Principles of Radar

an introductory view

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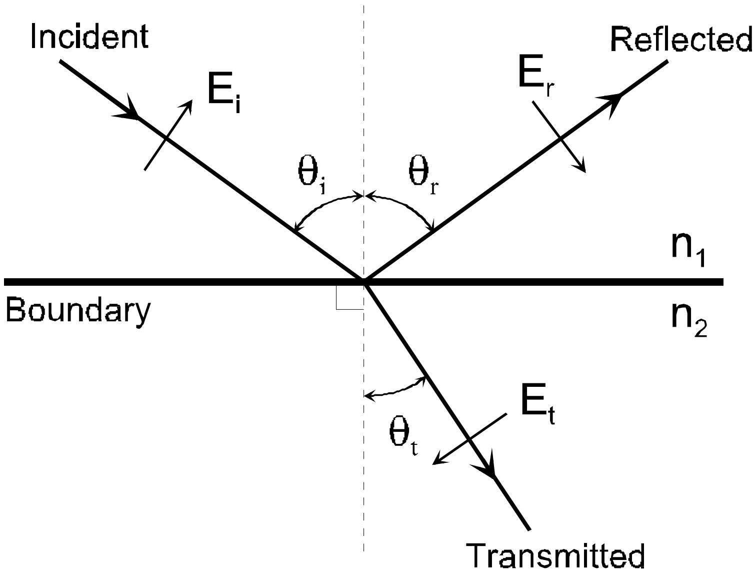
Basic concepts

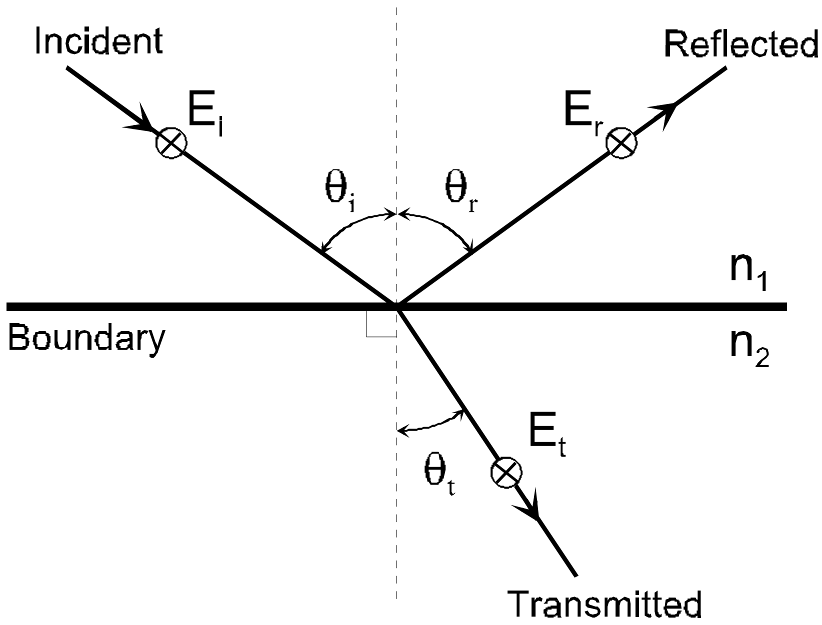
- EM signal transmission
- Signal reception
- Infer information about the 'target' by comparing received signal with transmitted signal

EM signals

- Frequency, wavelength, polarization, and speed of light
- signals propagate at speed of light, $c = 3 \times 10^8$ 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

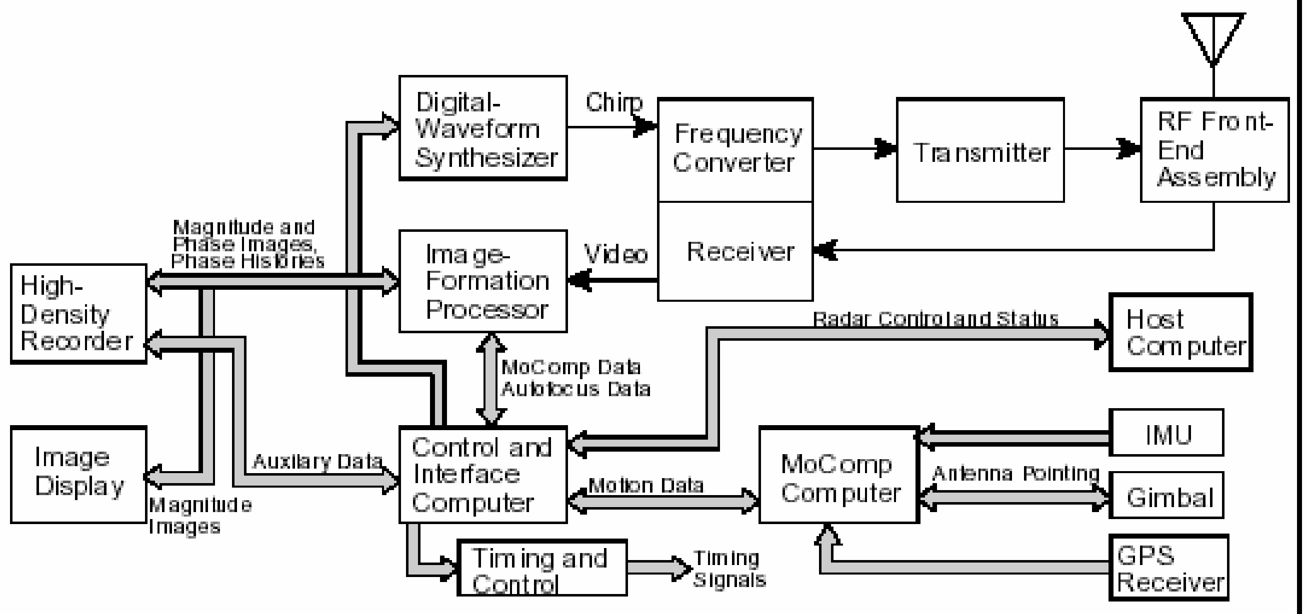


Figure 4. Simplified Block Diagram of the Twin-Otter SAR

What can be measured

Target range

Transmitted signal is time-gated sinusoid,

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

(pulse duration is τ)

