Radar Remote Sensing

Paul A. Rosen
Jet Propulsion Laboratory
California Institute of Technology

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Acknowledgements

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Overview

- What is radar remote sensing?
  - Remote sensing problems, phenomenology, and radar solutions
- Radar observables and observing systems
- Example systems and applications

What is Remote Sensing?

From Wikipedia:

Remote sensing is the acquisition of information about an object or phenomenon, without making physical contact with the object.

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What is Remote Sensing?

In modern usage, **Remote sensing** generally refers to the use of aerial [or satellite] sensor technologies to detect and classify objects on Earth [or other planets] (both on the surface, and in the atmosphere and oceans) by means of propagated signals (e.g. electromagnetic radiation emitted from aircraft or satellites).

- Active
  - Radar, sonar, lidar…
- Passive
  - Multi/hyperspectral, photometers, radiometers, gravity sensors, field detectors, seismometers…
- Technique and sensor choice depends on what information is desired and the required accuracy and resolution for that information.

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Why Remote Sensing?

- The area to be investigated is too large, inaccessible or hazardous (e.g., the Amazon basin, other bodies in the solar system, around an active volcano) for in situ observation.
- Remote sensing systems may be sensitive to aspects of the environment that elude our senses.
- Remote sensing provides a mechanism to efficiently, objectively* and quantitatively* monitor the processes that govern changes to the environment either from natural or anthropogenic causes.

* (albeit often with models and assumptions)

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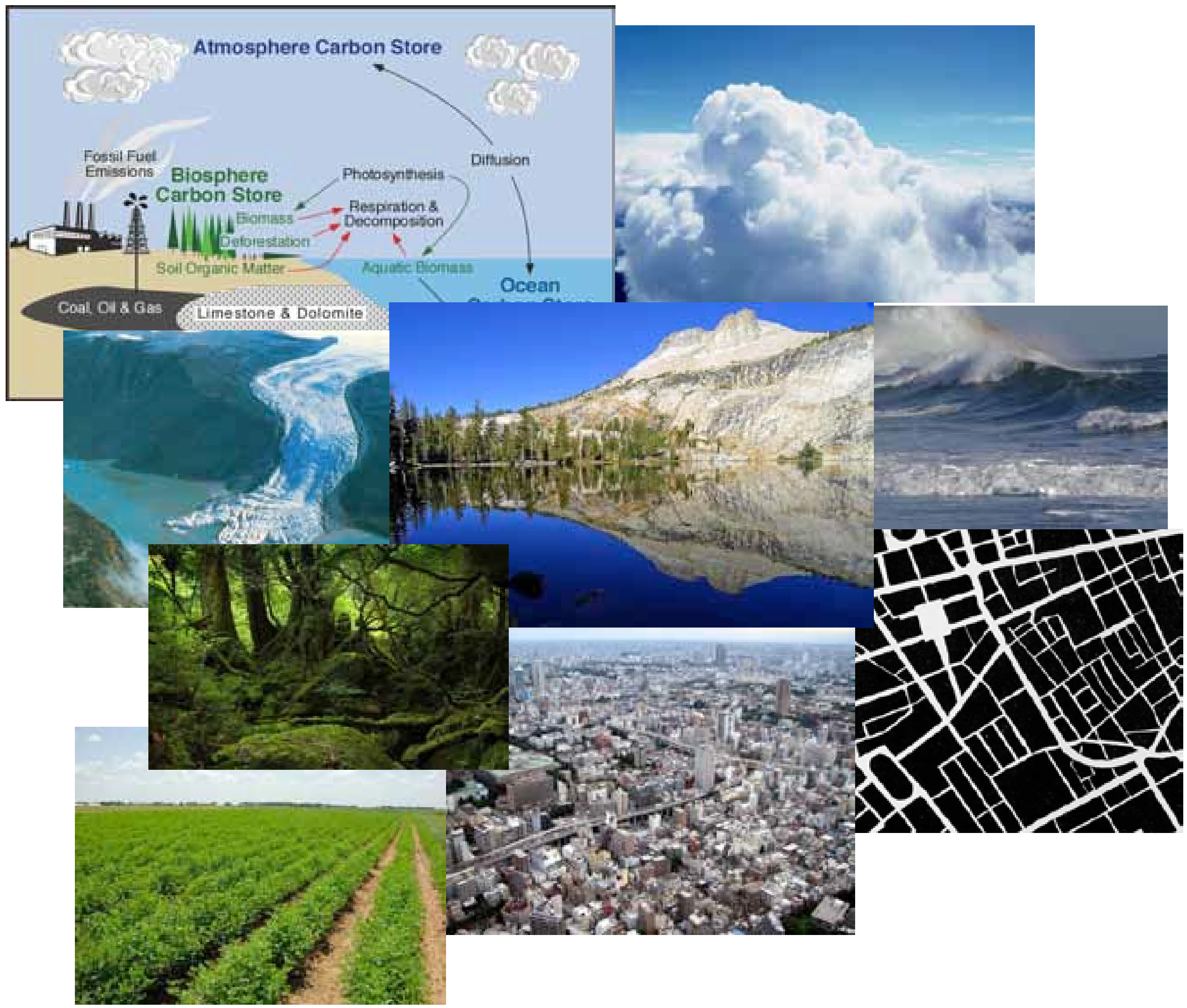
What do we want to measure?

- Topography
- Geography
- Chemistry
  - Composition
  - Phase
- Dynamics
  - Thermo-
  - Hydro-
  - Geo-
  - Bio-



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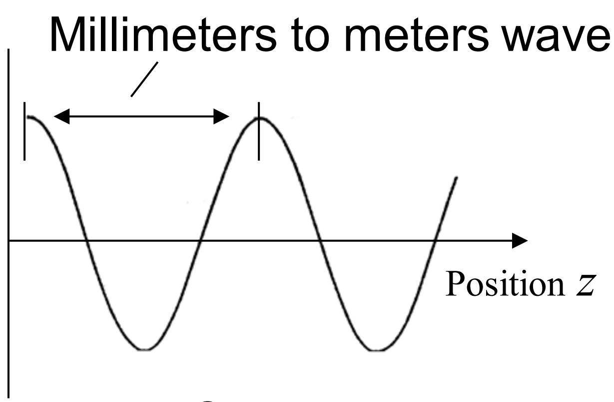
Radar and Light Waves



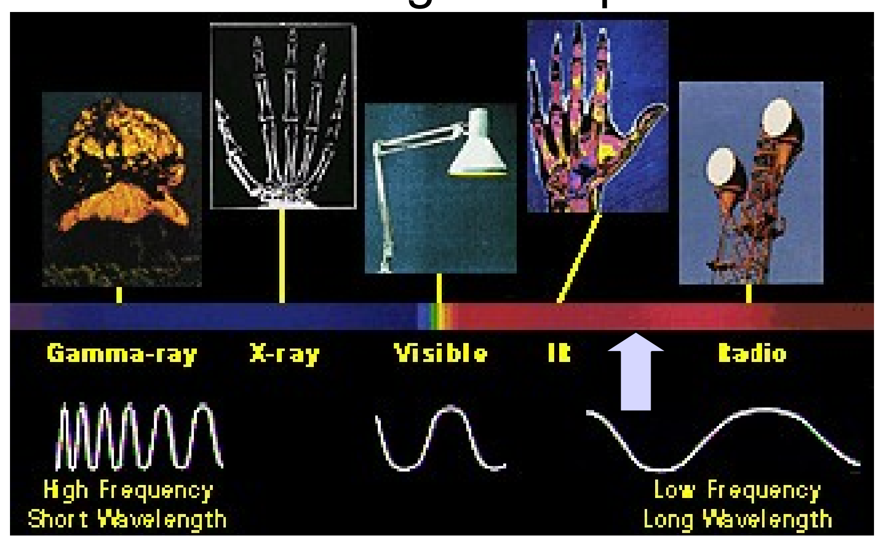
$$\lambda = \frac{c}{f}$$

- Radars operate at microwave frequencies, an invisible part of the electromagnetic spectrum
- Microwaves have wavelengths in the millimeter to meter range
- Like lasers, radars are coherent and nearly a pure tone

Common Radar Frequency Bands

Band	Ka	Ku	X	C	S	L	P
Wavelength (cm)	1	2	3	6	12	24	75
Frequency (G-cycles/s)	30	15	10	5	2.5	1.2	0.4

The Electromagnetic Spectrum



tiny 100’s μm mm’s to m’s

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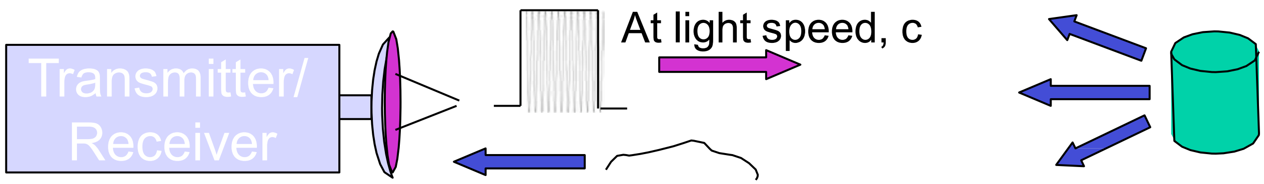
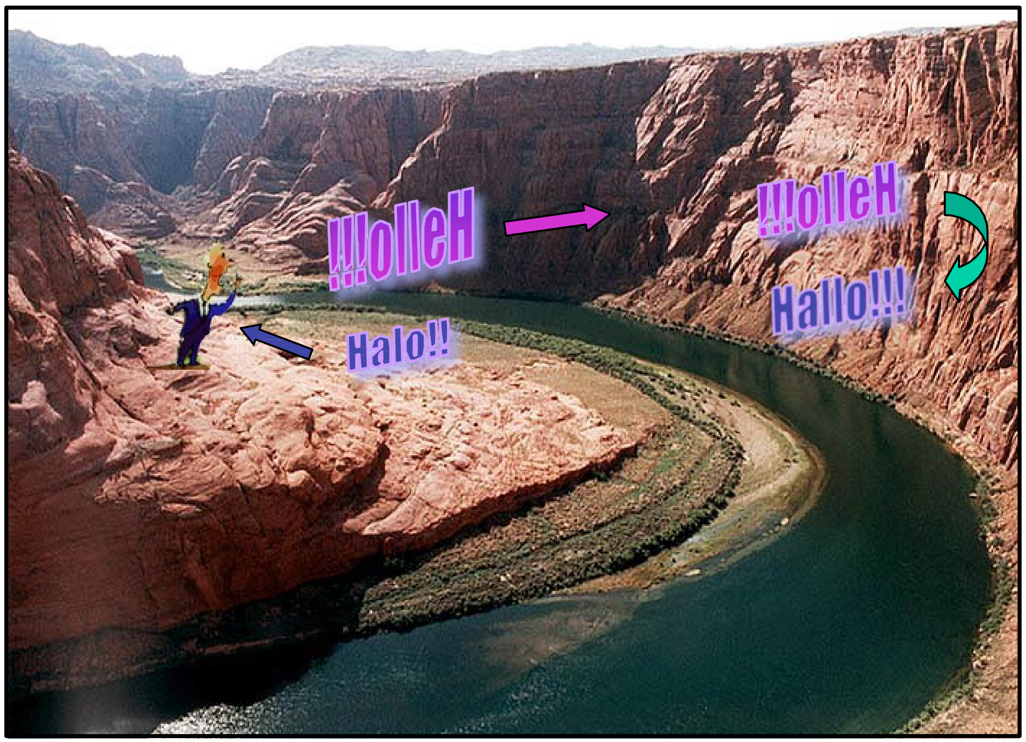
The Radar Concept



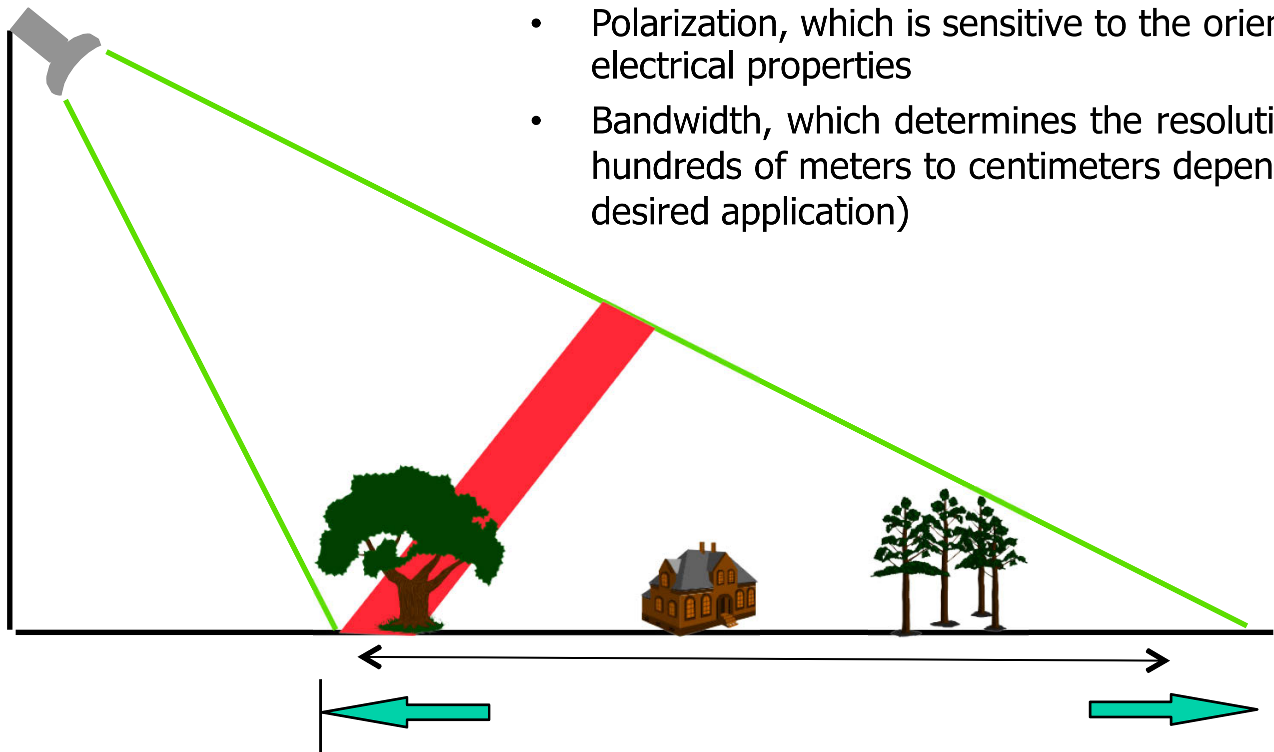
Object scatters energy back to radar



- Much like sound waves, radar waves carry information that echoes from distant objects
- The time delay of the echo measures the distance to the object
- The changes of the message in the echo determine the object characteristics

Radar Remote Sensing

- Radar works by emitting microwave radiation from an antenna and recording the energy reflected from objects in the field of view
  - The returned radar signal depends on several radar parameters
    - Frequency (wavelength) — radar is most sensitive to objects larger than 1/10 of the radar wavelength. Electrical properties of objects change depending on their material composition and on the wavelength
    - Polarization, which is sensitive to the orientation of objects as well as their electrical properties
    - Bandwidth, which determines the resolution of the data (it varies from hundreds of meters to centimeters depending on the radar system and desired application)



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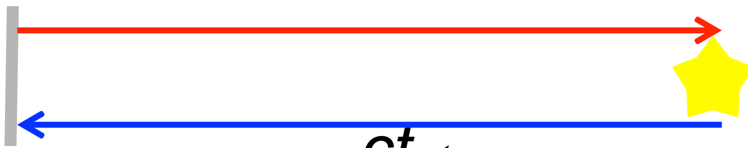
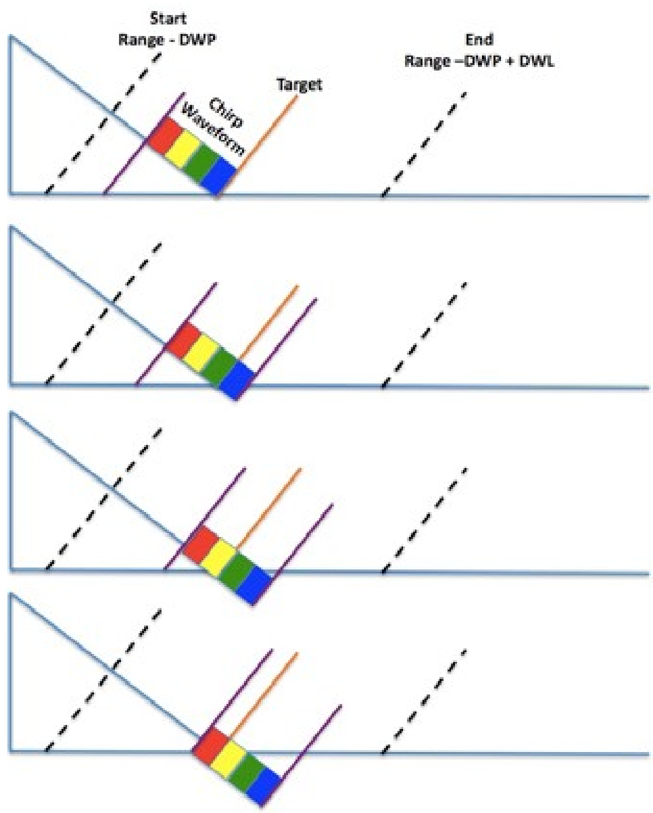
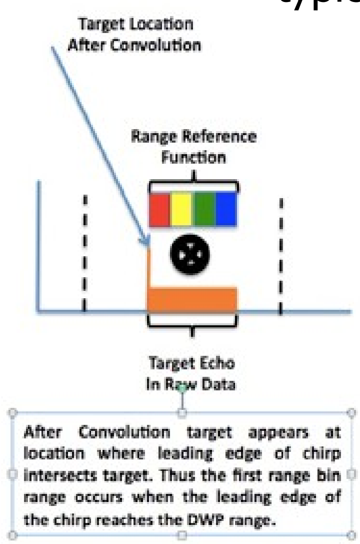
Range and Range Resolution

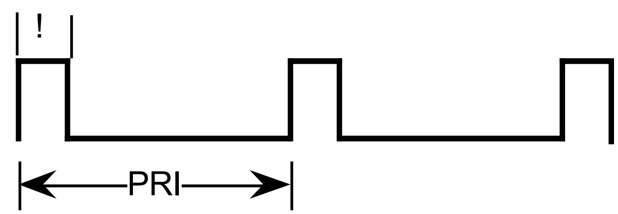


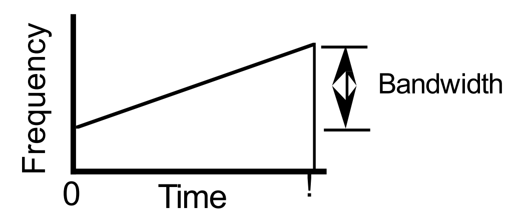
$$\rho = \frac{c t_{rt}}{2}$$





- Range is the distance between the radar and an object
  - Range resolution would normally be limited by the length of the emitted pulse.
  - Better resolution is achieved by transmitting coded waveforms. Most typical encoding is a chirp.





