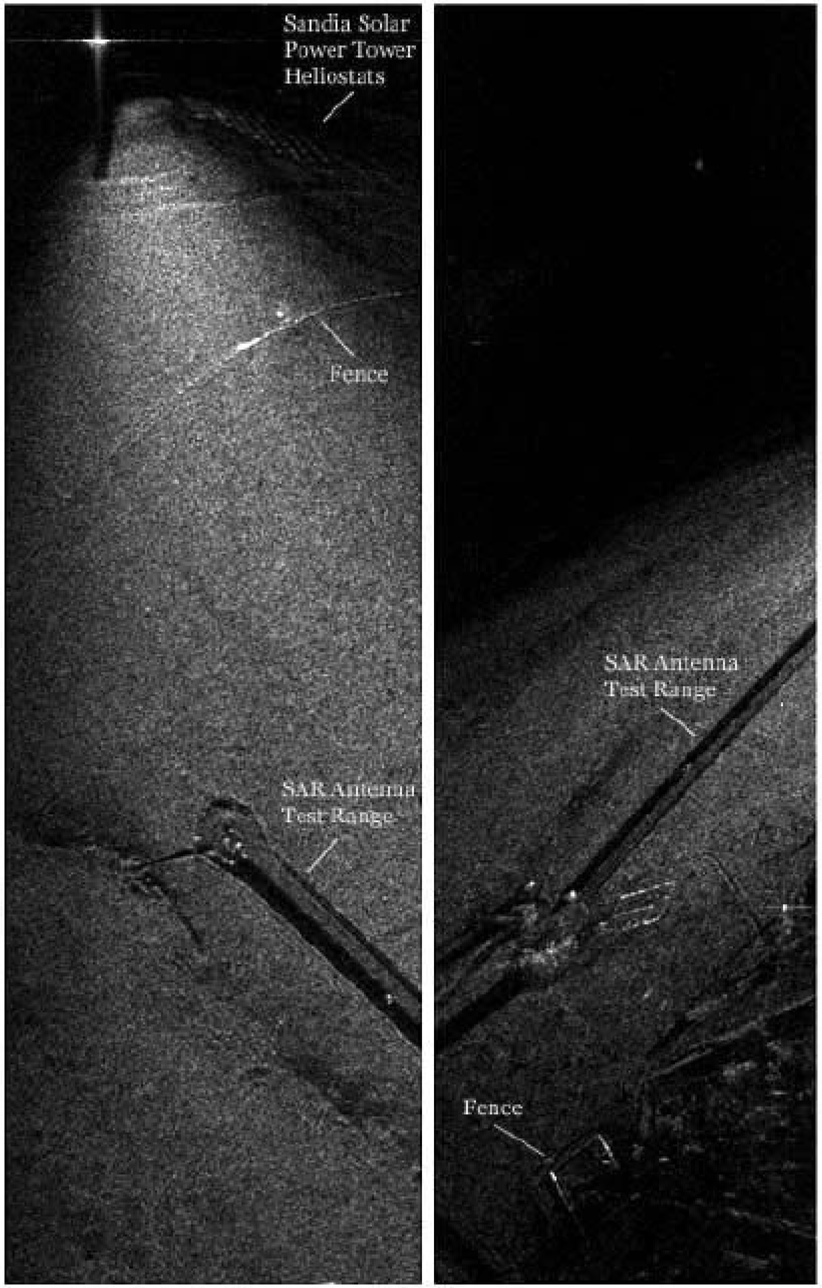
- Bi-static SAR places Transmitter and Receiver on separate vehicles

- Allows unusual geometries
  - stationary transmitter or receiver,
  - looking straight ahead