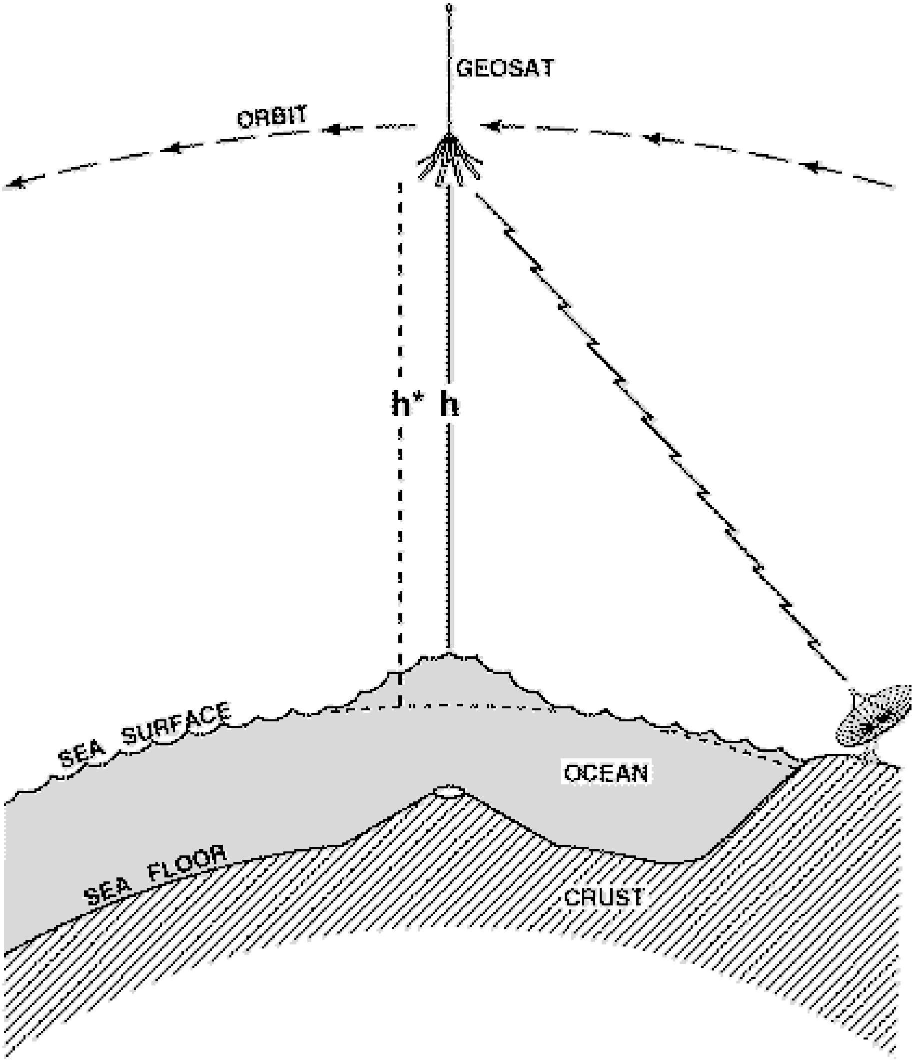
Received signal is

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

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

and we can measure time with great precision