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

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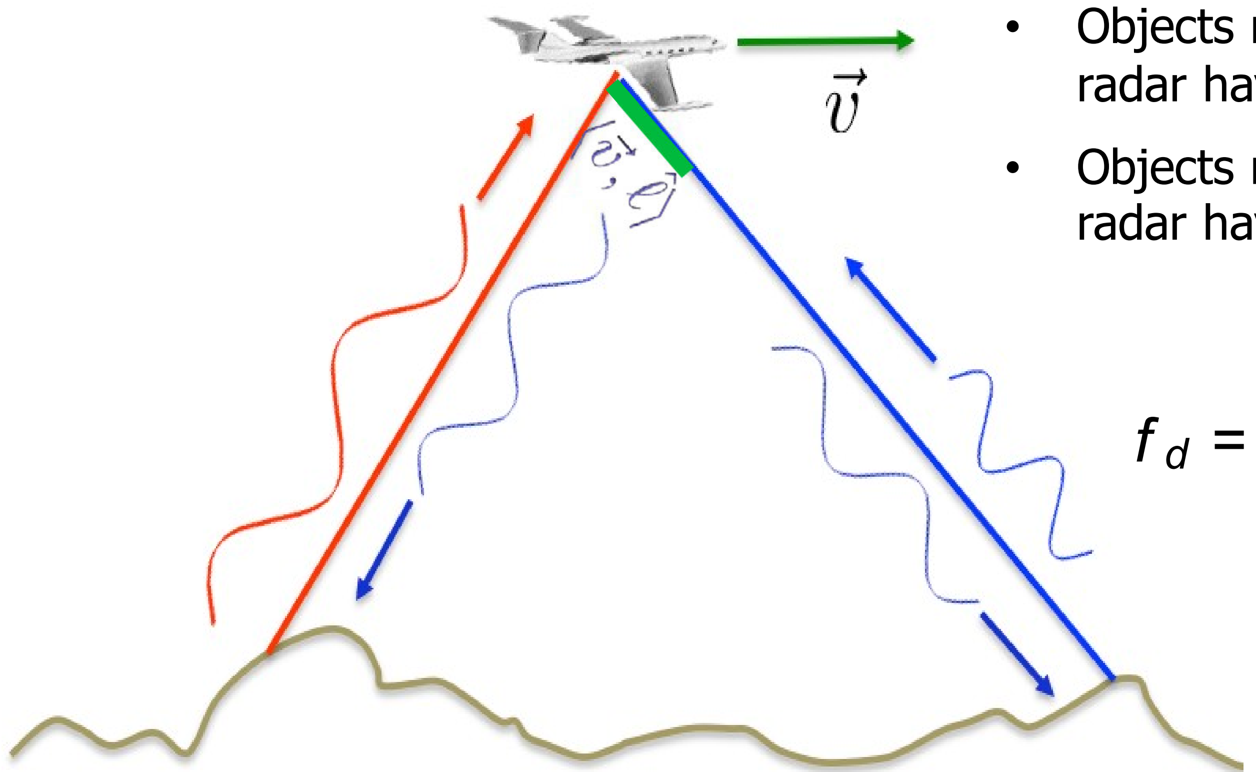
Doppler Shift



- Objects moving relative to a radar experience a frequency shift called the Doppler shift.
- Objects moving toward the radar have higher frequencies
- Objects moving away from the radar have lower frequencies.

$$f_d = \frac{2\langle v, \hat{l}\rangle}{\lambda} = \frac{2v\cos\theta_{sq}}{\lambda}$$

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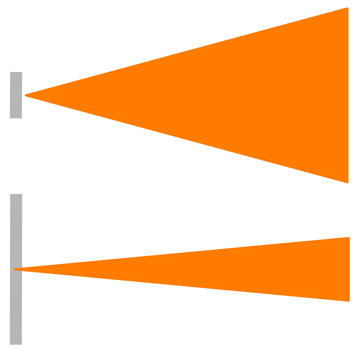
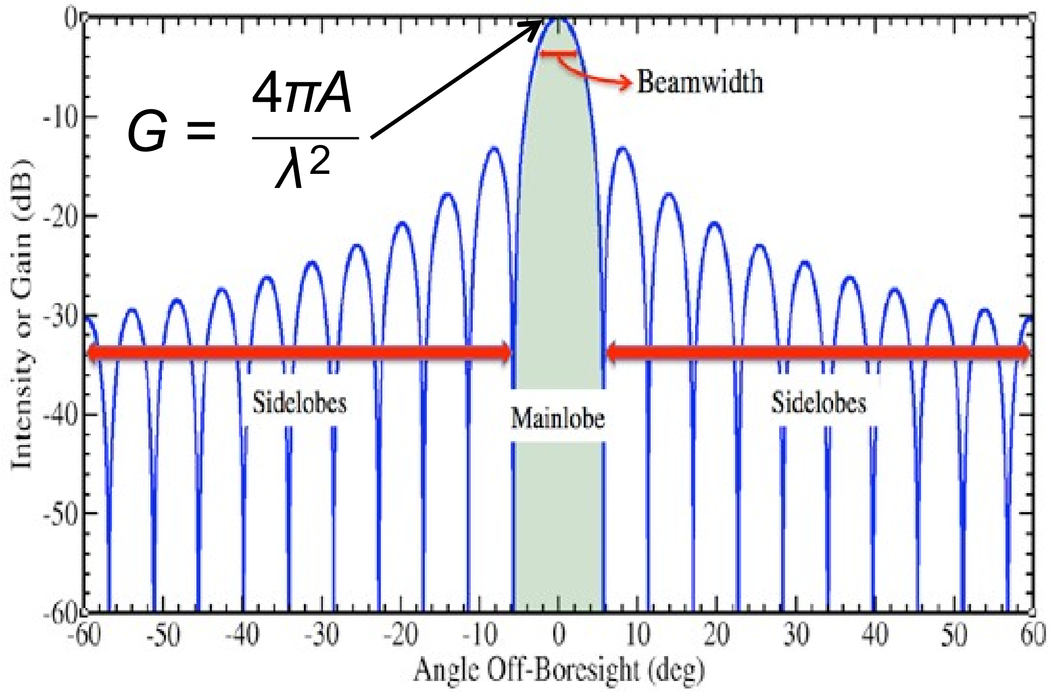
Introduction to Microwaves – Antennas

- Antennas direct the radiation into a desired angular region that depends on the size of the antenna and its wavelength.

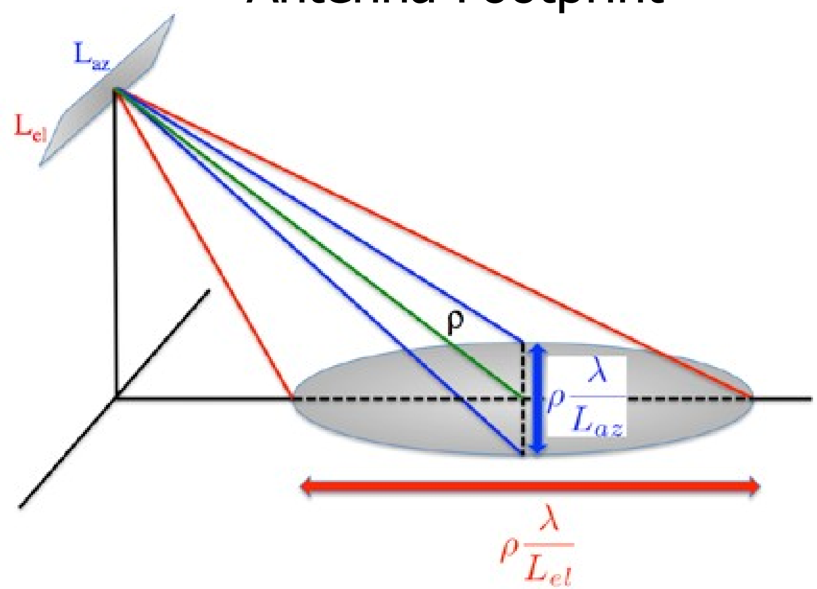
$$\theta_{3dB} \approx k\frac{\lambda}{L}$$



Antenna Gain Pattern



Antenna Footprint



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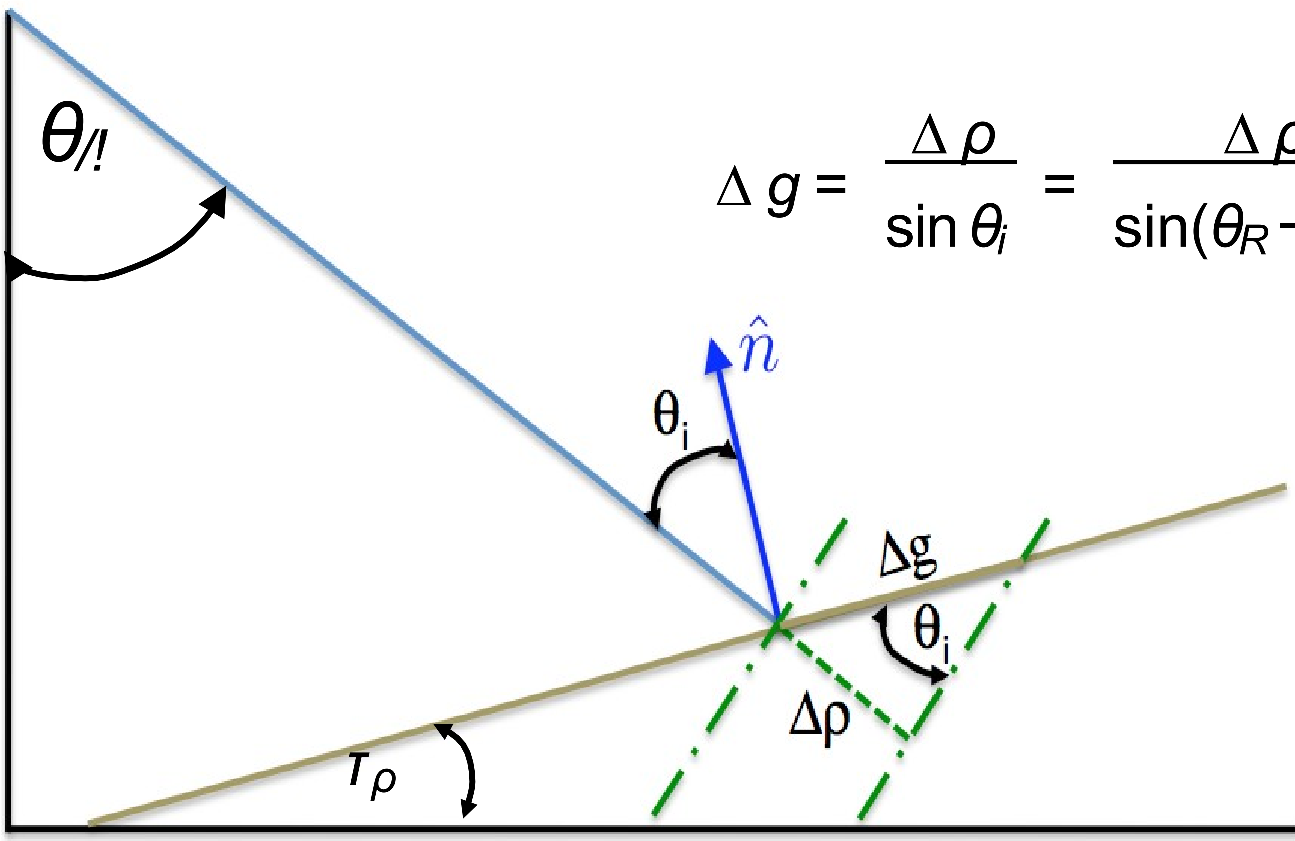
Ground Resolution

- The amount of ground resolution, ! g, depends on the range resolution and incidence angle, ! i.
- Incidence angle is the angle between the wave propagation direction or line-of-sight and the normal to the surface.

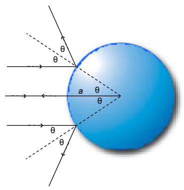
$$\Delta g = \frac{\Delta \rho}{\sin \theta_i} = \frac{\Delta \rho}{\sin(\theta_R - \tau_\rho)}$$

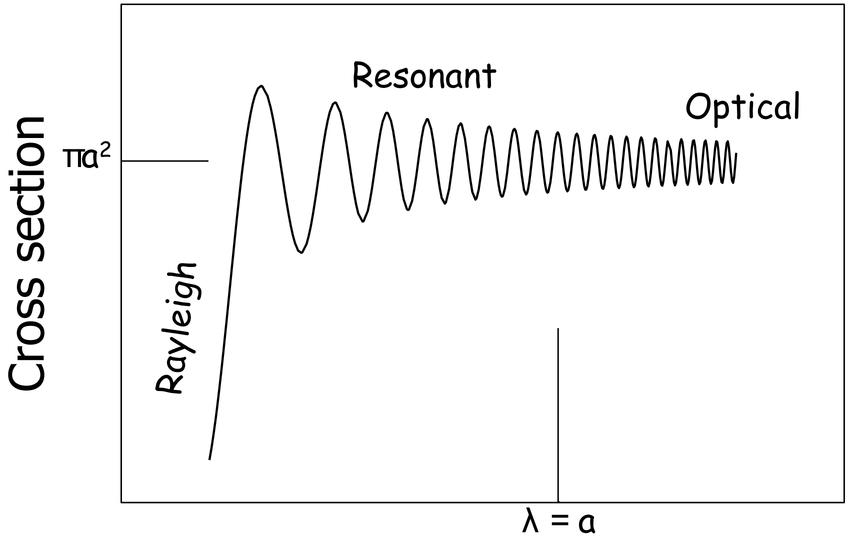


Surface and Volume Scattering Models for Radar

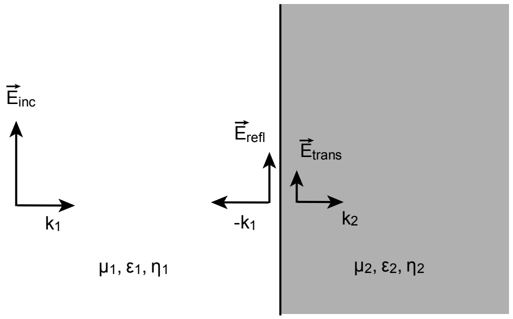
We can model simple scattering from particles or surfaces…

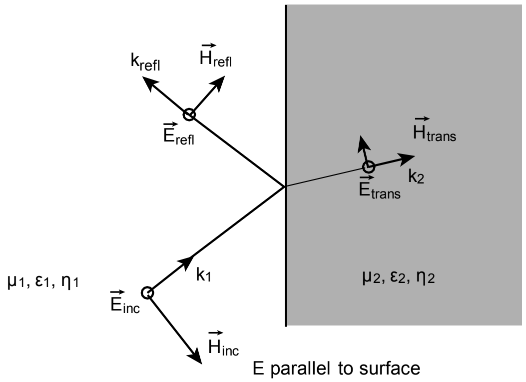
Cross section of a large sphere is its projected area

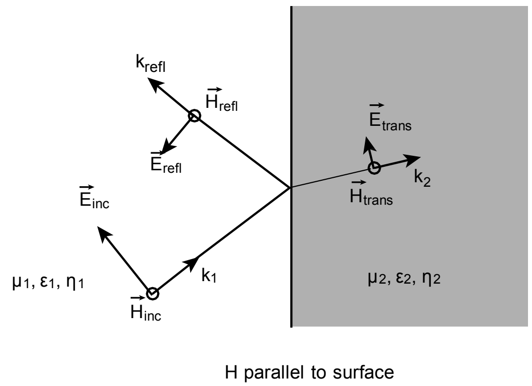




Cross section of a large flat facet goes as area squared







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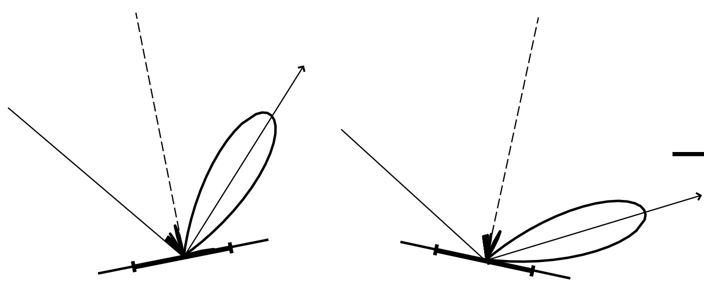
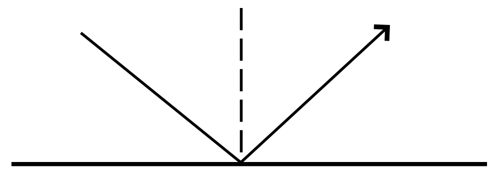
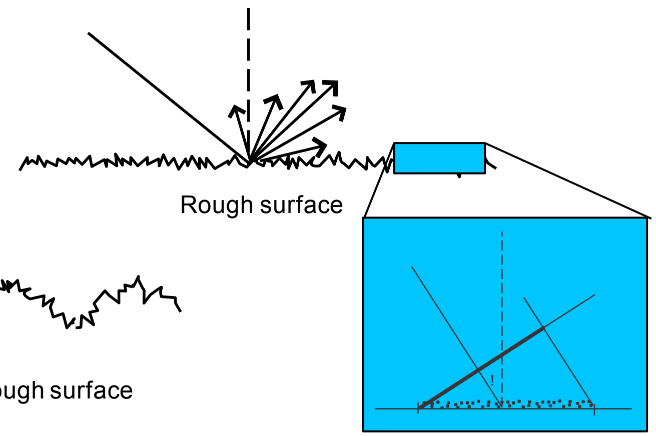
Surface and Volume Scattering Models for Radar





Smooth surface

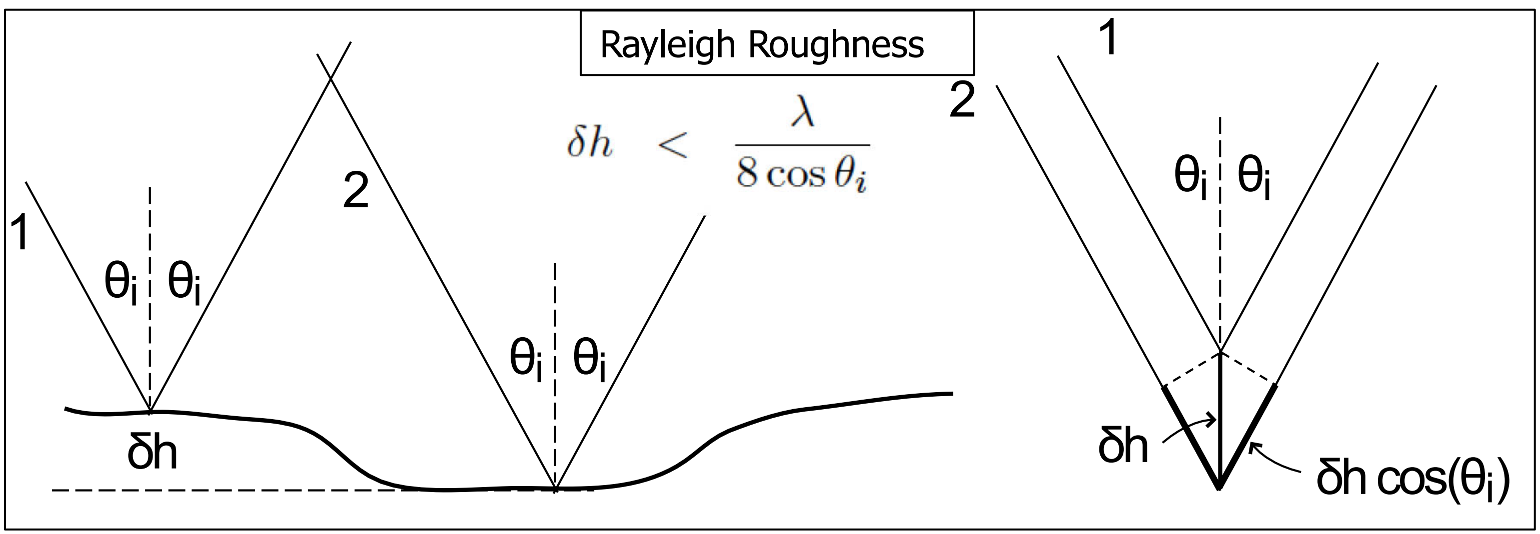


Rough surface

Random point model

Faceted rough surface

And we can develop intuition from combinations of these elements…



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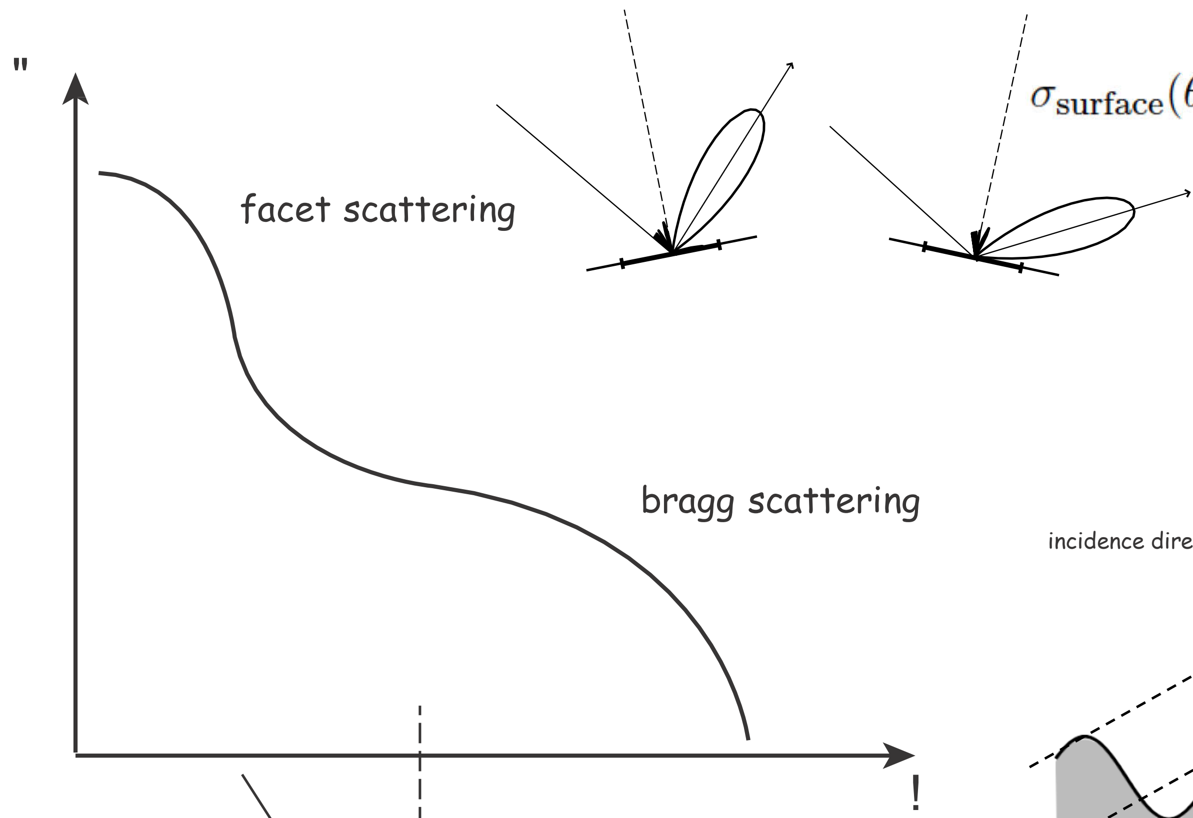
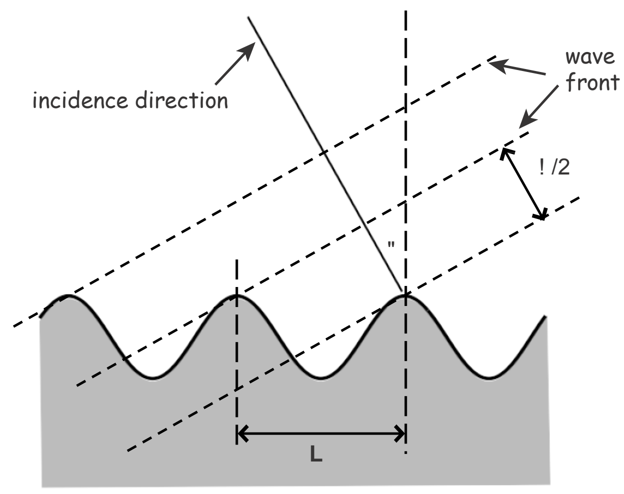
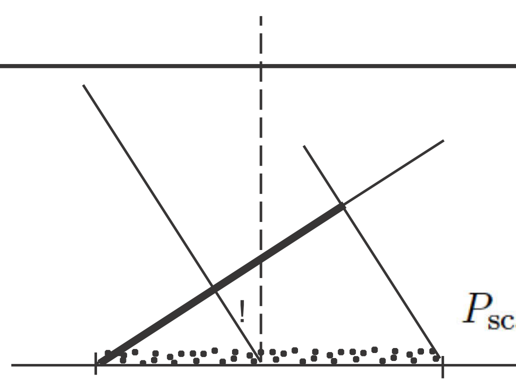
Surface and Volume Scattering Models for Radar



$$\sigma_{\mathrm{surface}}(\theta) = \Gamma^2_{\mathrm{Refl}} \sum_j p^2(\theta, \theta_{\mathrm{inc}} - \alpha_j)$$





$$P_{\mathrm{scat,d}} = \frac{P_{\mathrm{inc,d}}}{4\pi r^2} \sigma_{\mathrm{point}} \cos\theta_i N$$