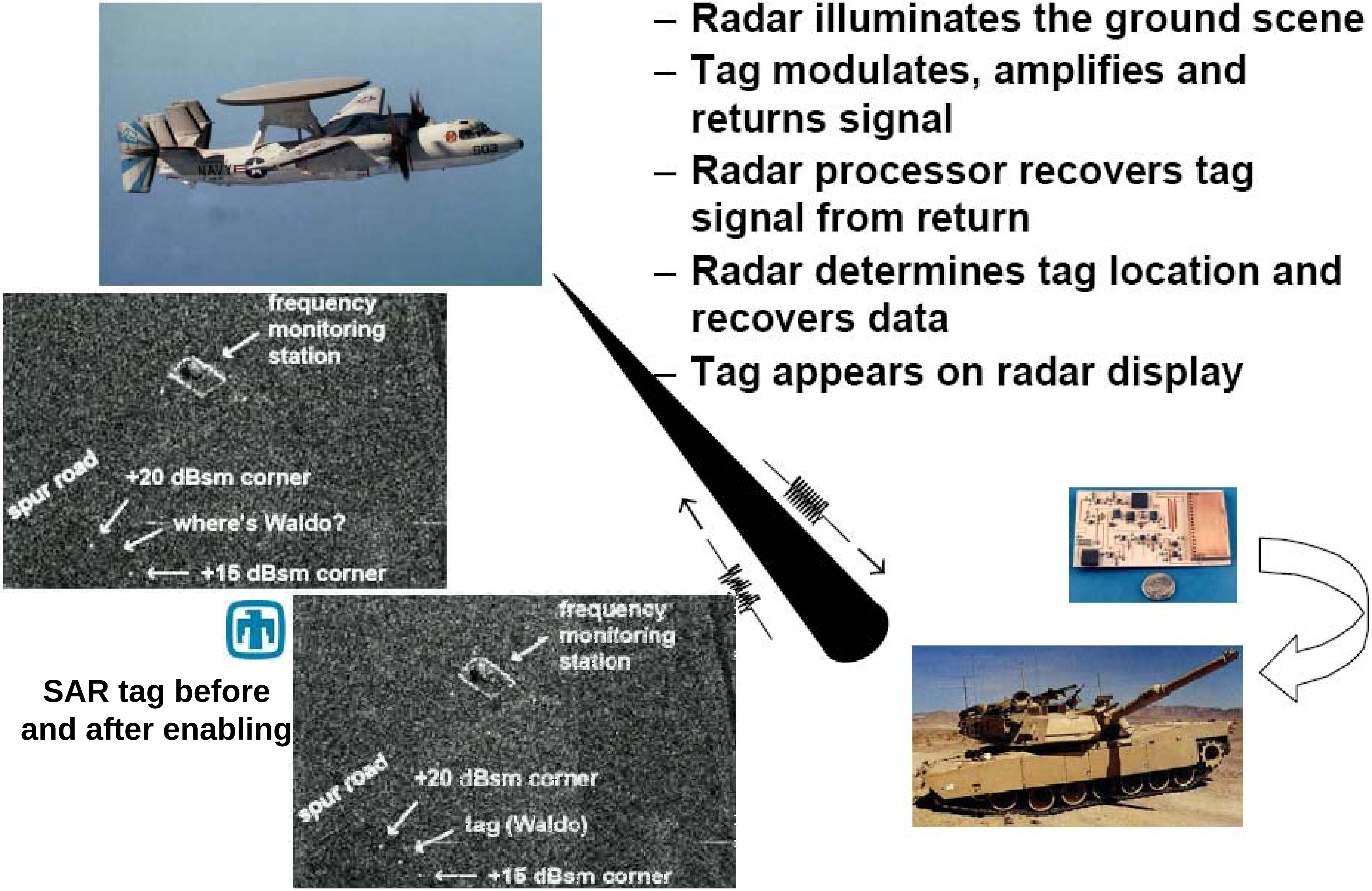
Bistatic Images of Antenna Range

1 Meter Resolution / July 28, 1994



Bistatic Angle = 10° Bistatic Angle = 80°

Radar Responsive Tag System



- Radar illuminates the ground scene
- Tag modulates, amplifies and returns signal
- Radar processor recovers tag signal from return
- Radar determines tag location and recovers data
- Tag appears on radar display

SAR tag before and after enabling

Challenges in radar

Weak received signal power (spherical spreading loss) $P_R \propto P_T \big/ (4\pi)^2 R^4$

	Basketball court	Sear's tower	Jet aircraft	Space station	Moon
R	(94') 29 m	(1450') 442 m	(30,000') 10 km	360 km	384,400 km
$1 / (4\pi)^2 R^4$	9×10^{-9}	1.7×10^{-13}	6.3×10^{-19}	3.8×10^{-25}	2.9×10^{-37}
P_R*	0.0009 W	1.7×10^{-8} W	6.3×10^{-14} W	3.8×10^{-20} W	2.9×10^{-32} W

* assumes $P_T = 100$ kW $= 10^5$ W (KANU effective broadcast power)

Noise (anything above absolute zero radiates thermal noise) $P_N = kTB$

k = Boltzmann's constant (1.38×10^{-23} J/K)

T = temperature in Kelvin (normal room temperature is ~290 K)

B = bandwidth (Hz)

Bandwidth impacts the ability to measure range accurately or to resolve multiple targets at similar ranges, otherwise we'd set B to a very small value.

Range resolution, ρ, is bandwidth dependent, $\rho = \frac{c\tau}{2} = \frac{c}{2B}$

	10 Hz	1 kHz	200 kHz	10 MHz	300 MHz
P_N	4×10^{-20} W	4×10^{-18} W	8×10^{-16} W	4×10^{-14} W	1.2×10^{-12} W
ρ	15,000 km	150 km	750 m	15 m	50 cm

Challenges in radar

Clutter (one man's trash is another man's treasure)
Example, when looking for subsurface targets (land mines, subglacial features, subterranean structures, etc.) the surface echo can obscure the desired echo.

Antennas (size $\propto$ wavelength)
Key properties include: frequencies of operation (bandwidth), beamwidth, polarization, steerability, size, weight, cost.

Different radar applications

- Weather radar (ascertains precipitation's location, intensity, and nature (snow vs. rain))
- Police radar
- Collision avoidance radar
- Ground-penetrating radar (archeology, geology, crime scene investigation, civil engineering, …)
- Aircraft detection and tracking (military) (measures aircraft's altitude, speed, heading, type, …)
- Projectile tracking (defense ICBM early warning radar, asteroid tracking, source of mortar fire)
- Imaging radar (geography, military, scientific exploration, surface elevation, etc.)

Radar research thrusts

- Making smaller, more versatile radars (programmable, low cost, network of radars)
- Designing optimum radar for particular application (looking for water/ice on Mars, characterizing Europa's icy shell)
- Advanced signal processing (clutter rejection, super resolution, autofocus, …)
- Bistatic or multistatic radar (new capabilities because of new geometry, detecting stealthy targets)
- Passive radar (take advantage of transmitters of opportunity: TV, FM, GPS, DirecTV, etc.)