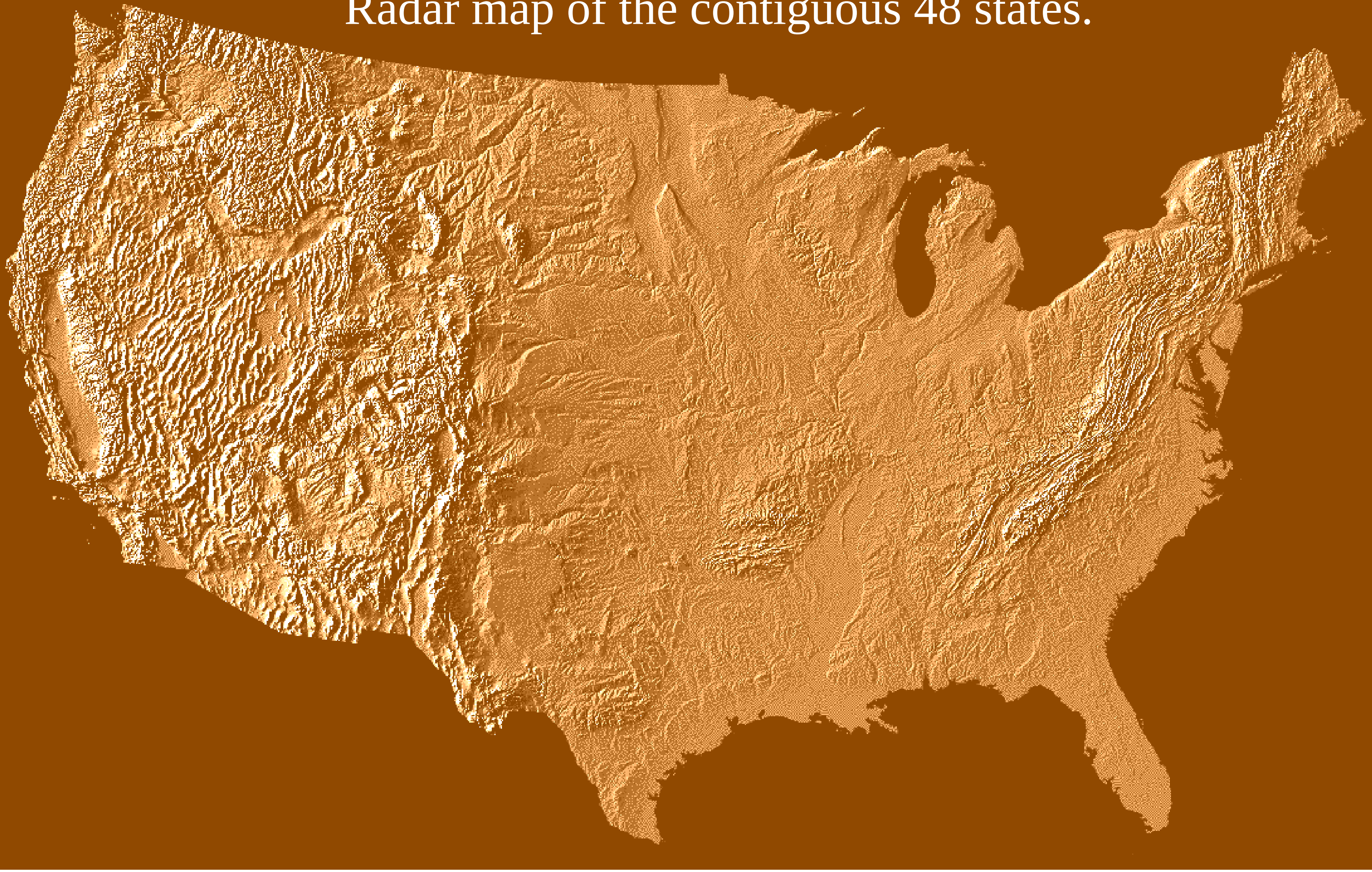
Target Range - Altimeter



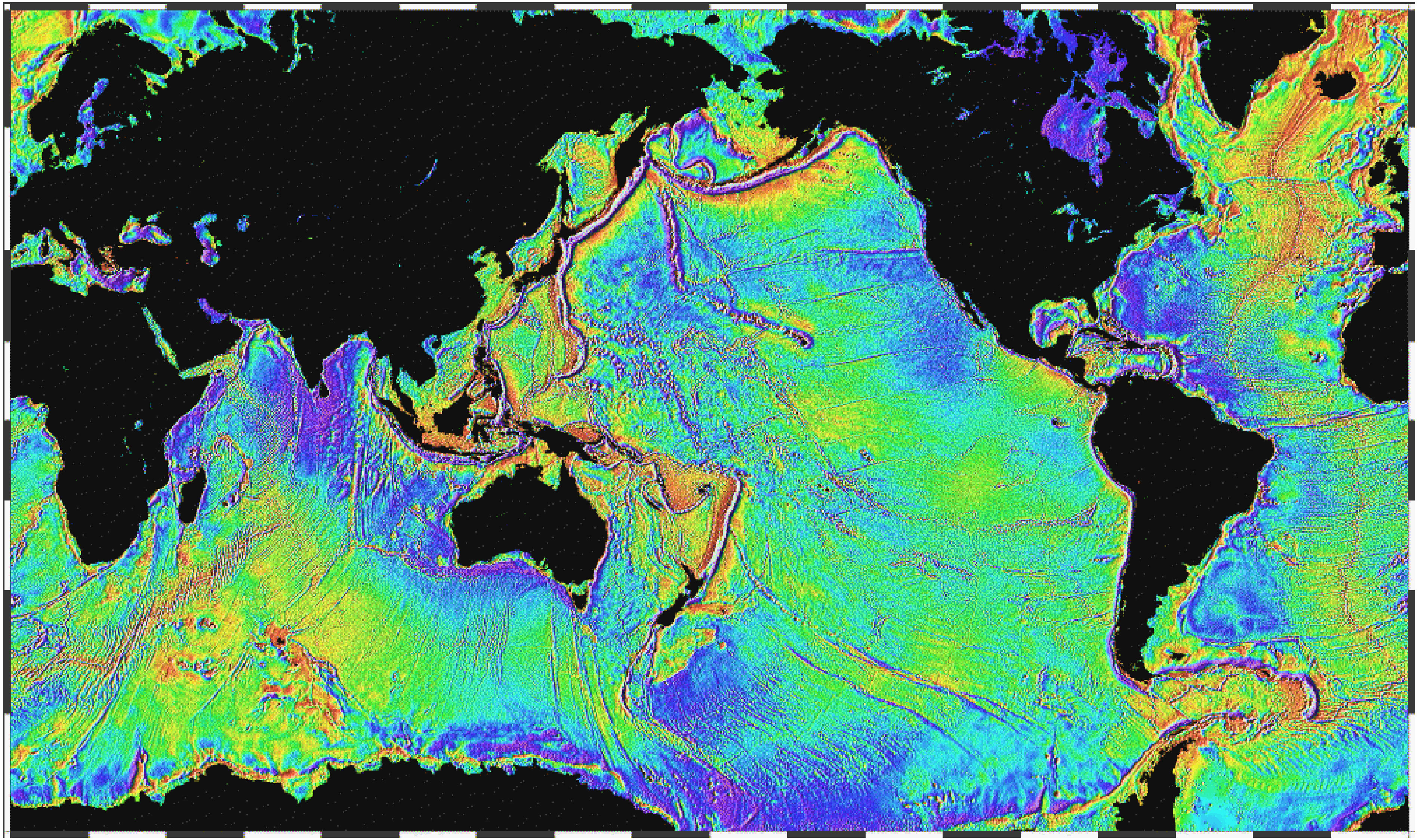
Altimeter concept.

Altimeter data

Radar map of the contiguous 48 states.