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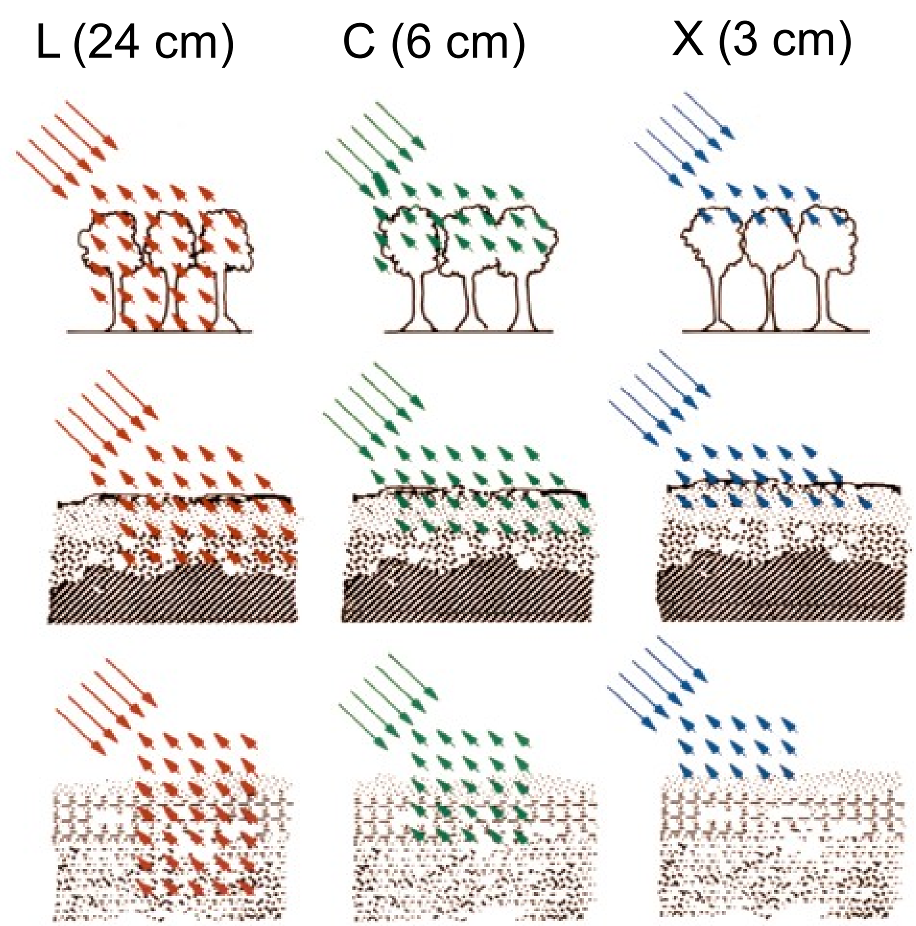
Wavelengths—a Measure of Surface Scale Sizes

Light interacts most strongly with objects on the size of the wavelength.



Forest: Leaves reflect X-band wavelengths but not L-band.

Dry soils: The surface looks rough to X-band but not L-band.

Ice: The surface and layering look rough to X-band but not L-band.

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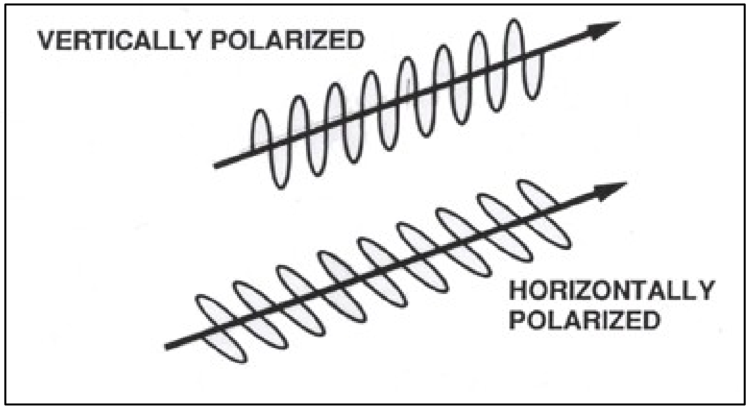
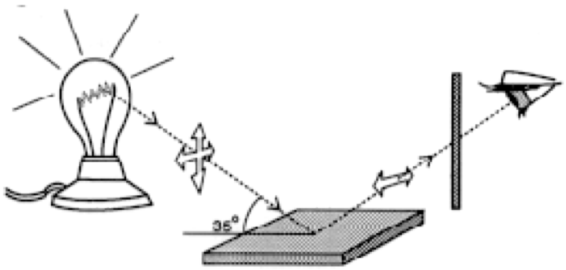
Polarization—A Measure of Surface Orientations and Properties

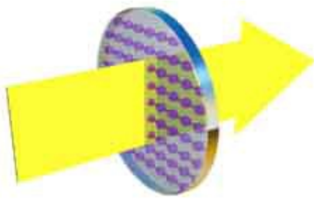
Wave Polarization



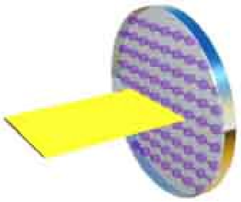


Mostly horizontal polarization is reflected from a flat surface.

Polarization Filters



Vertical polarization passes through horizontally arranged absorbers.



Horizontal polarization does not pass through horizontally arranged absorbers.

Color figures from www.colorado.edu/physics/2000

Radar Remote Sensing Trade Space

- Other radar instrument characteristics affect the science performance
  - Wavelength and antenna size determine illuminated area and real-aperture resolution
  - Antenna size in flight direction determines resolution for a synthetic aperture radar
  - Antenna area determines ambiguity, or aliasing, performance and swath extent
- Sensitivity of the measurement determined by ″radar equation″

$$\mathrm{SNR} = P_T \cdot G_T(\lambda) \cdot \frac{1}{4\pi R^2} \cdot \sigma(\lambda) \cdot \frac{1}{4\pi R^2} \cdot A_R \cdot \epsilon(\lambda) \cdot \frac{1}{kTB}$$

Signal-to-Noise Ratio

Transmit Power

Transmit Antenna Gain

Range (distance)

Radar cross-section or ″Reflectivity″

Receive Antenna Area

System Efficiency/Losses

Receiver Temperature

Receiver Bandwidth

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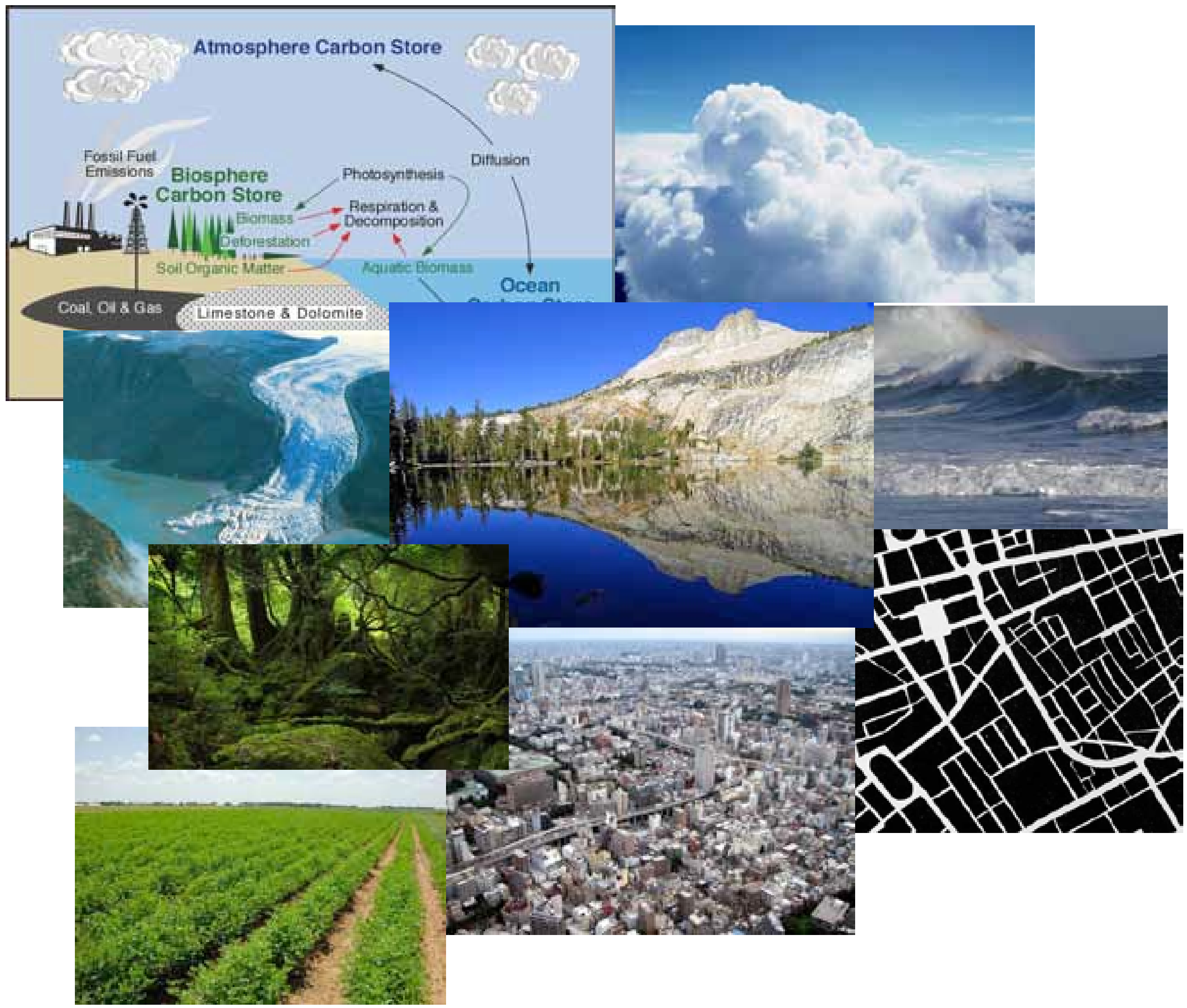
But the Real World is Complicated

- Interpretation of physical signal is often accomplished through empirical relationships between backscatter and the signal of interest



Types of Radar Sensors

Altimeters determine the height of a surface by measuring the round trip time it takes for a radar signal to reflect from the surface to determine surface elevation

Sounders/Profilers measure the reflected power over range

Scatterometers measure the magnitude of the backscattered reflected energy from the surface in the radar beam. The backscatter is related to both the surface composition, through the dielectric constant, and to the surface roughness at the wavelength scale

Synthetic Aperture Radar (SAR) Imagers generate fine resolution backscatter imagery, using the motion of the platform to synthesize a long antenna

Polarimeters generate backscatter measurements from multiple polarizations. Polarimetric information helps distinguish surface roughness from surface composition effects on the backscatter

Interferometers: interferometric systems generally require fine resolution, hence are SAR systems. Data collected from different vantages determine topographic information. In interferometric systems the parallax is typically much less than a pixel so the topographic information is obtained from a phase measurement that makes highly accurate parallax measurements possible. These phase measurements are then converted into elevation measurements.

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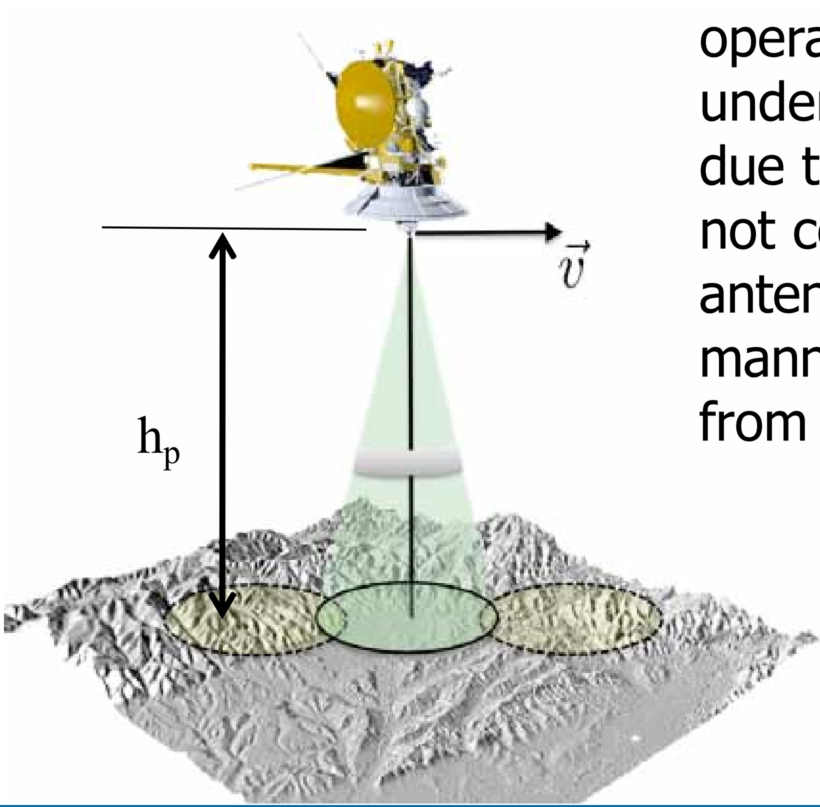
Altimeters

$$h_t = h_p - \rho$$



- Radar altimeters are downward or nadir pointing sensors that measure terrain elevation.
- Although the basic concept of altimeter operation is very simple, in practice understanding the measurement is complex due to the fact that the terrain elevation is not constant within the footprint of the antenna beam on the ground and the manner in which microwaves backscatter from the terrain.

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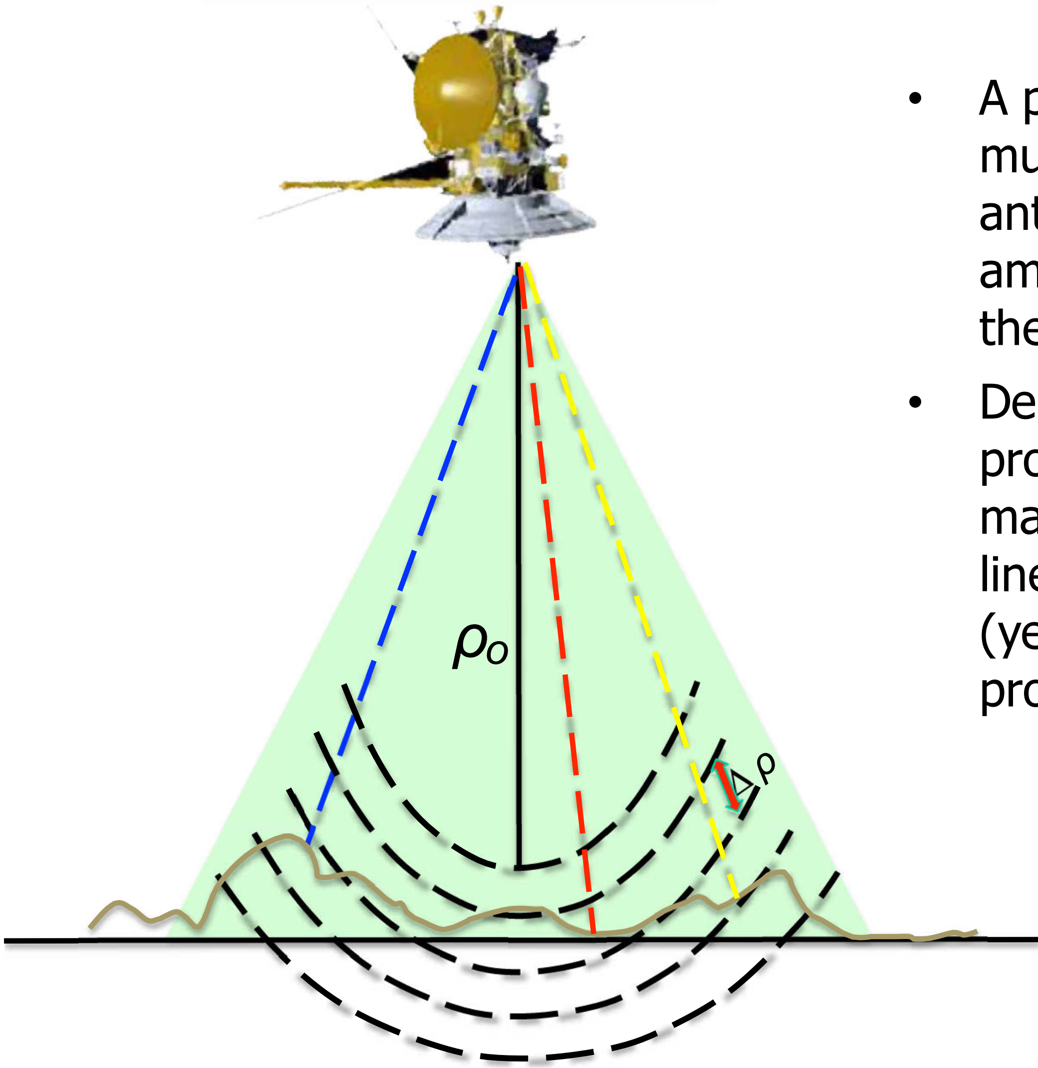
Pulse-Limited and the Echo Profile



- A pulse-limited altimeter will make multiple range measurements within an antenna footprint that is related to the amount of topographic variation called the echo profile.
- Depending on the algorithm used to process the data the reported elevation may correspond to the highest (blue line), lowest (red line) or some average (yellow line) elevation with the echo profile.