Altimeter data



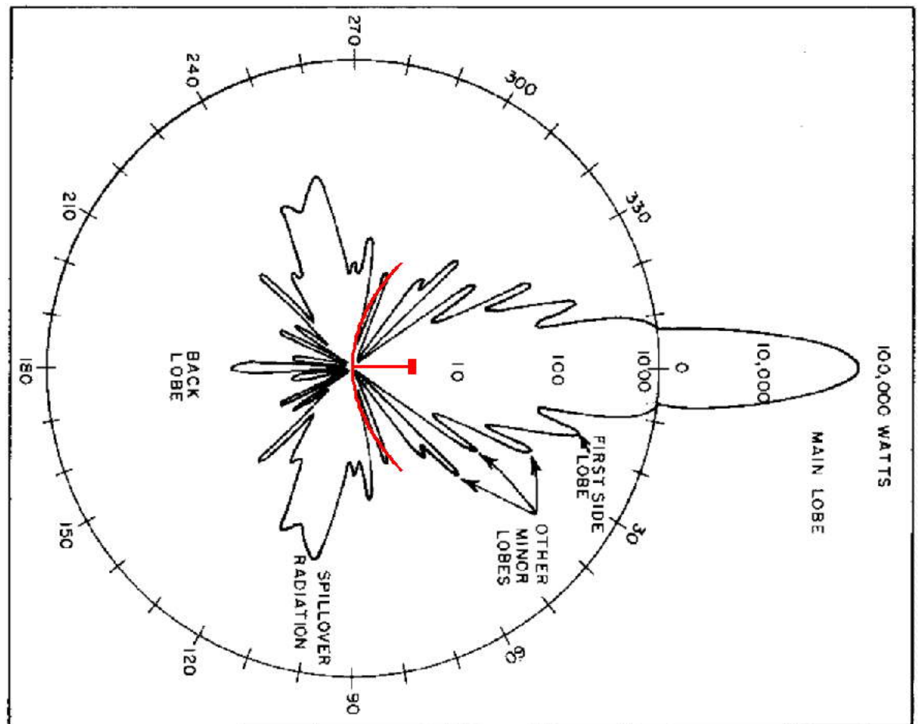
Global topographic map of ocean surface produced with satellite altimeter.

What can be measured

Spatial extent of target

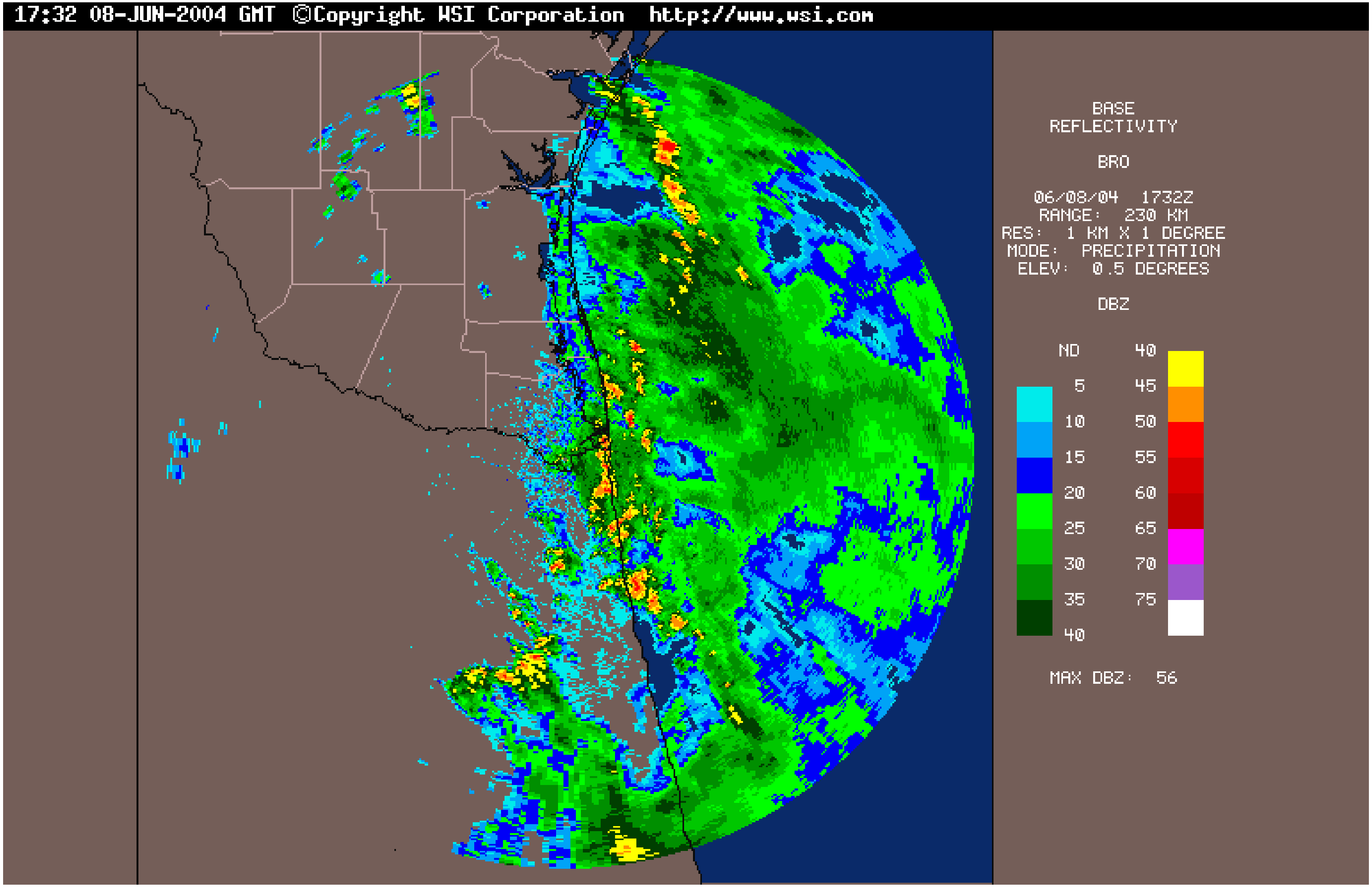
Antenna directs radar signal in narrow beam, rotating antenna enables radar to scene in a circular fashion

Radar antenna.



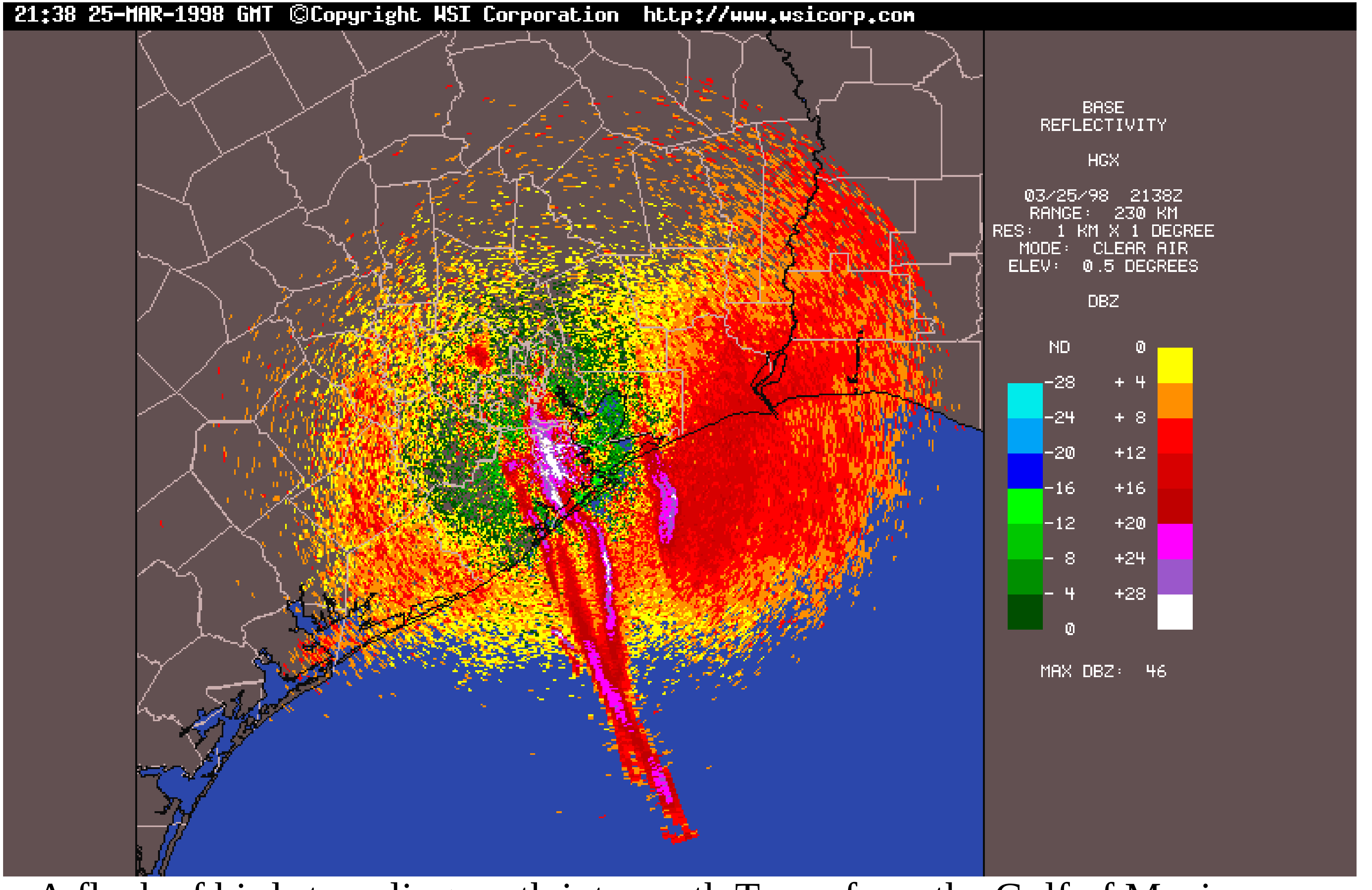
Radiation pattern of radar antenna.