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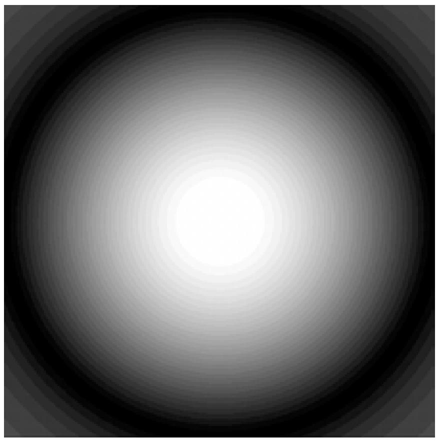
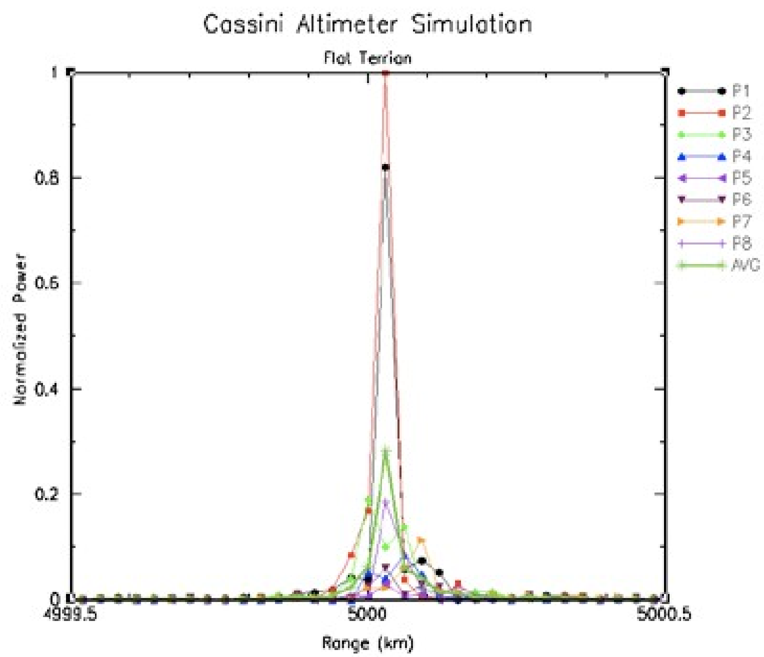
Echo Profile For a Flat Surface

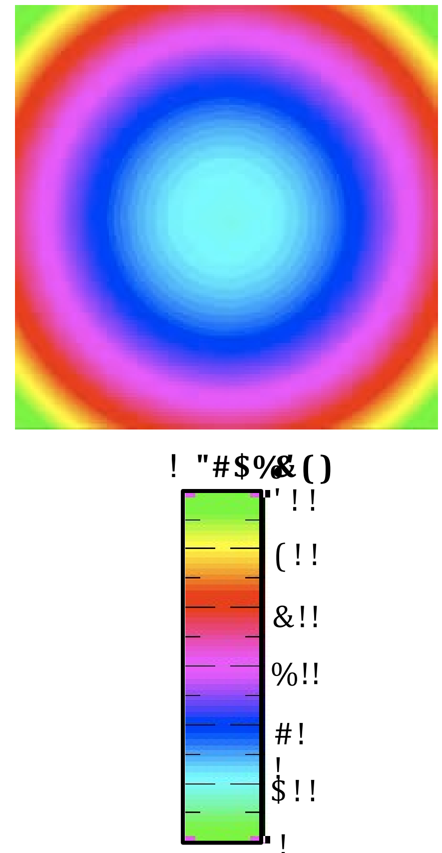
Simulated Surface Reflectivity Map



Compressed Echo Profile



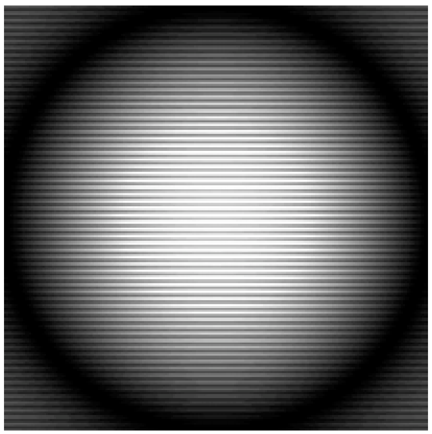
Simulated Relative Range Map



- Echo profile over simulated flat terrain
- Cassini-like altimeter at an altitude of 5000 km

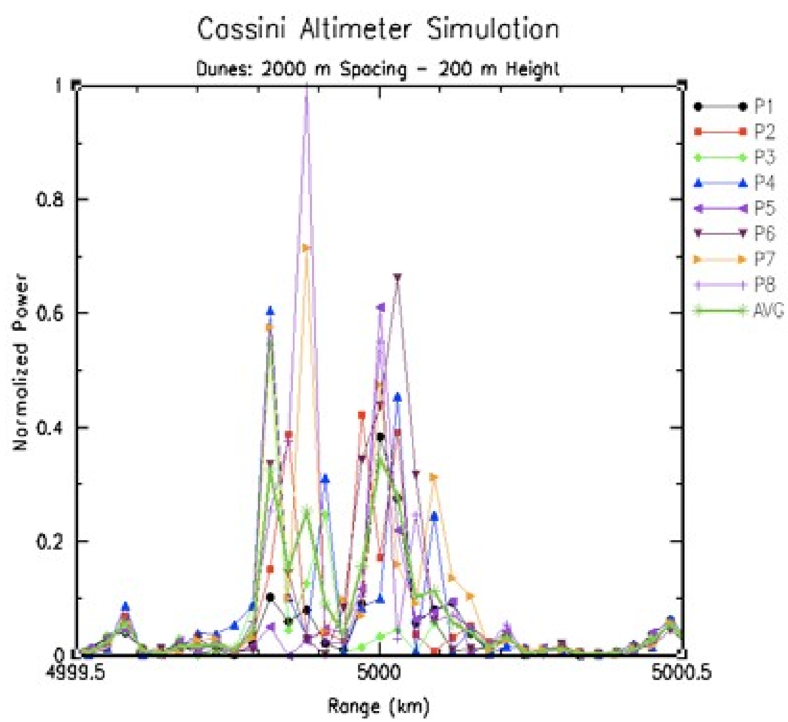
Echo Profile for Sinusoidal Hills

Simulated Surface Reflectivity Map



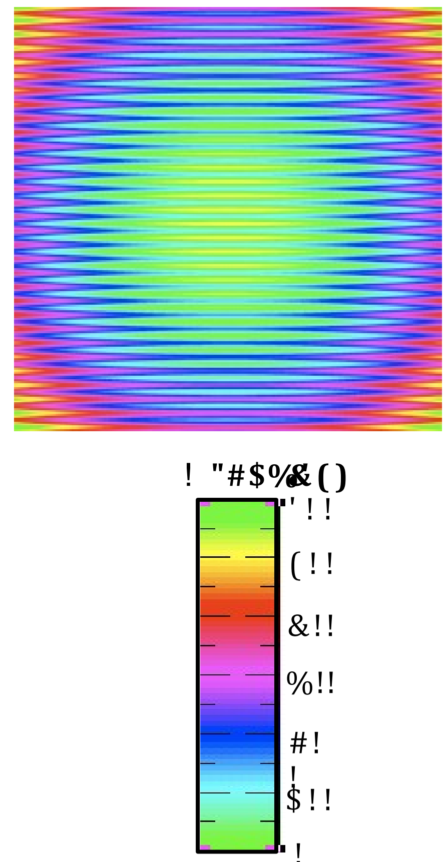
- Echo profile over simulated sinusoidal hills oriented perpendicular to the flight direction.
- Elevation Sinusoid:
  - Wavelength: 2 km
  - Amplitude: 200 m

Compressed Echo Profile

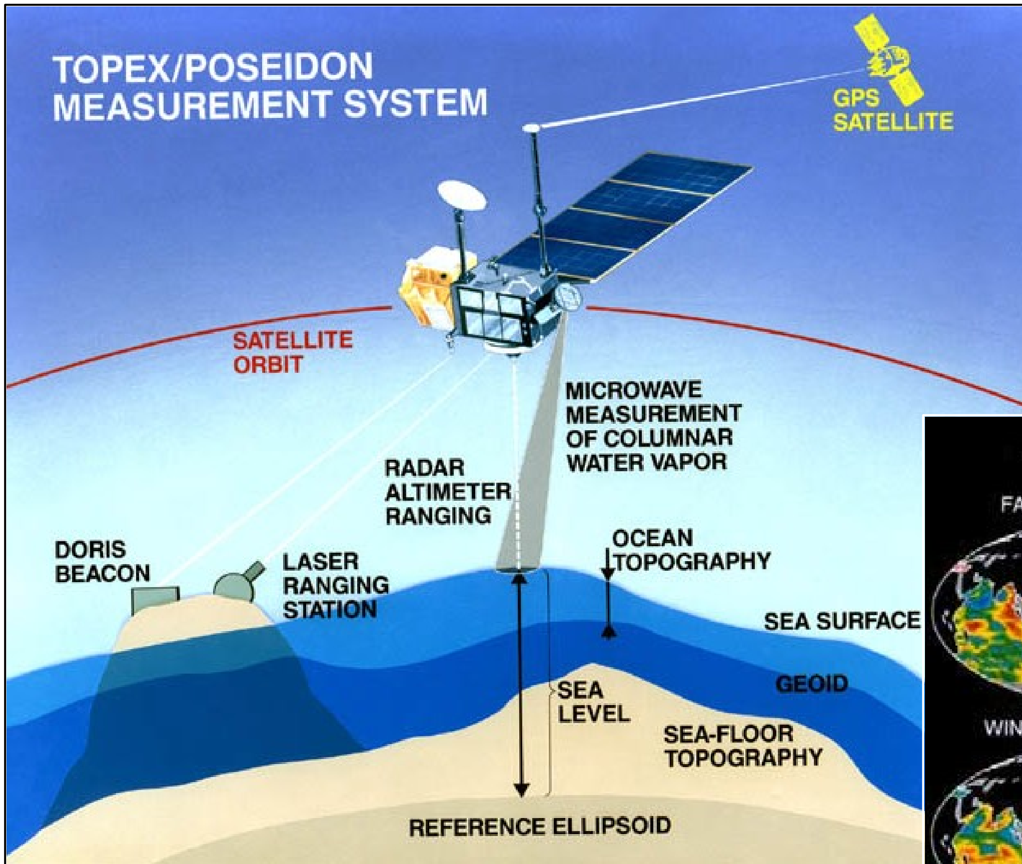


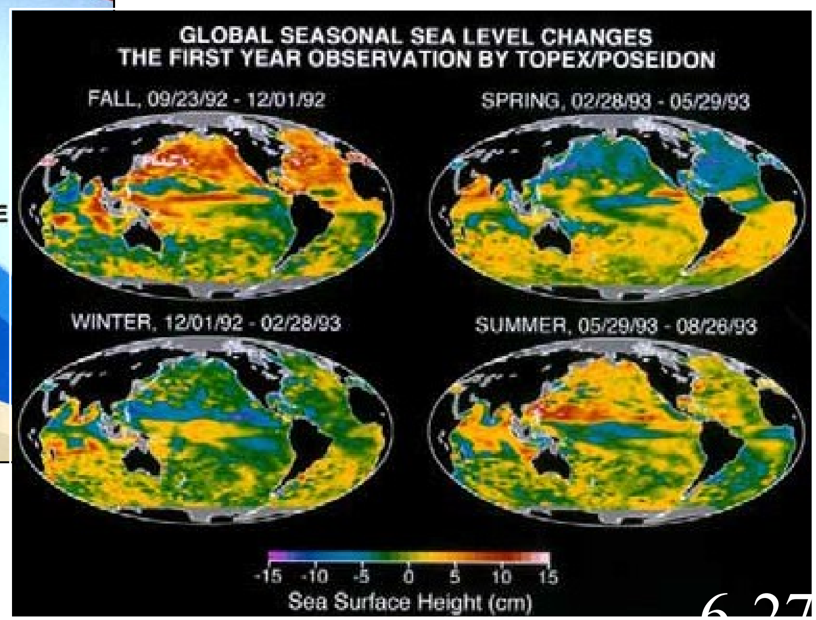
- Cassini-like altimeter at an altitude of 5000 km

Simulated Relative Range Map



Radar Altimeters for Ocean Height Measurements





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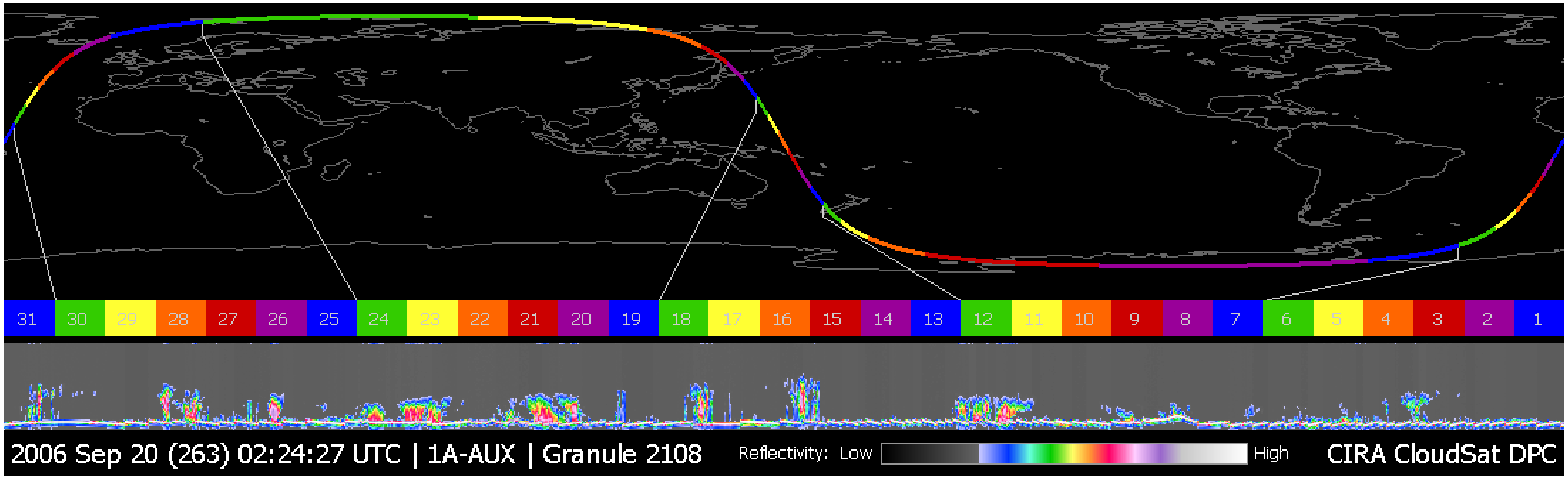
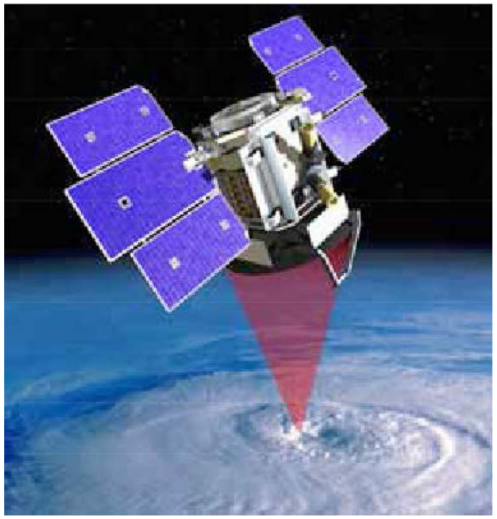
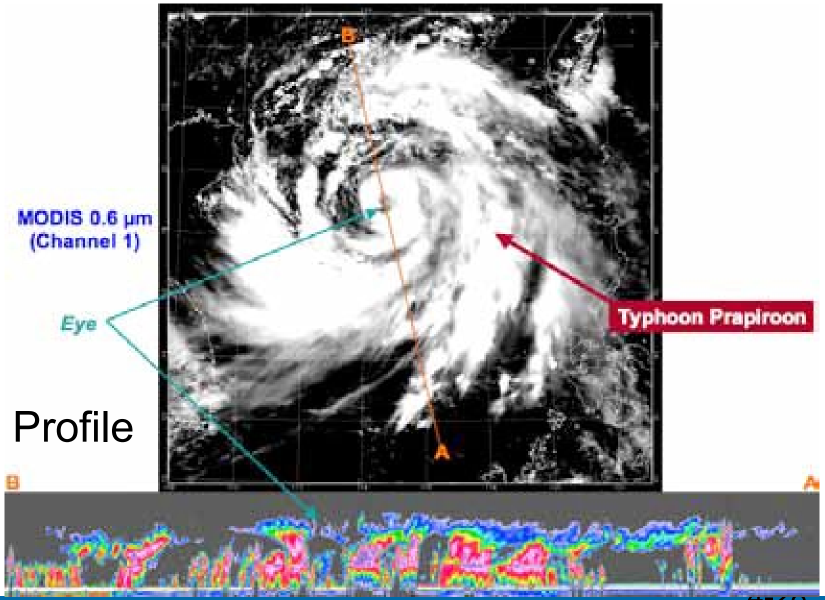
CloudSat – 94 GHz Profiling Cloud Radar



Typical Orbital Profile



Typhoon Profile



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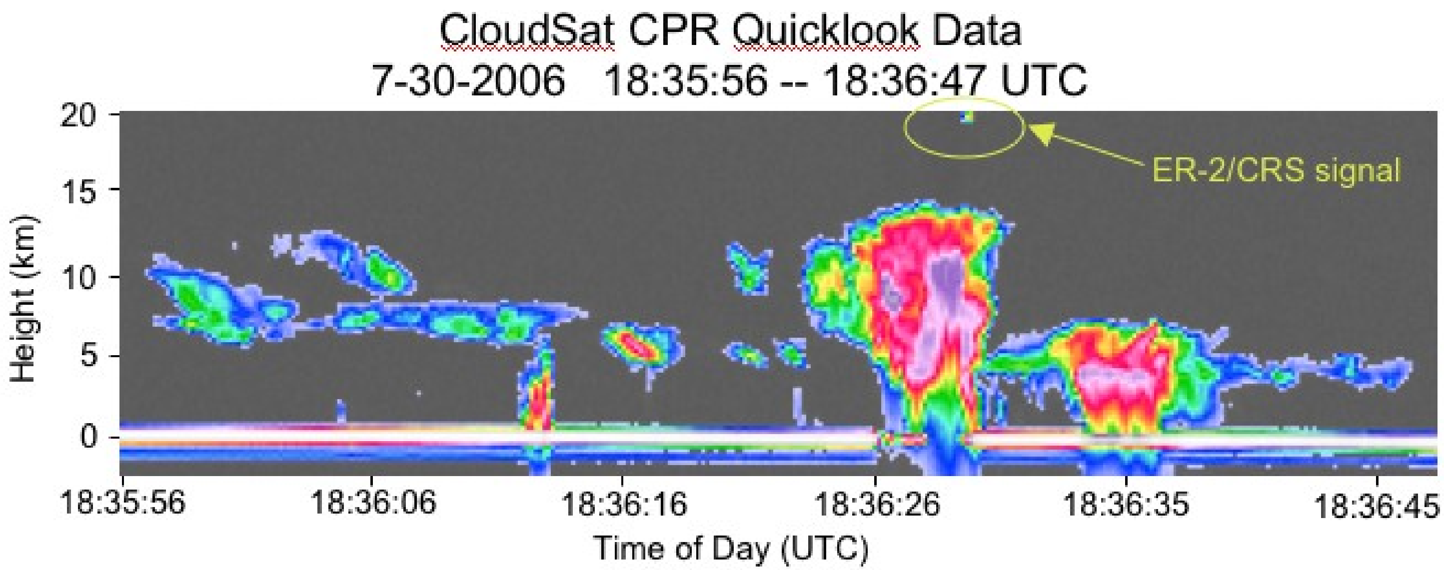
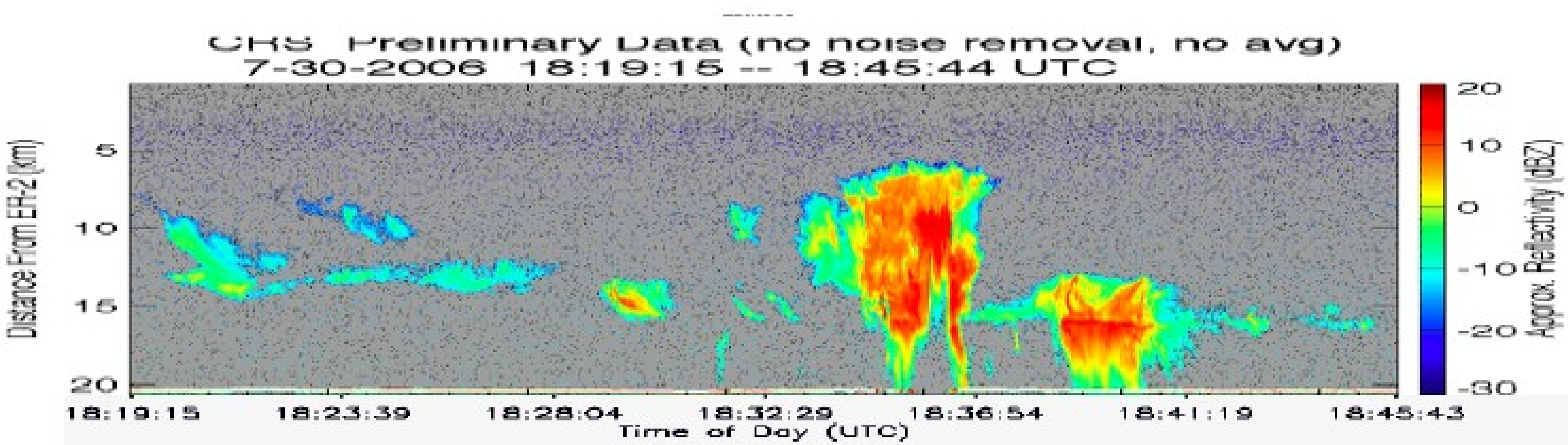
CloudSat CPR Power Returns vs Underflying ER-2 cloud radar (CRS) Reflectivity Measurements

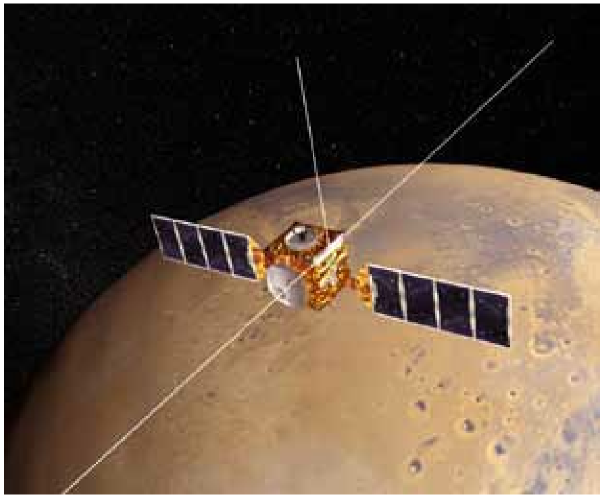


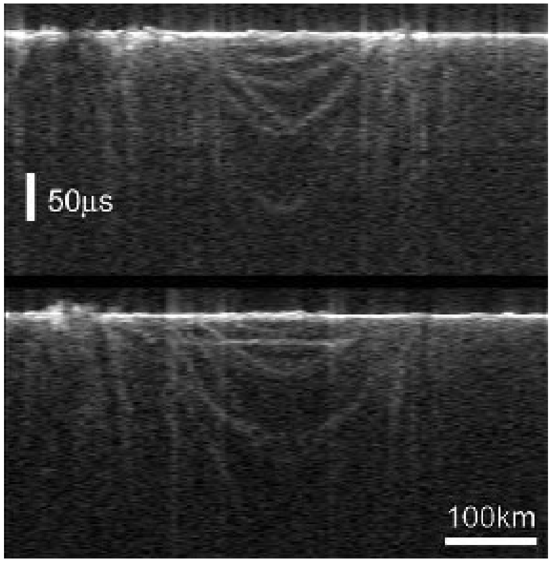


Mars Advanced Radar for Subsurface and Ionospheric Sounding on ESA Mars Express

Mission/Goals
- Primary Goal: To characterize the surface and subsurface electromagnetic behavior/variation in order to elucidate the geology (Search for water, material property, stratigraphy, structure, etc) at global scales with penetration depth of up to 5 km.
- Secondary Goal: To characterize the ionosphere of Mars
- NASA OSS, ″follow the water″.