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

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

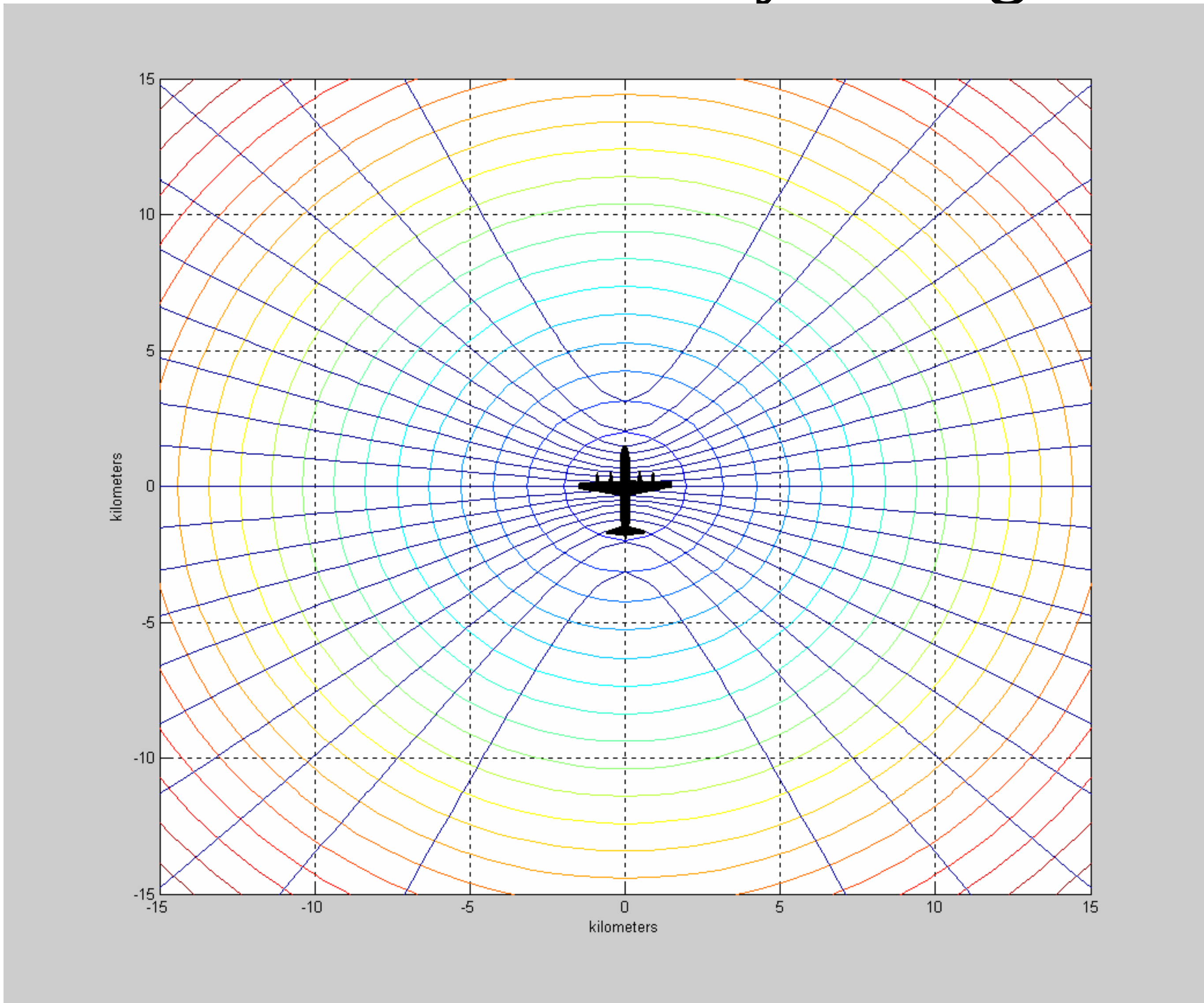
which can be shown to be

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

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

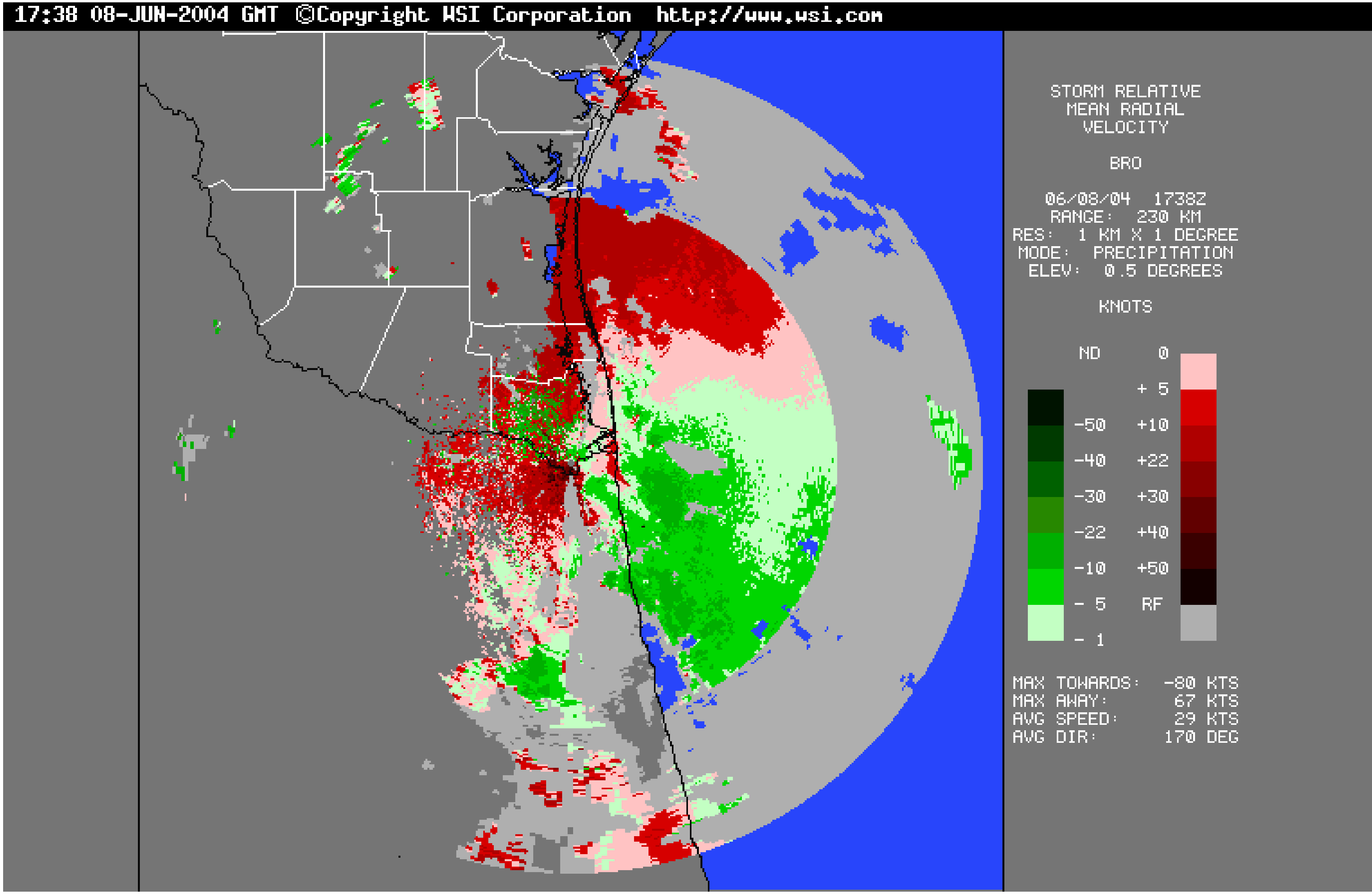
$$p(t) = B\cos[2\pi(f_{TX} + f_D)t + \phi_{TX}] \qquad \text{for } T \le t \le T + \tau$$

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

Relative radial velocity of target

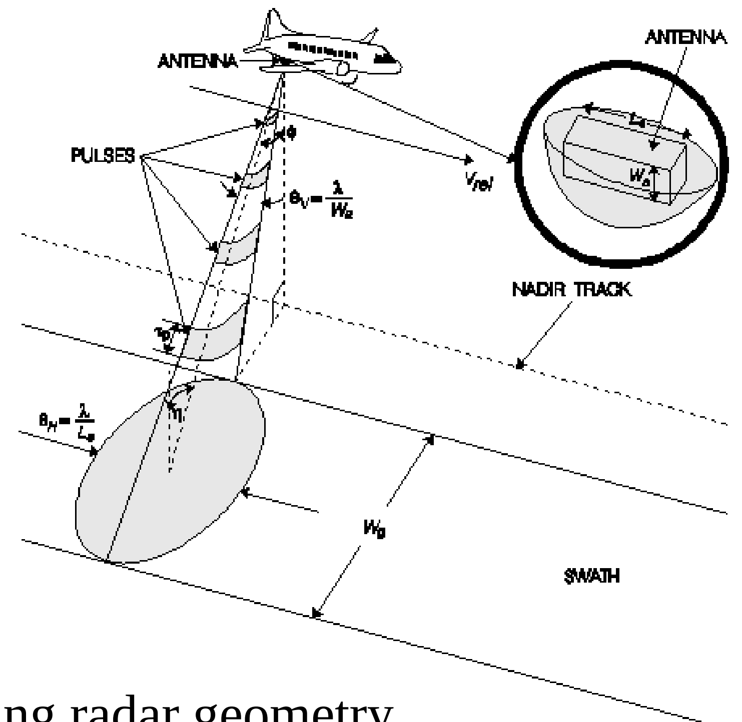


Radial velocity of precipitation near Brownsville, Texas.

What can be measured

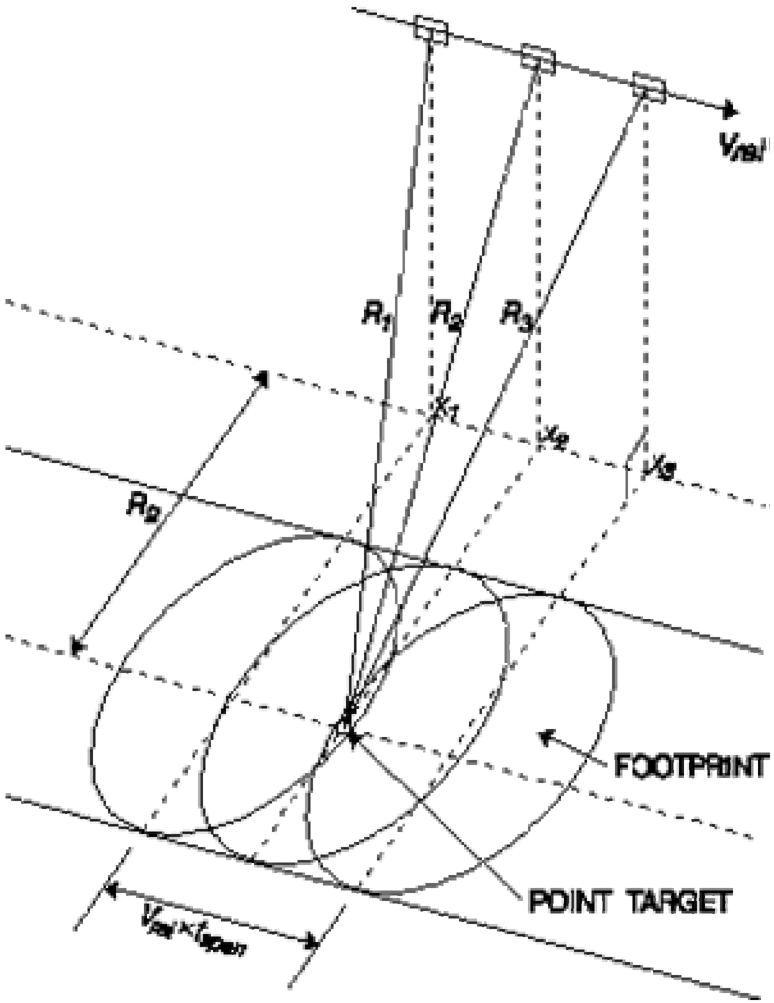
Target reflectivity

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.