Technology Areas
- Large antenna size due to low HF operation frequency)
- Complicated Matching networks due to wide relative bandwidth (0.1-5.5 MHz)
- Low frequency (HF) operation close to ionospheric plasma frequency
- Instrument calibration
- Requires specialized on-board and ground post-processing algorithms for science data calibration





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Scatterometry

- Transmit a radar pulse at the surface
- Measure the backscattered energy
  - Measurement also includes thermal noise
- Subtract thermal noise from the energy measurement
  - Need to make an estimate of the thermal noise
    - Different time, different frequency, different bandwidth
  - Result is an estimate of the echo energy
- Solve the radar equation to estimate sigma-0
- Use sigma-0 measurements and the model function to infer something about the surface

$$\mathrm{SNR} = P_T \cdot G_T(\lambda) \cdot \frac{1}{4\pi R^2} \cdot \sigma(\lambda) \cdot \frac{1}{4\pi R^2} \cdot A_R \cdot \epsilon(\lambda) \cdot \frac{1}{kTB}$$

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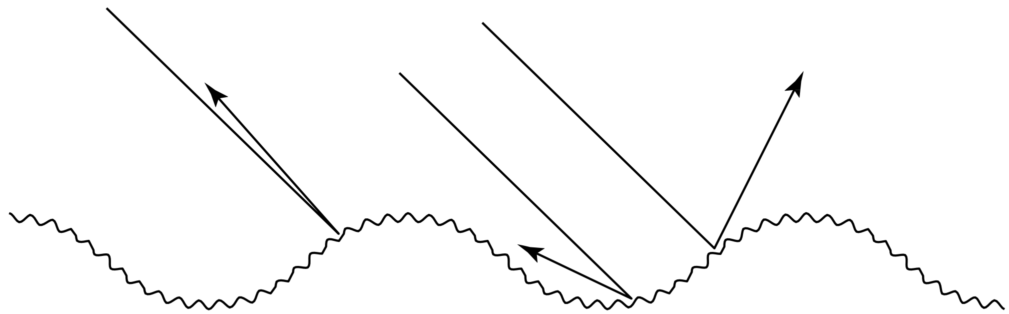
Scatterometry for Ocean Winds

Physics of ocean scattering

Bragg resonance scattering
The geometry of the ocean's surface affects its
reflectivity Wind roughens the surface of the ocean



- Sigma-0 is affected by the wind speed and direction
  - Higher wind speeds roughen the surface more, increasing sigma-0
  - Wind direction aligned with the viewing vector have a larger sigma-0 than wind directions that are perpendicular
- The sigma-0 of wind-driven ocean is a function of
  - Polarization, incidence angle, wind speed, and relative wind direction
  - Other things (salinity, sea surface temperature, swells, …)
- Sigma-0 tends to increase as incidence angles decrease

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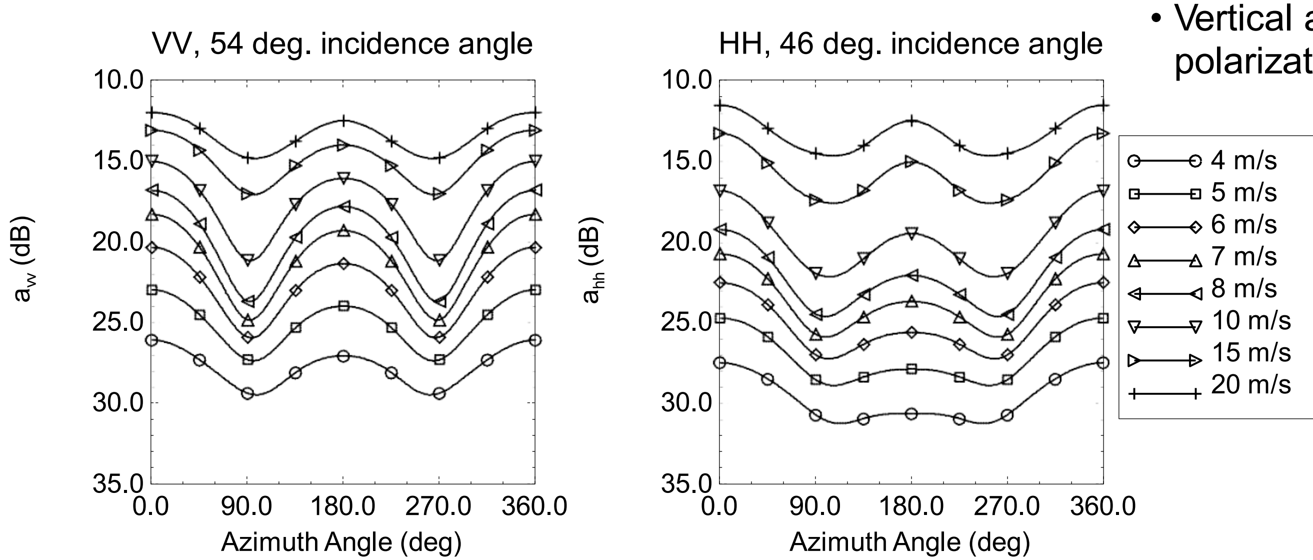
Geophysical Model Function

For a given polarization, incidence angle, and wind speed:

$$" _0 = A_0 + A_1 \cos(!\ ) + A_2 \cos(2!\ )$$

- Where " is the wind direction relative to the incident radiation, and A_0, A_1, and A_2 are constants
- Higher order terms are used when developing the model function, but are less significant

- The model function is determined empirically by comparing sigma-0 measurements to model wind fields and/or buoy measurements



- Vertical and horizontal polarization differ
  - V pol tends to have stronger backscatter than H pol
  - H pol has larger upwind/ downwind asymmetry
  - V pol has larger upwind/ crosswind asymmetry

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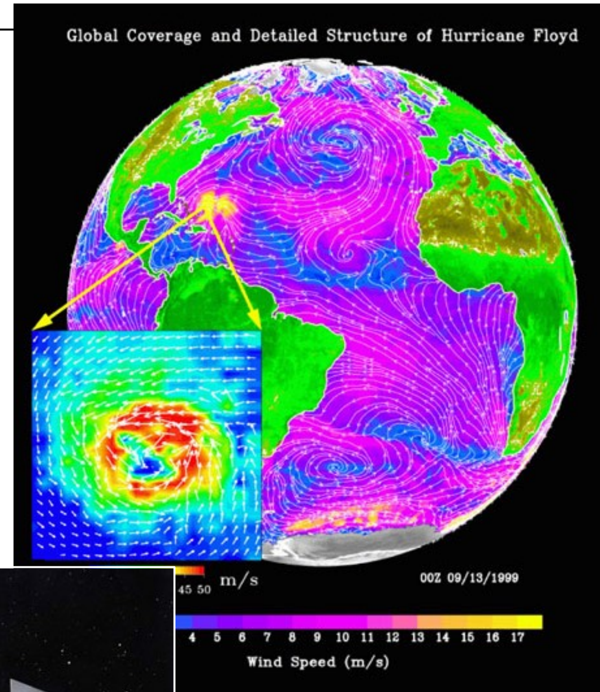
Scatterometers for Ocean Wind

- Motivation
  - Obtain global wind vectors on a daily basis
    - Research, climatology, weather operations
  - Other applications
    - Ice edge detection, land change detection, snow cover, freeze/ thaw detection, flood detection
- Scatterometers are radar instruments that measure the reflective properties of the Earth's surface
- A measure of radar reflectivity is the normalized radar cross section called sigma-0



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SeaWinds

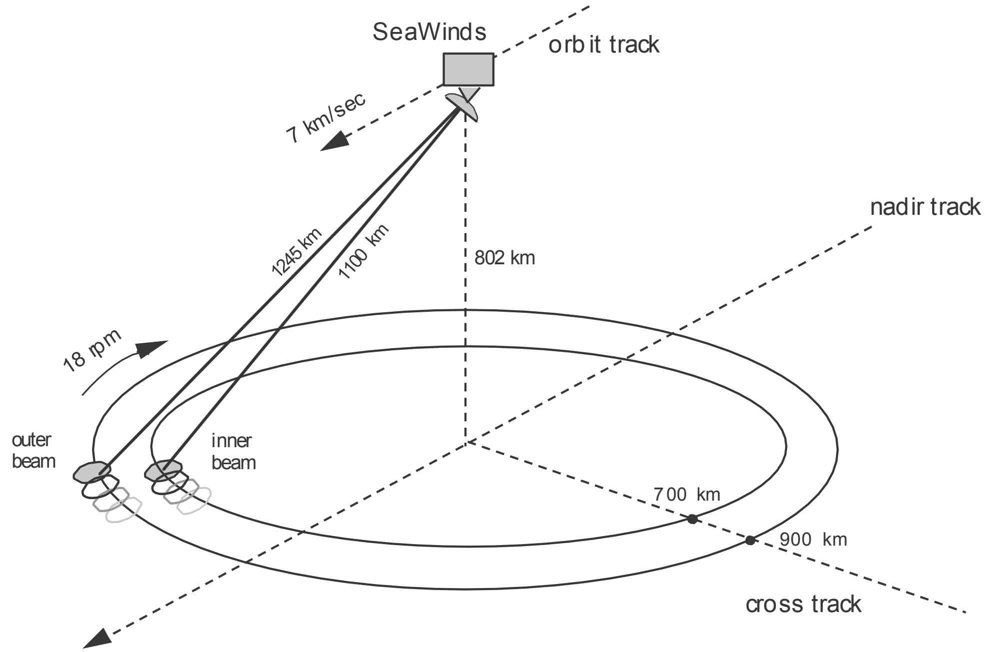
Beam geometry and polarization

Inner/Outer: H/V pol, 40°/46° look angle, 46°/54° incidence angle

RF: 13.402 GHz, Ku band, 185 Hz PRF

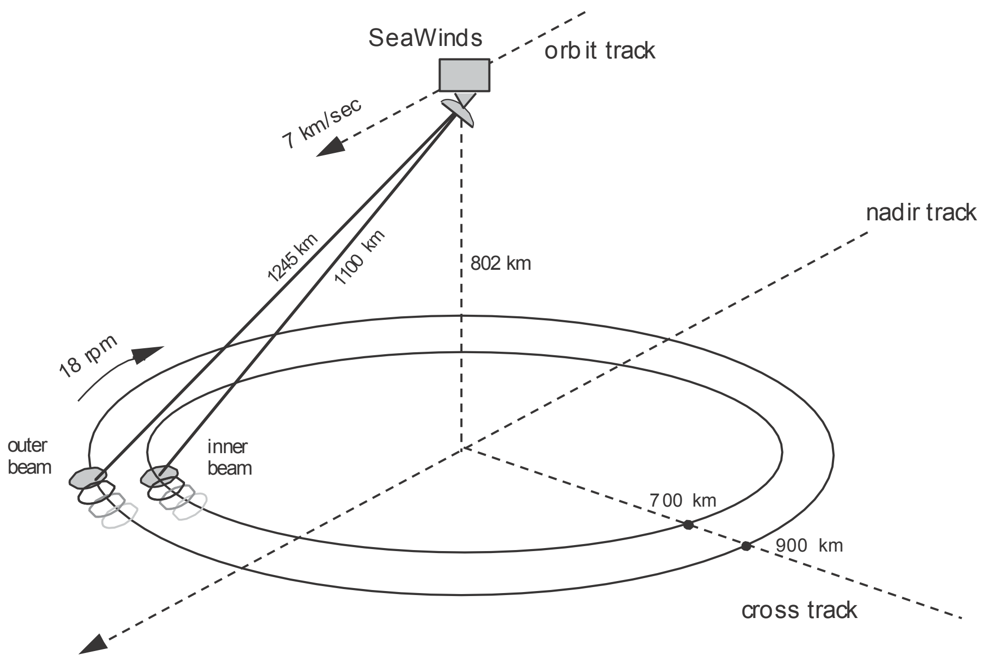
Swath width

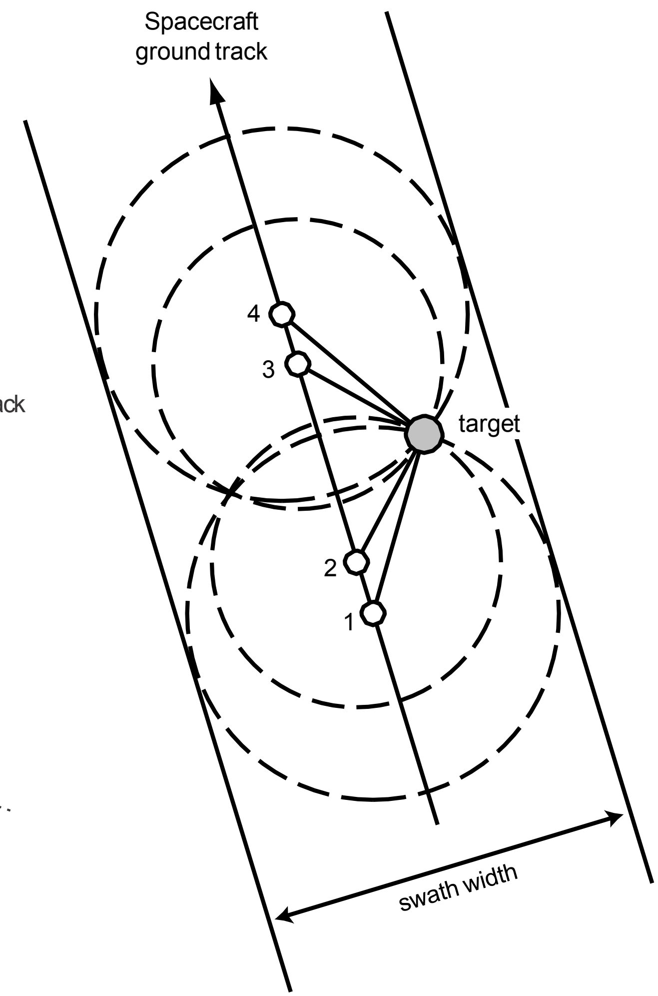
1400/1800 km for inner/outer beam



90% daily coverage

Wind Vector Cell Geometry





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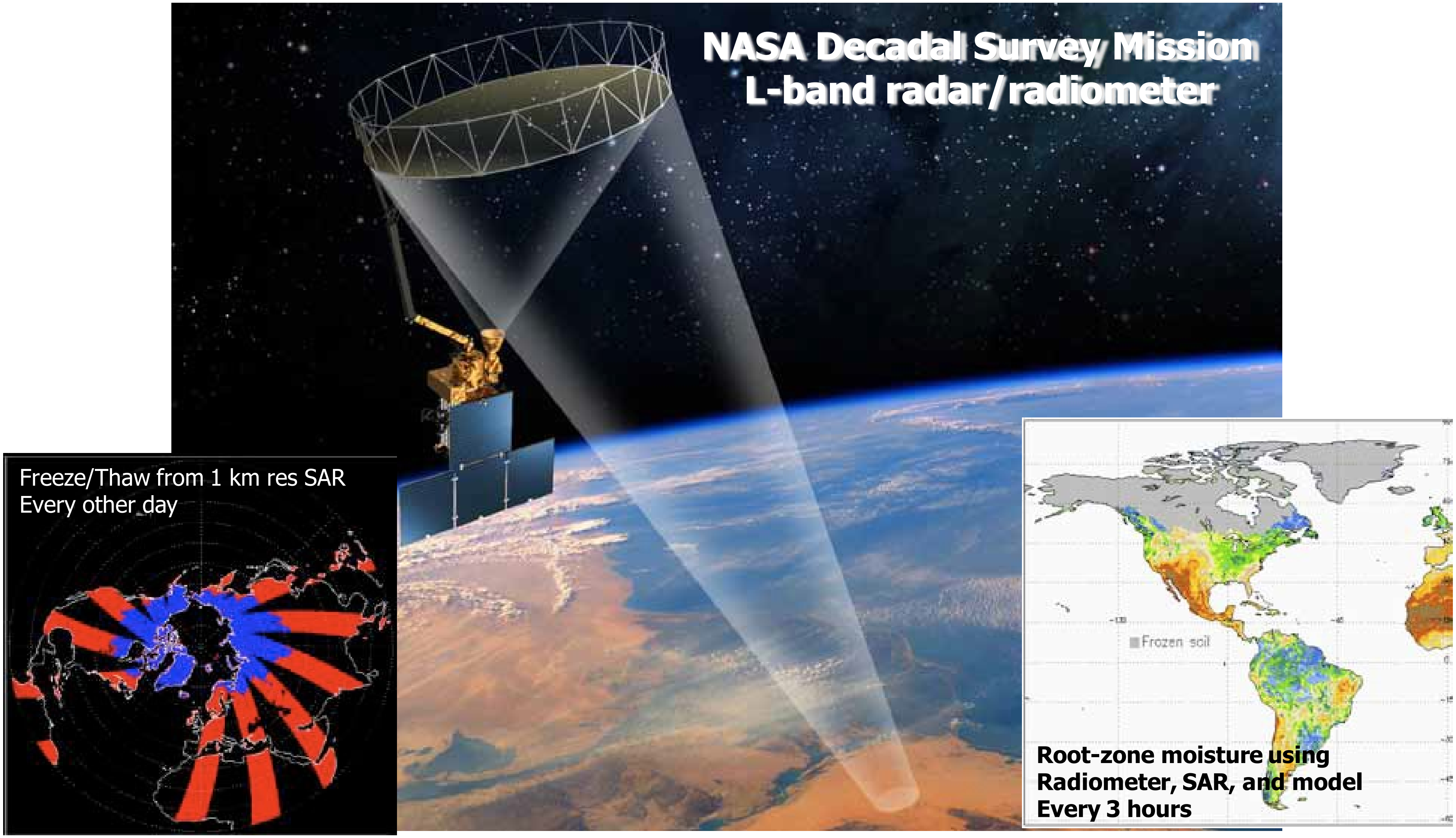
Soil Moisture Active/Passive (SMAP)



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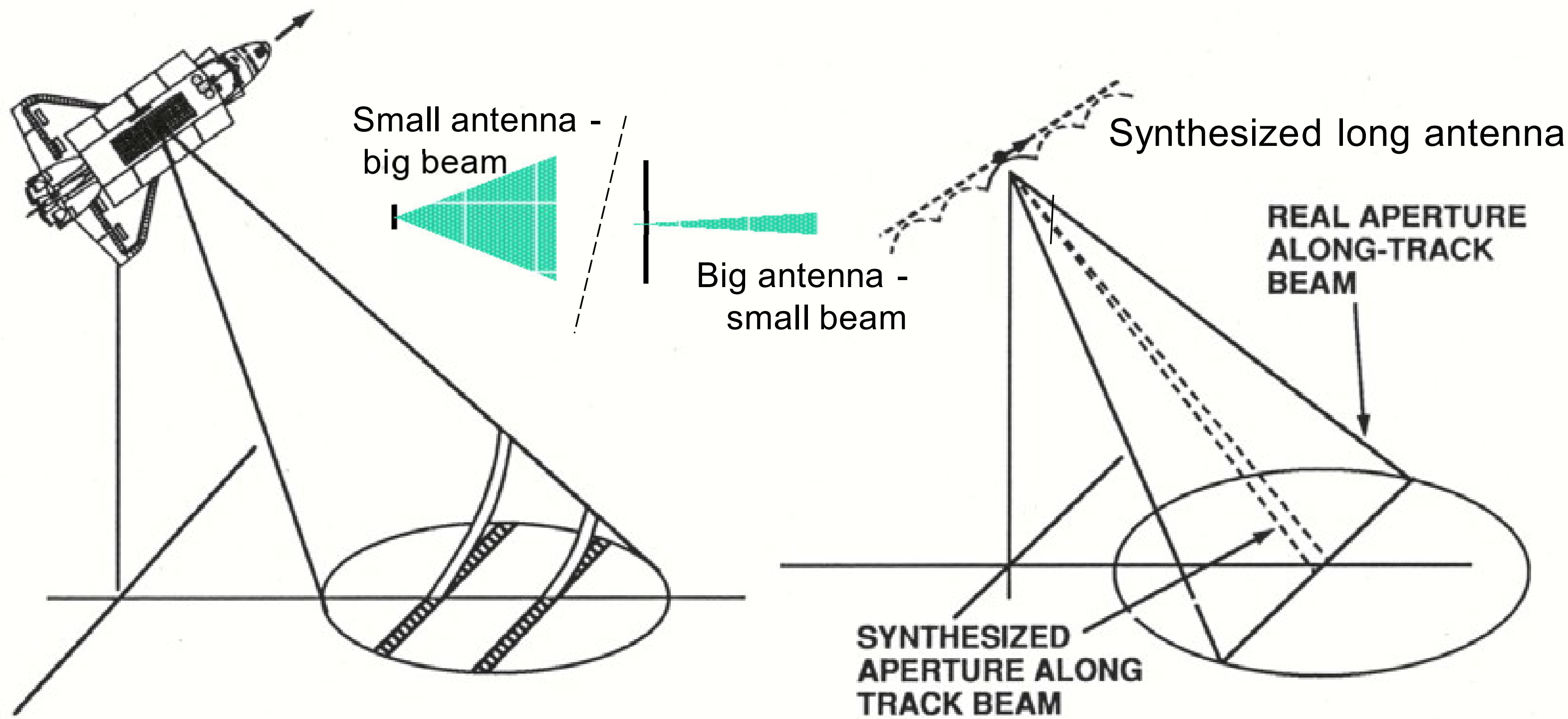
Imaging Radar

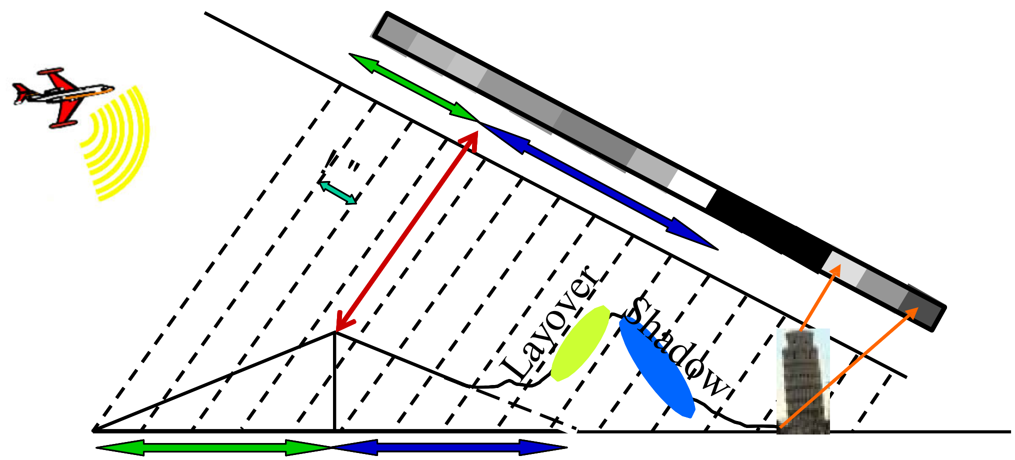


CROSS-TRACK RESOLUTION ACHIEVED BY SHORT PULSE LENGTHS (HIGH BANDWIDTH)

ALONG-TRACK RESOLUTION ACHIEVED BY COHERENTLY COMBINING ECHOES FROM MULTIPLE PULSES ALONG-TRACK (SYNTHESIZE A LONG ANTENNA)

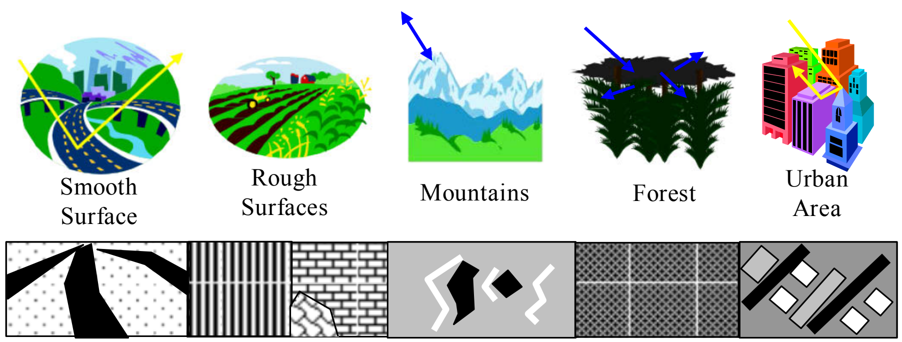
- RESOLUTION α ANTENNA LENGTH
- INDEPENDENT OF RANGE/FREQUENCY

Radar Imaging Properties



Foreshortening

- Radar images are distorted relative to a planimetric view
- Slopes facing toward or away from the radar appear foreshortened
- Steep slopes are collapsed into a single range cell called layover and areas occulted by other areas are said to be shadowed



- Radar is primarily sensitive to the structure of objects being imaged whereas optical images are primarily sensitive to chemistry
- The scale of objects relative to the radar wavelength determines how smooth an object appears to the radar and how bright or dark it is in the imagery

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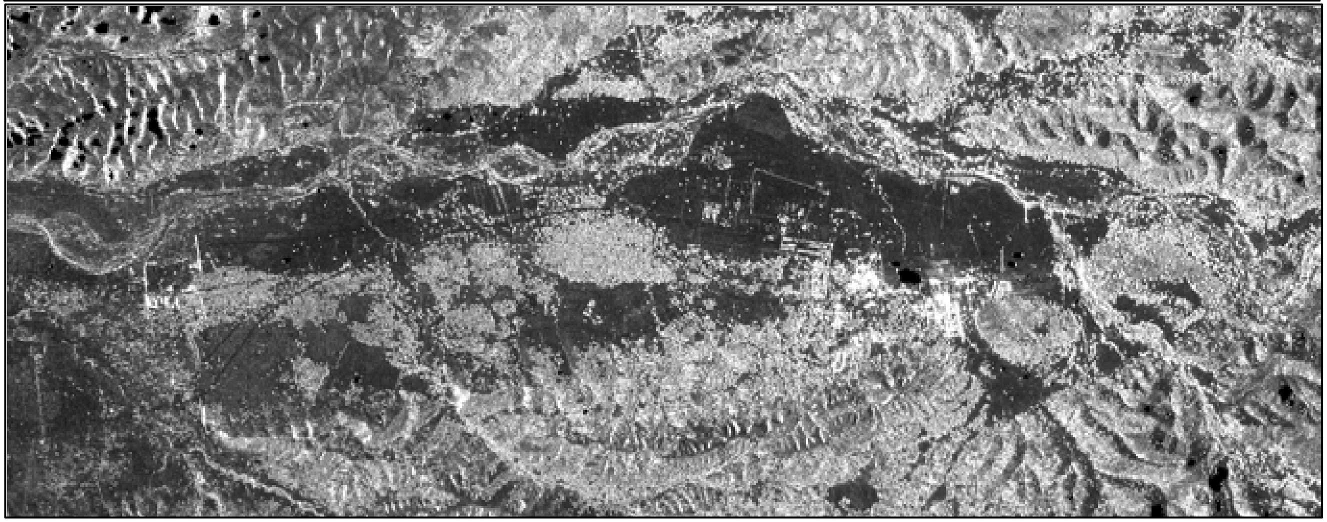
Image Frequency Comparison

X-band
3 cm



P-band
85 cm

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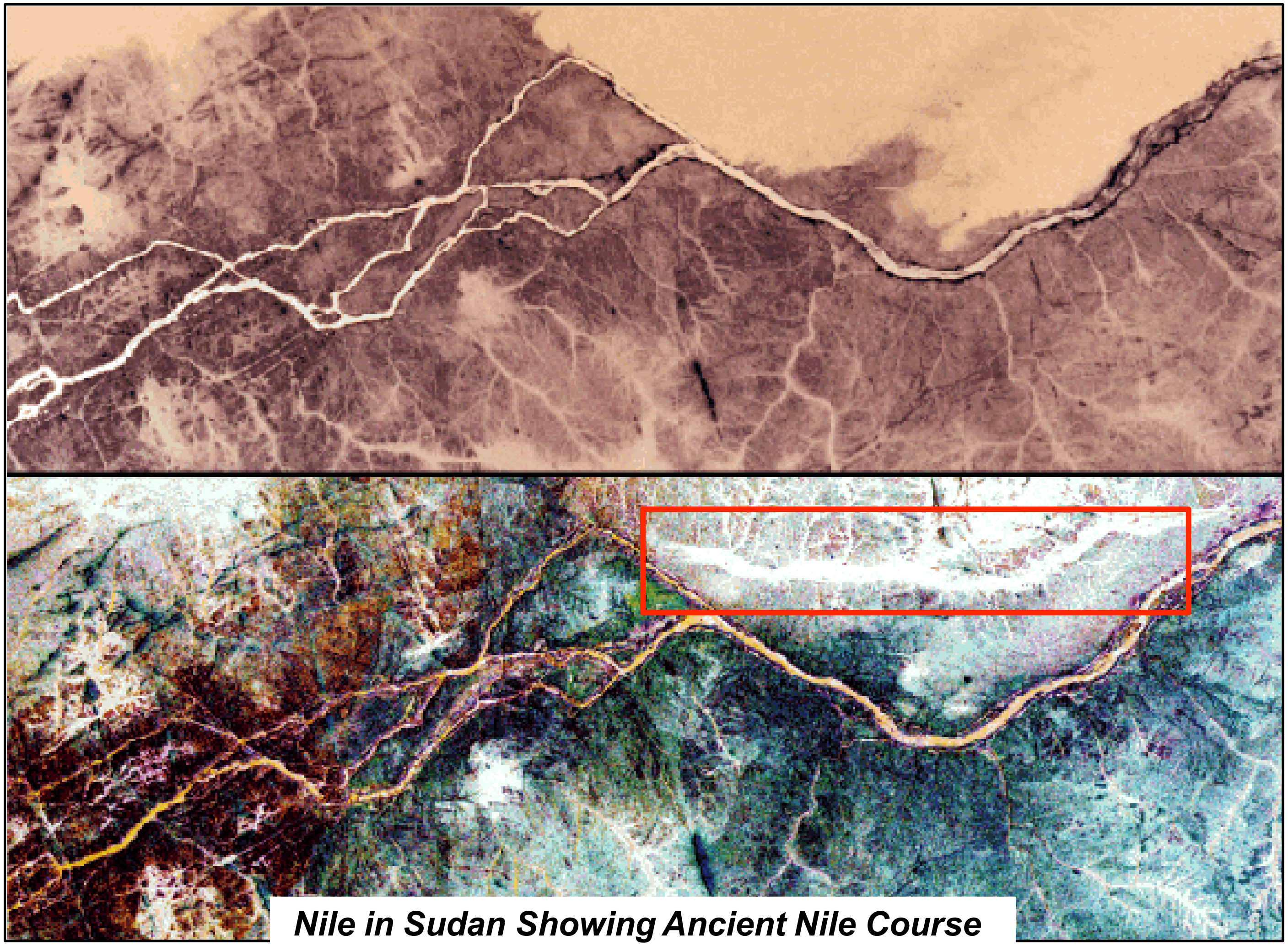
Visible (Upper) and Radar (Lower)



Nile in Sudan Showing Ancient Nile Course

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Polarimetric SAR at Death Valley

HH-Red HV – Green VV – Blue

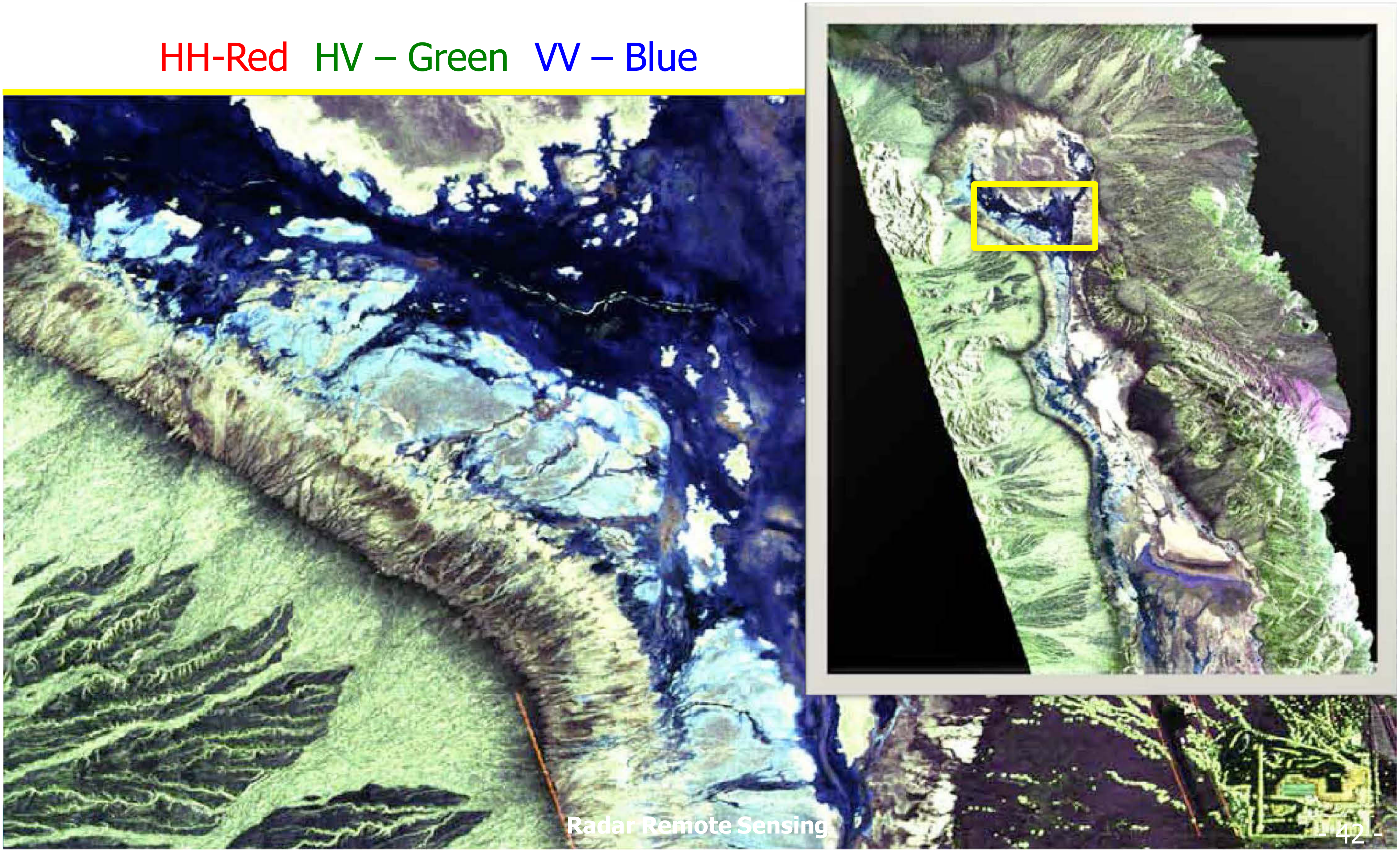

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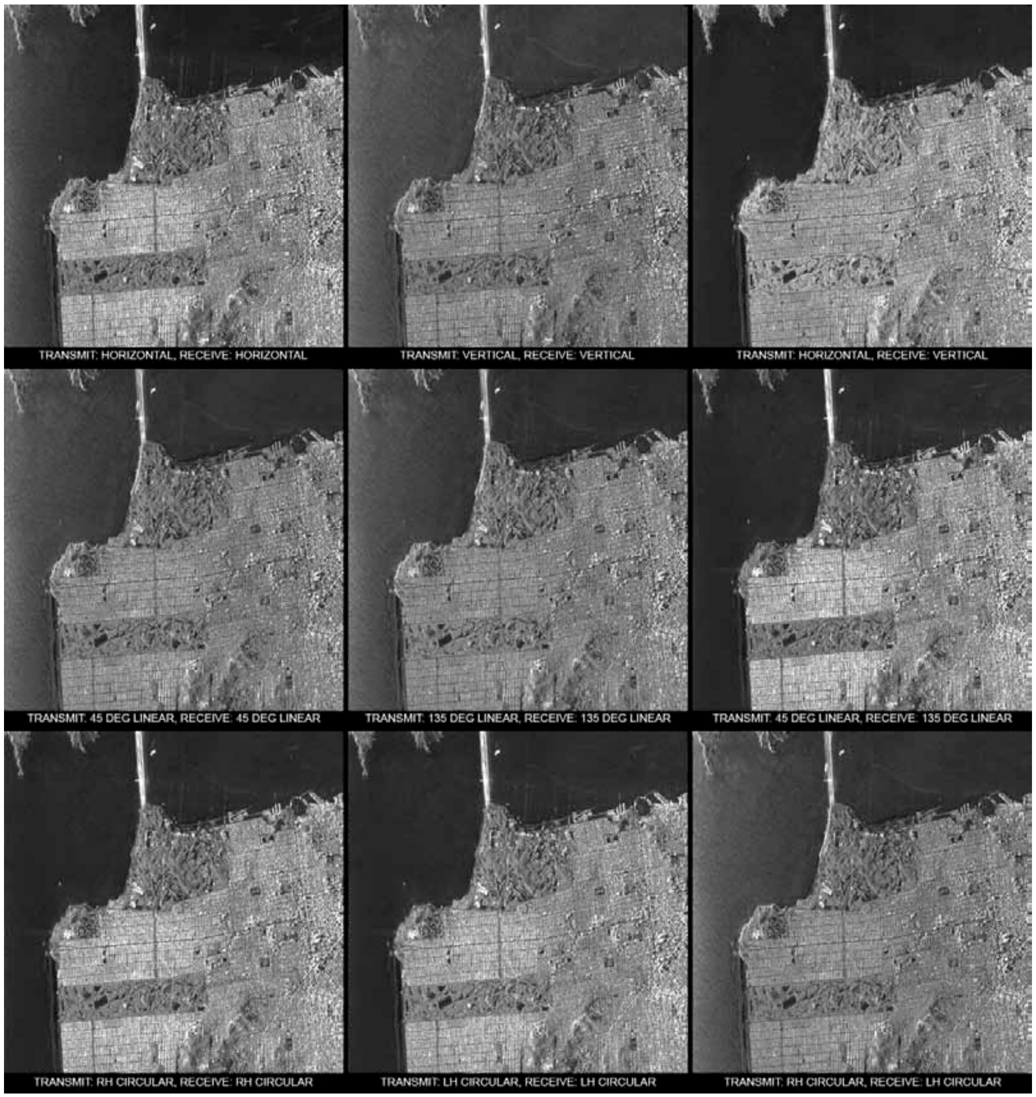
Image Intensity for Selected Polarizations



- View of San Francisco for various polarizations.
- Different land cover types respond differently to different polarizations.
- This diversity can be exploited both in classifications and quantitative surface parameter determination.

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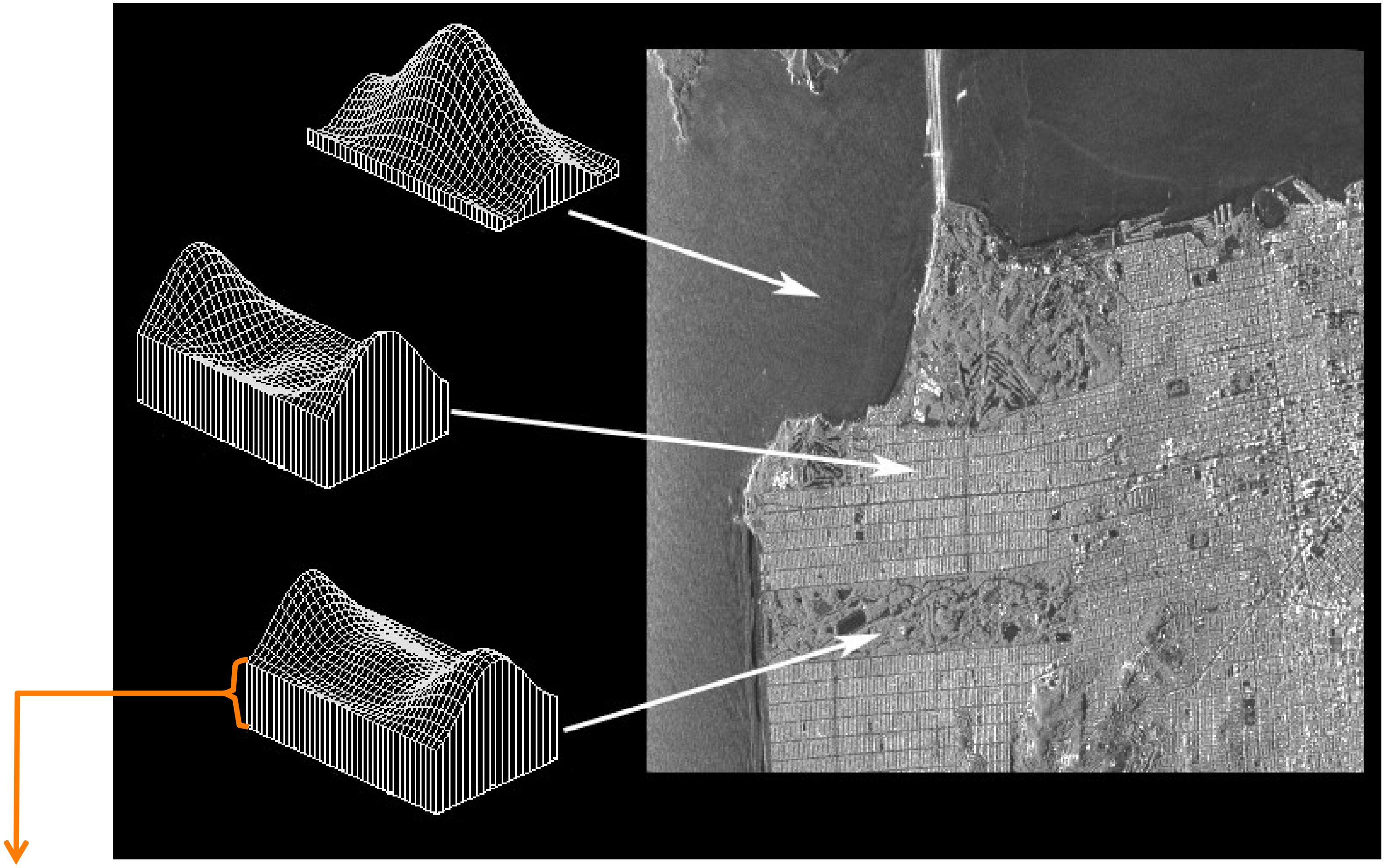
Polarization Signatures



- Pedestal height of the polarization signature is related to wavelength scale surface roughness.