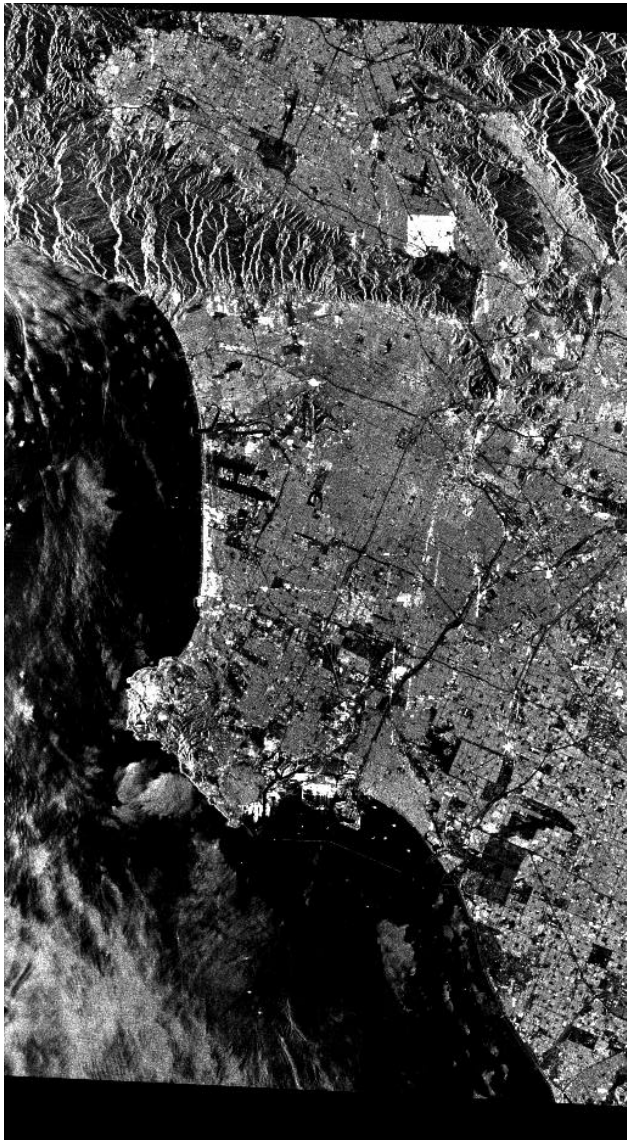


Imaging radar geometry

Target reflectivity



Synthetic-aperture radar (SAR) geometry



SAR image of Los Angeles, CA area.

Examples of SAR Imagery

Washington, D.C. area

Aerial photo, 8-m resolution (USGS)

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

Examples of SAR Imagery

Washington, D.C. mall area

Aerial photo, 8-m resolution (USGS)

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

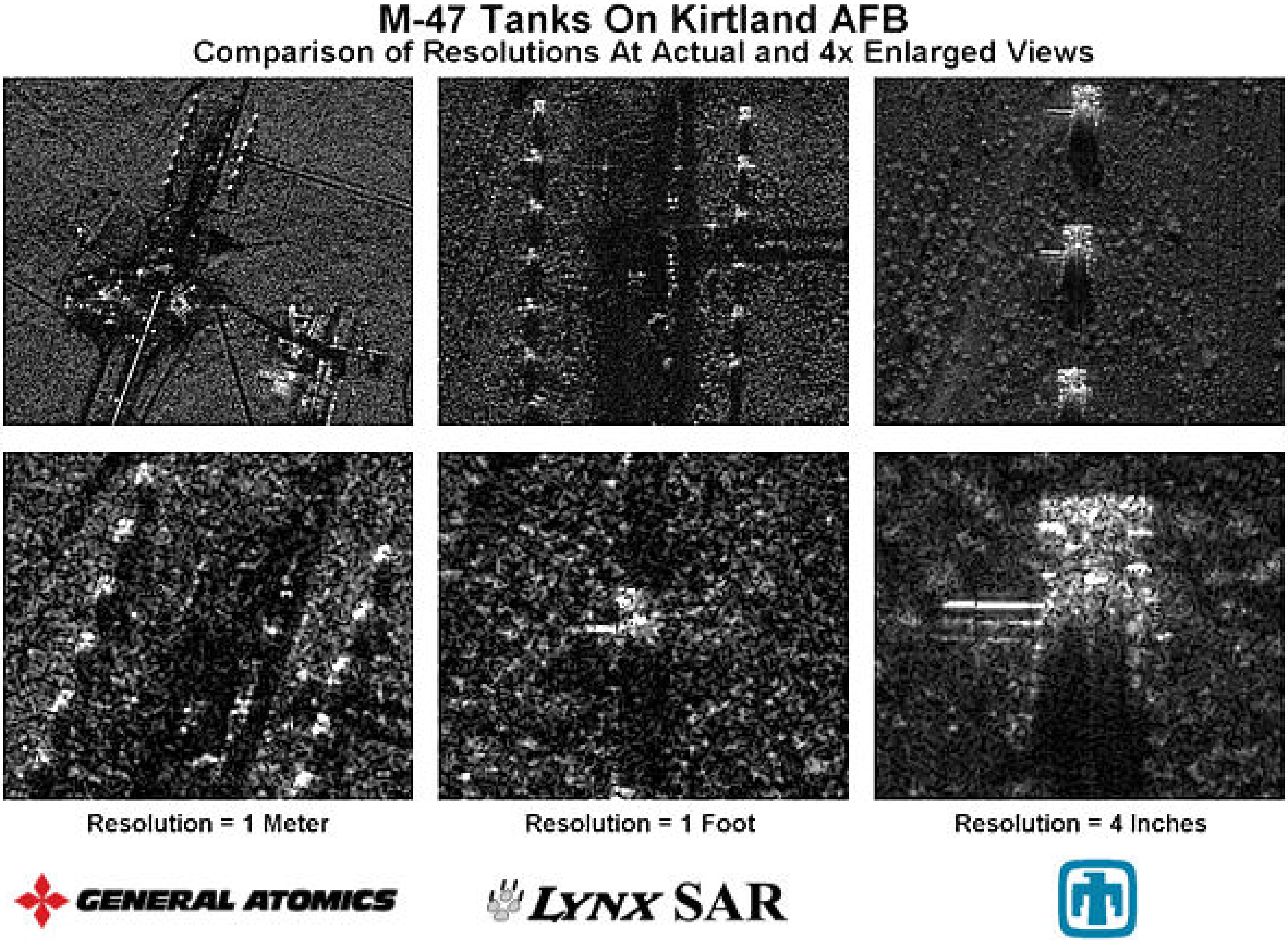
Examples of SAR Imagery

Capitol building, Washington, D.C.

Aerial photo, 1-m resolution (USGS)

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

Examples of SAR Imagery



SAR images of M-47 tanks at various resolutions (Sandia National Laboratory)

Photo of M-47 tanks at ground level

Challenges in radar

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

	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.)