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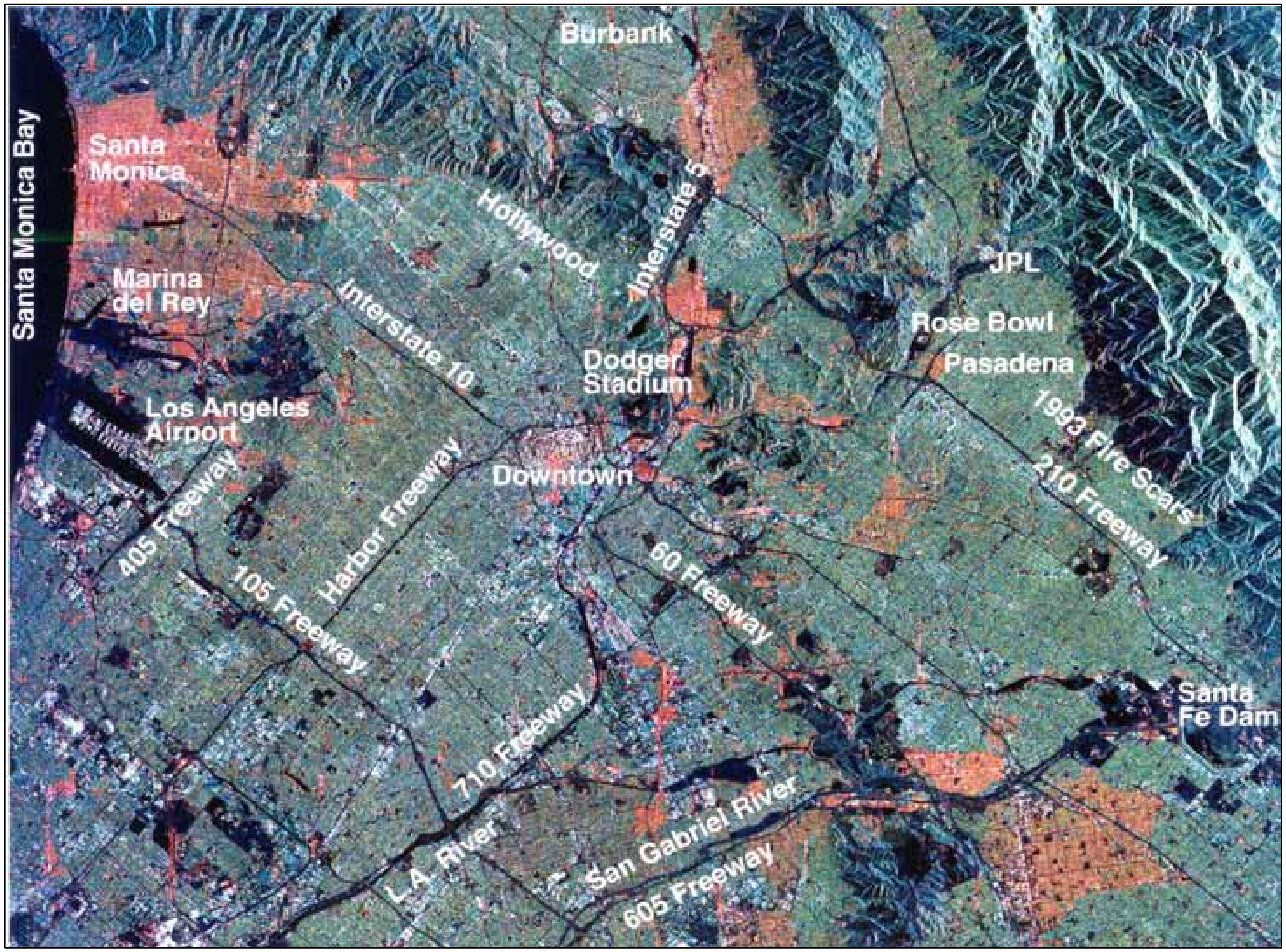
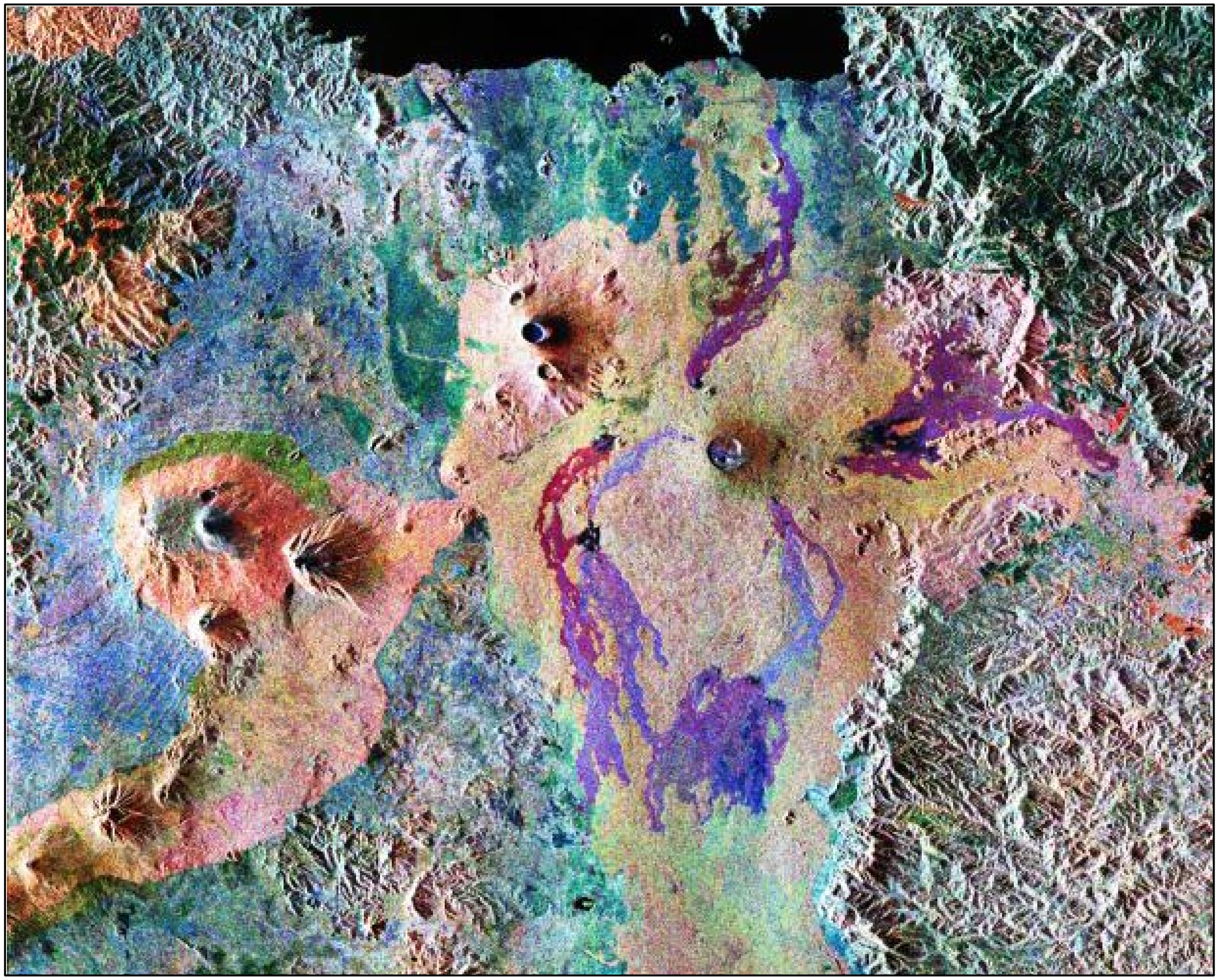
Polarimetry from SIR-C/X-SAR



SIR-C/X-SAR: Characterizing the Earth's Surface



Volcanoes

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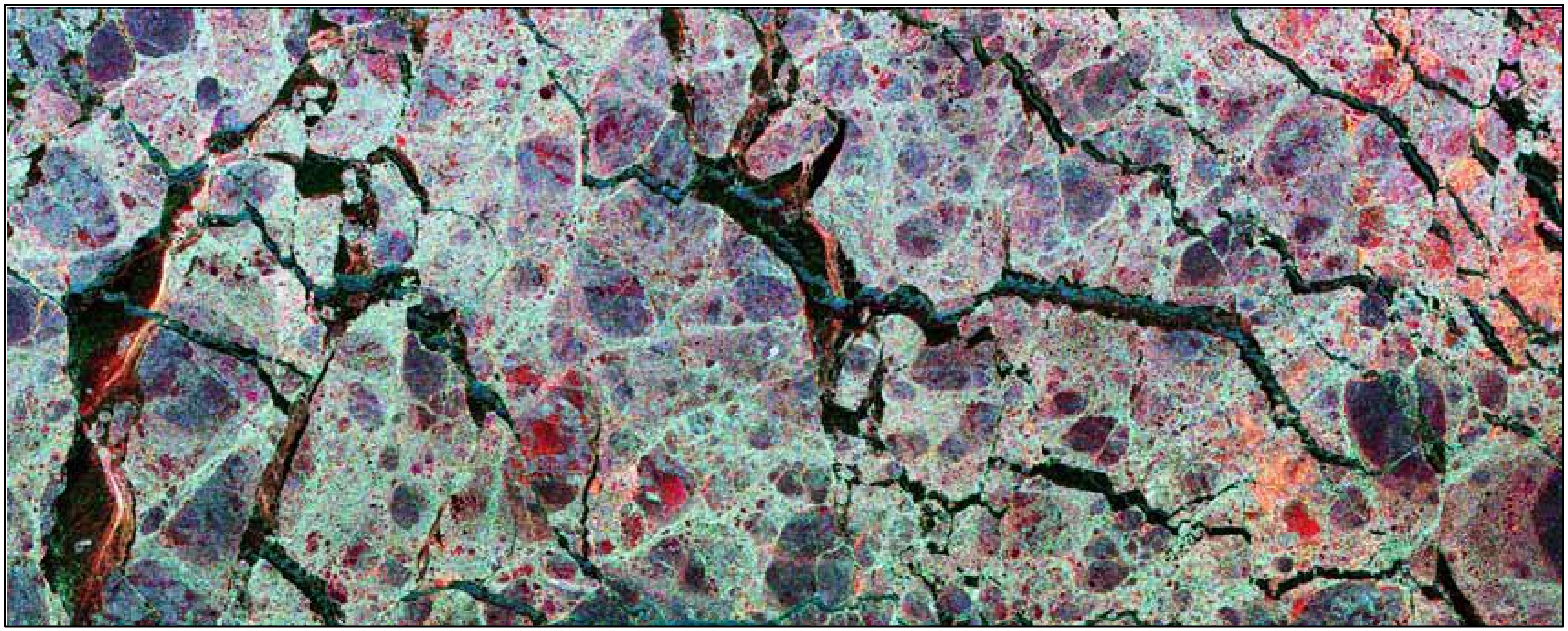
SIR-C/X-SAR Views Sea Ice

Multi-frequency, multi-polarization radar can measure the extent, thickness and morphology of the polar ice pack.



Weddell Sea, Antarctica

Red: CHH Green: LHV Blue: LHH

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San Joaquin Valley, California

Applications: soil moisture estimation, vegetation classification

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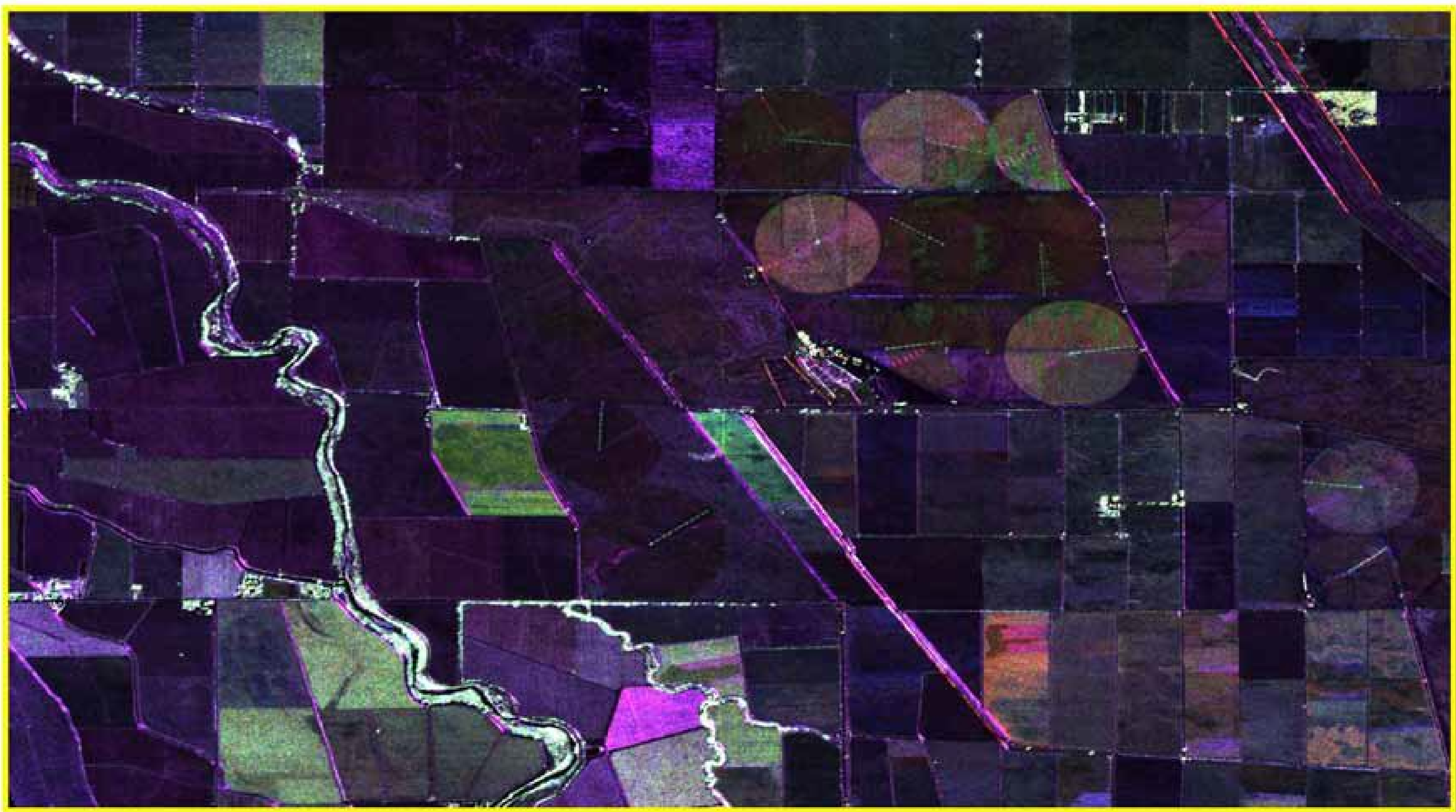
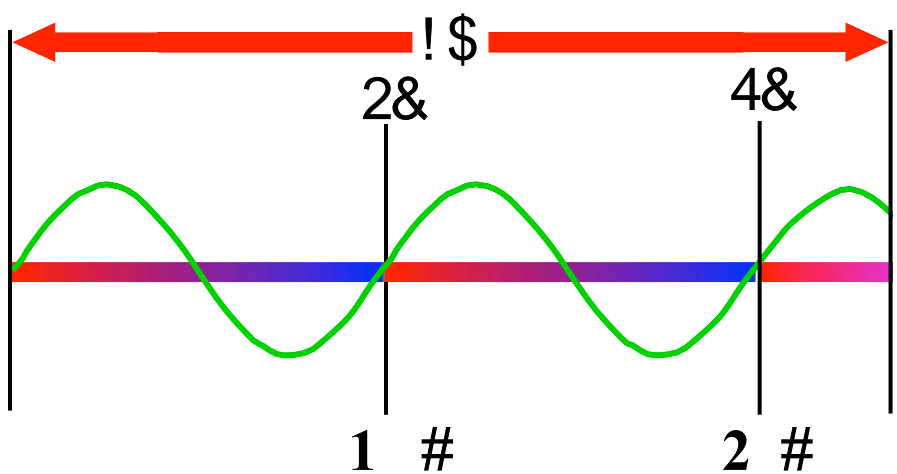


Phase and Radar Interferometry

- Interferometric phase is simply another means of measuring distance. Traditional stereoscopic measurement of the ″parallax,″ or relative displacement an object has from two stereo images, is proportional to the height of the object and the separation between the two imaging points
- For SAR systems, the parallax is the range difference from a point to the two observation antennas



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Radians per wavelength Number of wavelengths

- Phase measurements in interferometric systems can be made with degree-level accuracy, and with typical radar wavelengths in 3-80 cm range this corresponds to parallax measurements having millimeter accuracy

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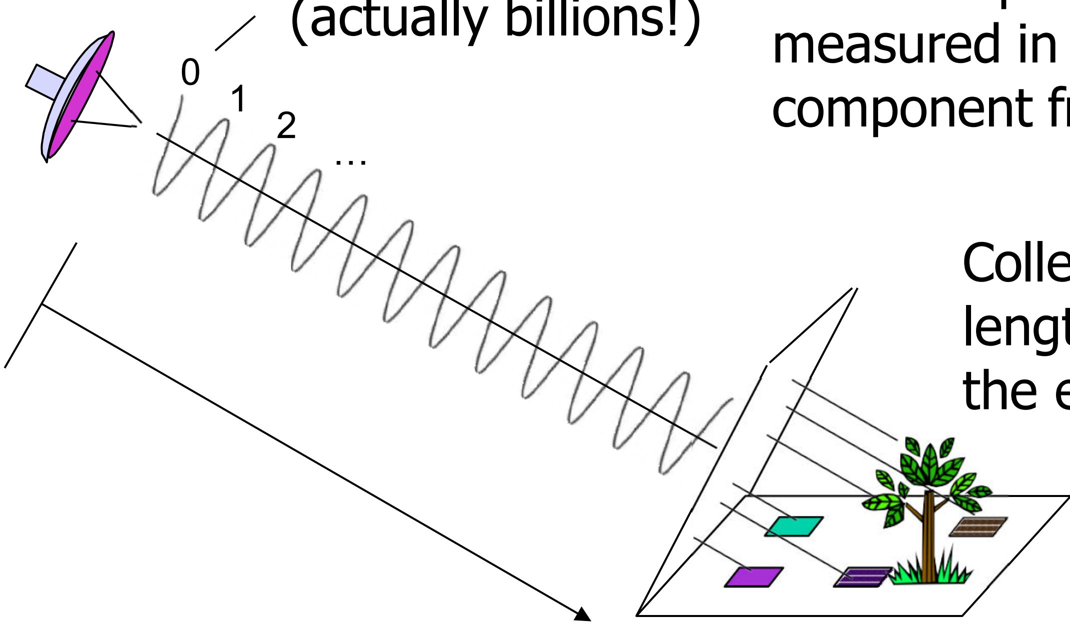
Phase - A Measure of the Range and Surface Complexity

The phase of the radar signal is the number of cycles of oscillation that the wave executes between the radar and the surface and back again.

Number of cycles (actually billions!)

The total phase is two-way range measured in wave cycles + random component from the surface



Collection of random path lengths jumbles the phase of the echo

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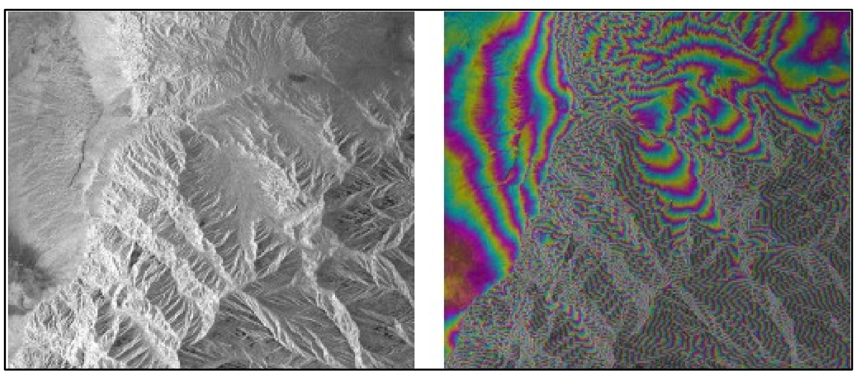
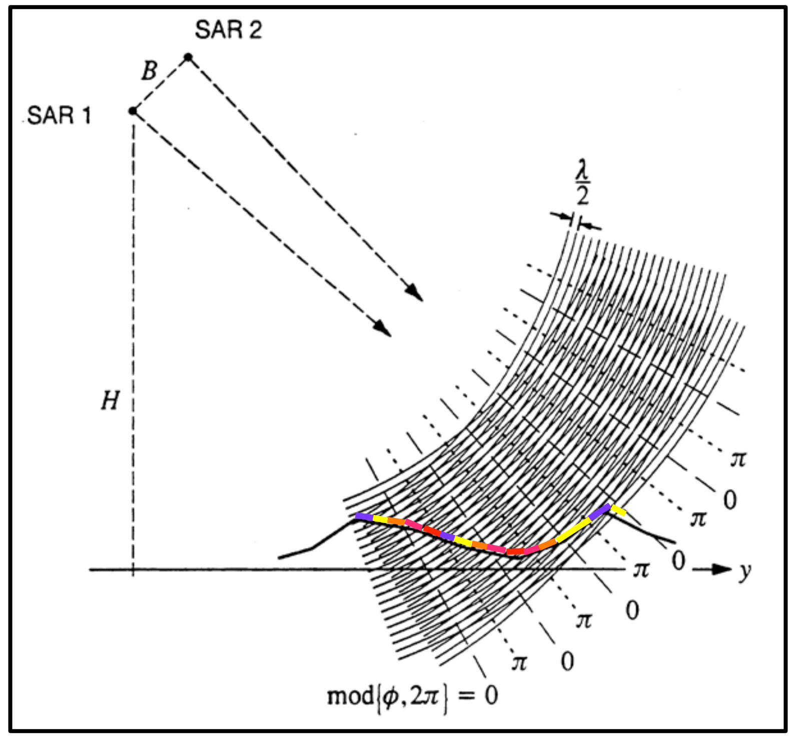
Radar Interferometry

- Radar has a coherent source much like a laser
- The two radar (SAR) antennas act as coherent point sources
- When imaging a surface, the phase fronts from the two sources interfere
- The surface topography slices the interference pattern





- The measured phase differences record the topographic information

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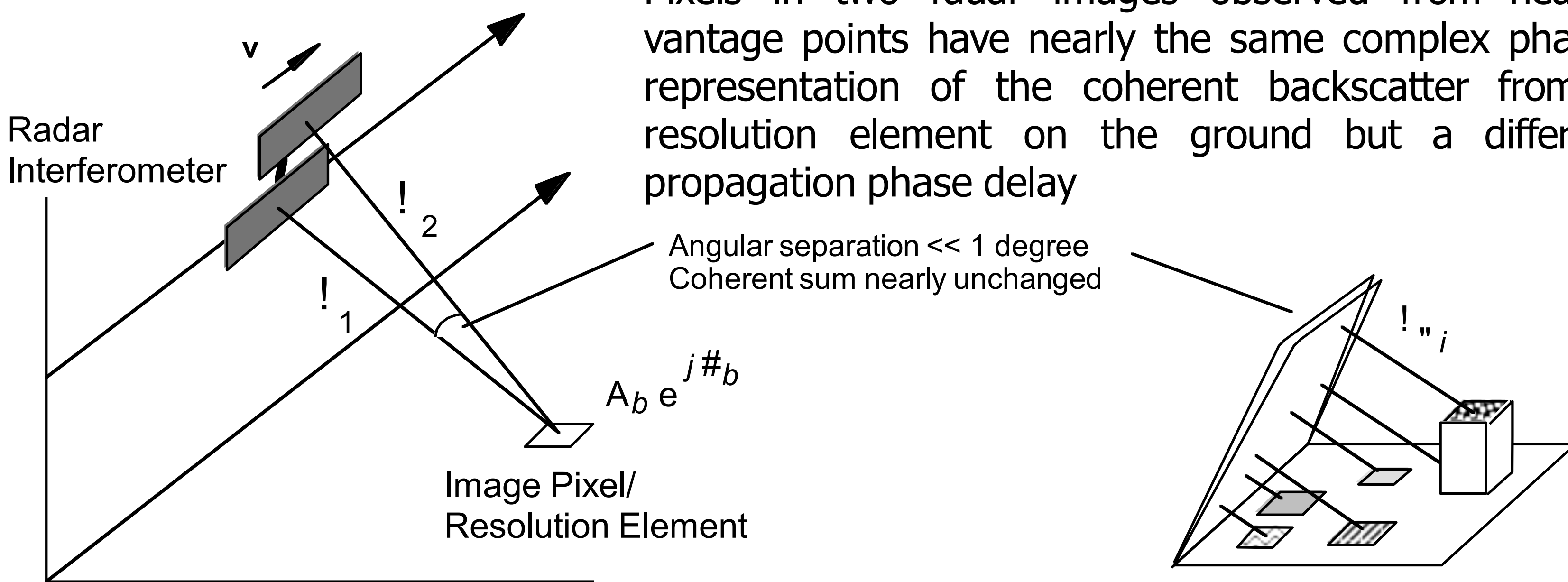
Interferometric Phase Characteristics

Pixels in two radar images observed from nearby vantage points have nearly the same complex phasor representation of the coherent backscatter from a resolution element on the ground but a different propagation phase delay



$$s_1 = A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda}\rho_1} \qquad s_2 = A_b e^{j\phi_b} e^{-j\frac{4\pi}{\lambda}\rho_2}$$

$$s_{int} = s_1 s_2^* = A_b e^{i\phi_b} e^{-i\frac{4\pi}{\lambda}\rho_1} A_b e^{-i\phi_b} e^{i\frac{4\pi}{\lambda}\rho_2} = A_b^2 e^{i\frac{4\pi}{\lambda}(\rho_2-\rho_1)}$$

Coherent backscatter term that is random from cell-to-cell cancels leaving phase that depends on differential path length!

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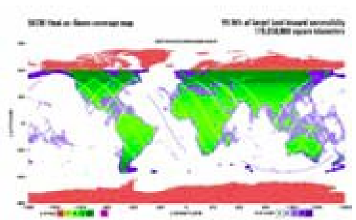
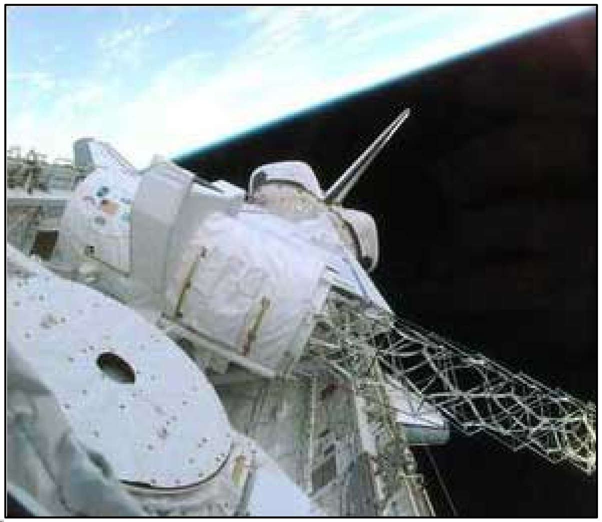
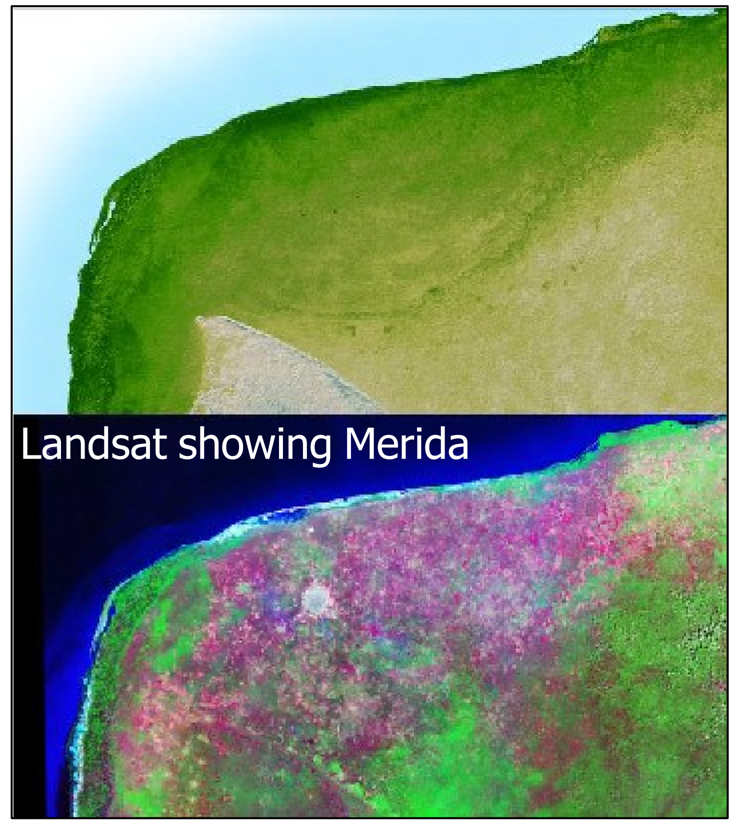
Shuttle Radar Topography Mission (SRTM)





3-dimensional SRTM view of Los Angeles (with Landsat data) showing San Andreas fault

SRTM image of Yucatan showing Chicxulub Crater, site of K-T extinction impact.



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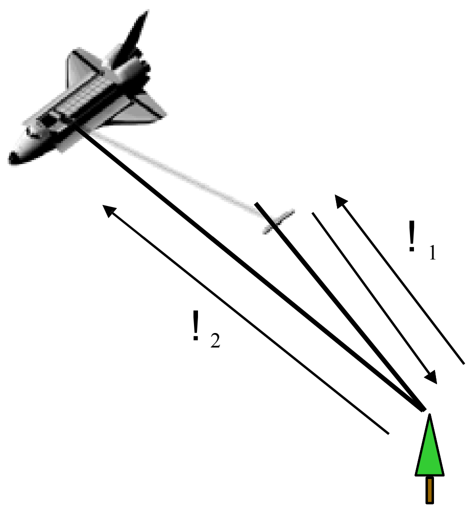
Data Collection Approaches

Single Pass

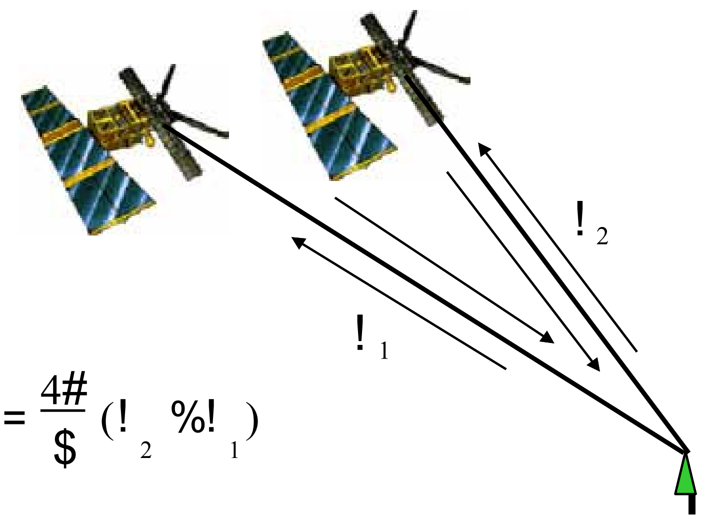
- **Interferometric radar data can be collected in a single pass interferometry (SPI) mode where both antennas are located on the same platform. One antenna transmits and both antennas receive the returned echoes**



$$" = \frac{2\#}{\$}(!_2 \%!_1)$$

Repeat Pass

- **In the repeat pass mode (RPI) two spatially close radar observations of the same scene are made separated in time. The time interval may range from seconds to years**



$$" = \frac{4\#}{\$}(!_2 \%!_1)$$

- **Temporal decorrelation — scene changes between observations**
- **Propagation delay variations — changes in troposphere or ionosphere between observations**

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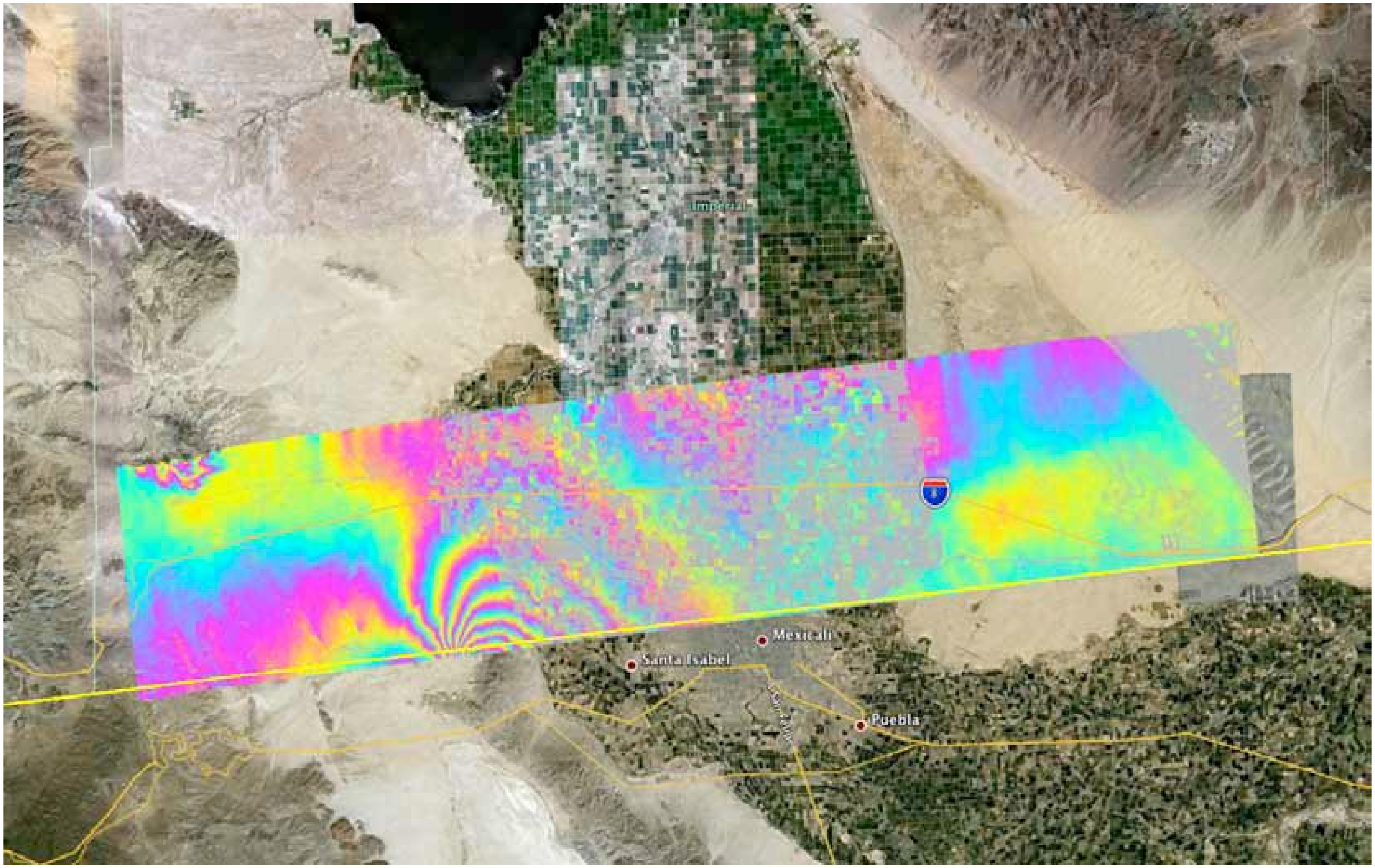
April 4, 2010 M 7.2 Baja California Earthquake

Airborne repeat-pass InSAR for geodetic imaging



Gallery of JPL Missions

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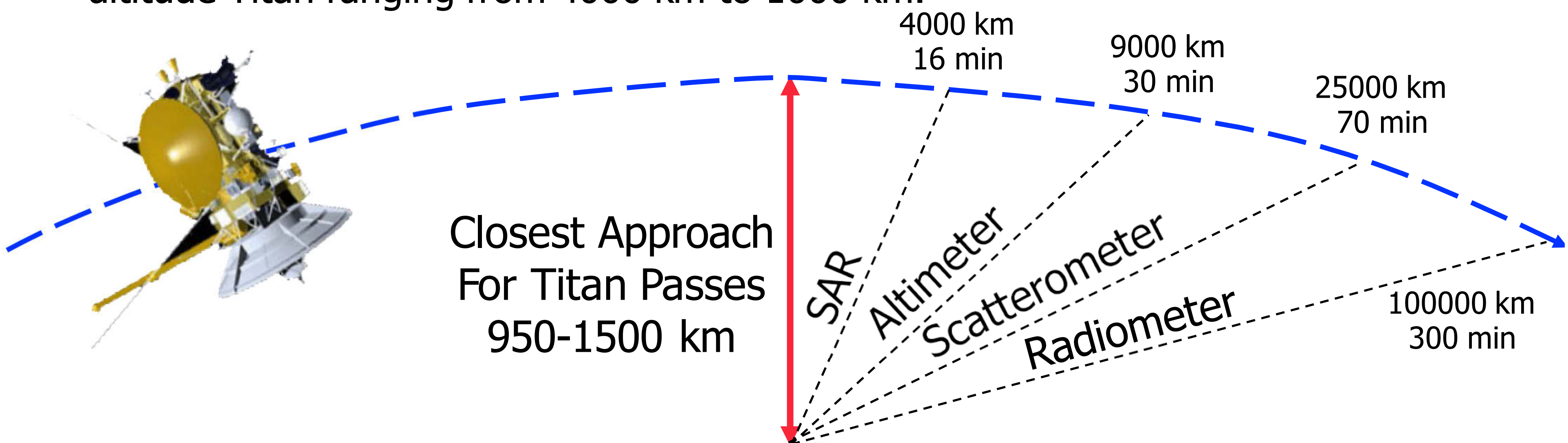
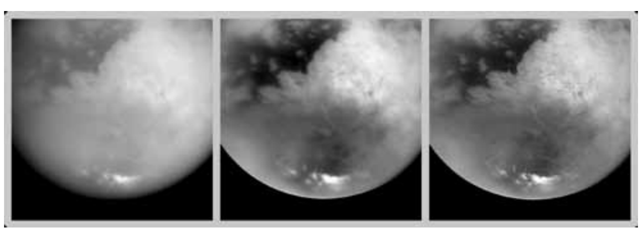
Titan Observation Geometry

SAR imaging takes place from around ±16 minutes from closest approach with altitude Titan ranging from 4000 km to 1000 km.



Infrared Images of Titan



<u>Titan:</u>

- Only moon with significant atmosphere (N_2)
- Surface Temperature: 85°K
- Radius: 2575 km
- Surface: Methane and other hydrocarbons ices and liquids

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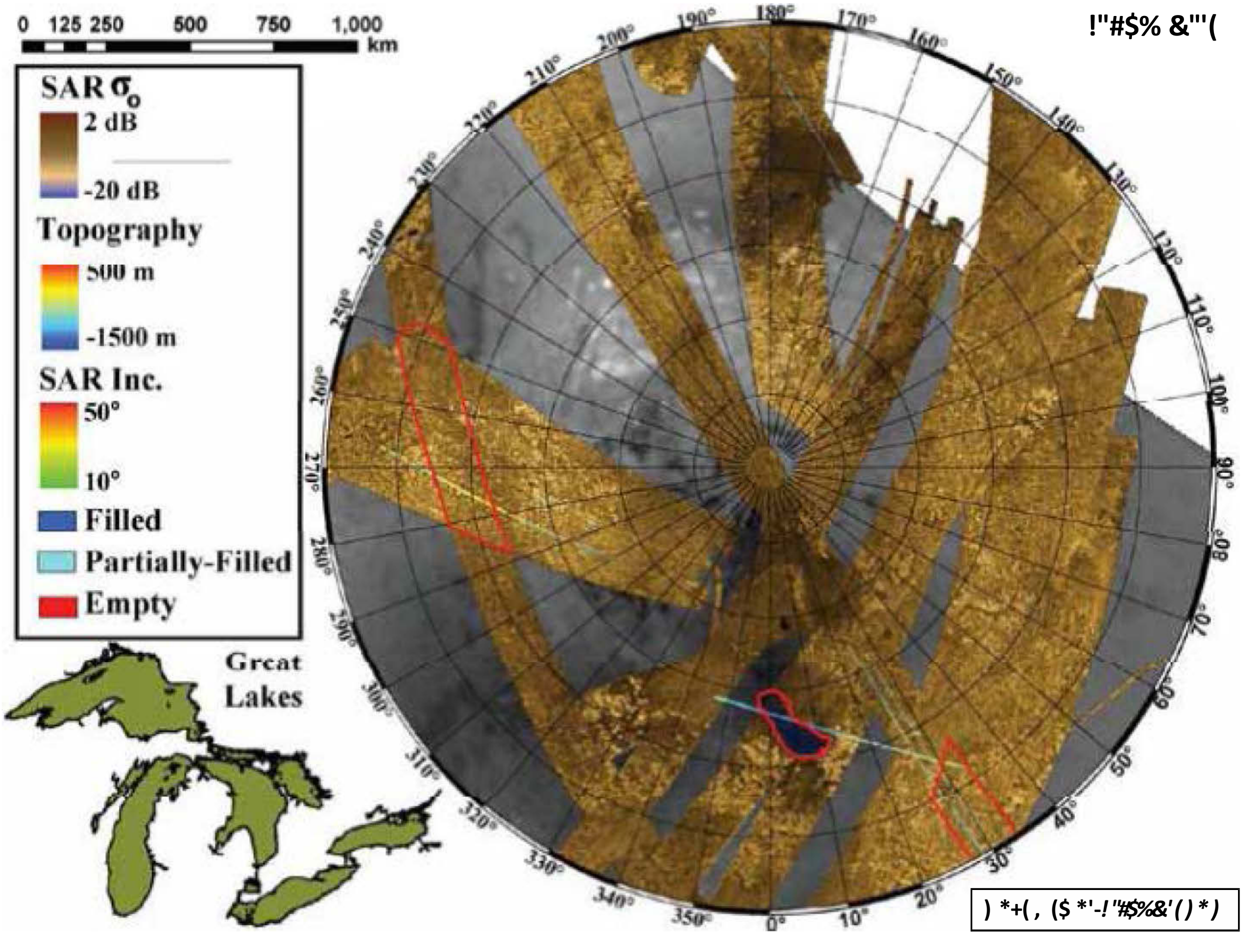
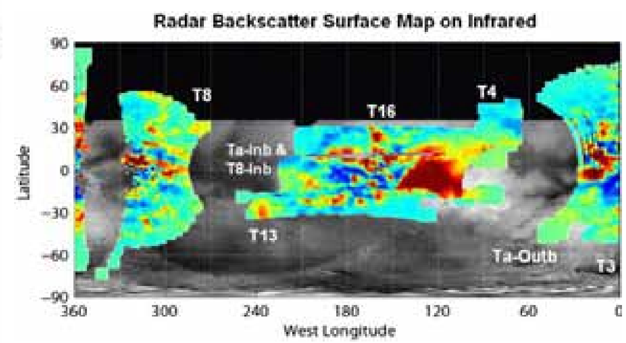
Cassini Radar Results



(Courtesy S. Hensley)



Wye et al. (Icarus, 2007)

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Summary

- This lecture was just a taste of radar remote sensing techniques and applications. Other important areas include
  - Stereo radargrammetry
  - PolInSAR for volumetric structure mapping
  - Agricultural monitoring, soil moisture, ice-mapping, …
- The broad range of sensor types, frequencies of observation and availability of sensors have enabled radar sensors to make significant contributions in a wide area of earth and planetary remote sensing sciences
- The range of applications, both qualitative and quantitative, continue to expand with each new generation of sensors