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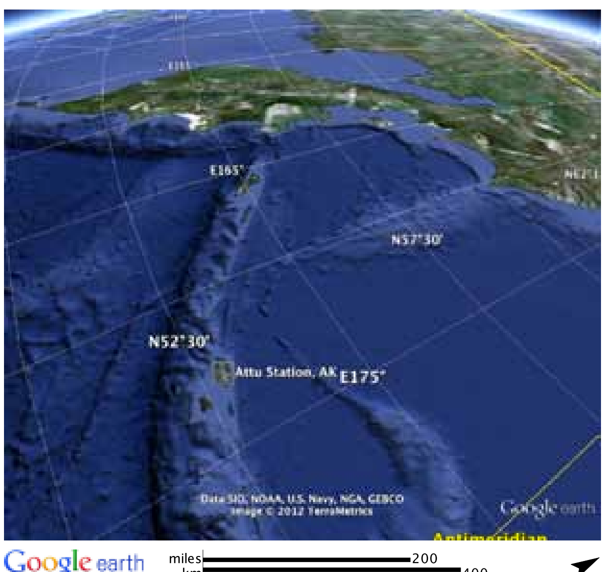
Reaching Out and Touching our Solar System

Jet Propulsion Laboratory's Radar Program for Earth and Planetary Exploration



Kamchatka Mountain Range
SRTM with Landsat Overlay

Paul A. Rosen
Jet Propulsion Laboratory
California Institute of Technology

October 5, 2012

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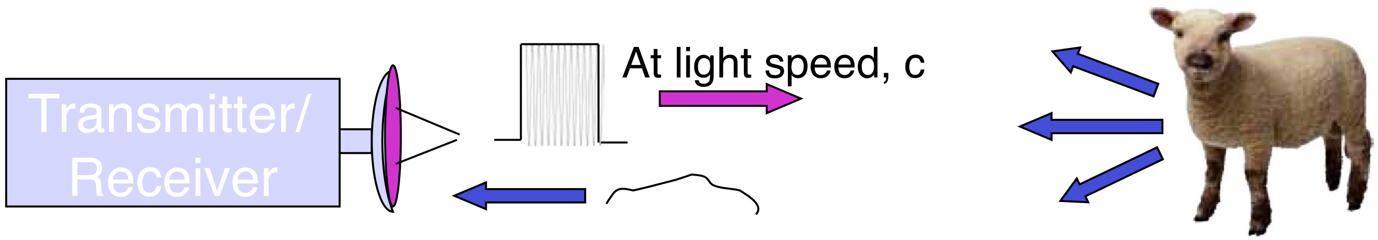
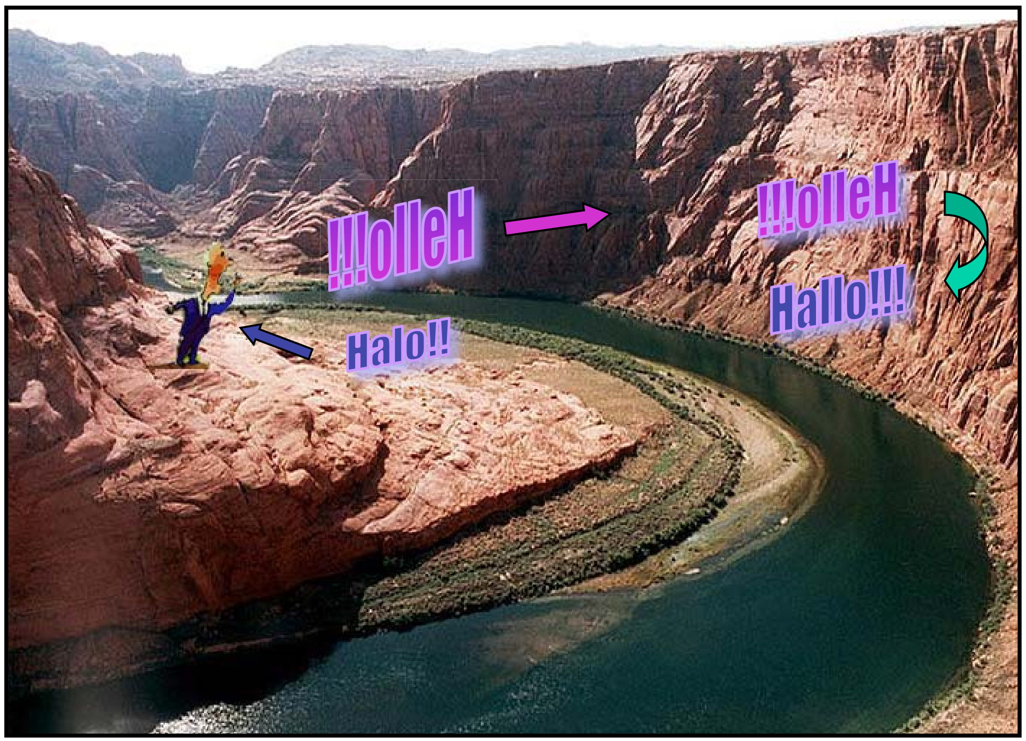
The Radar Remote Sensing Concept





- 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

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Why Radar 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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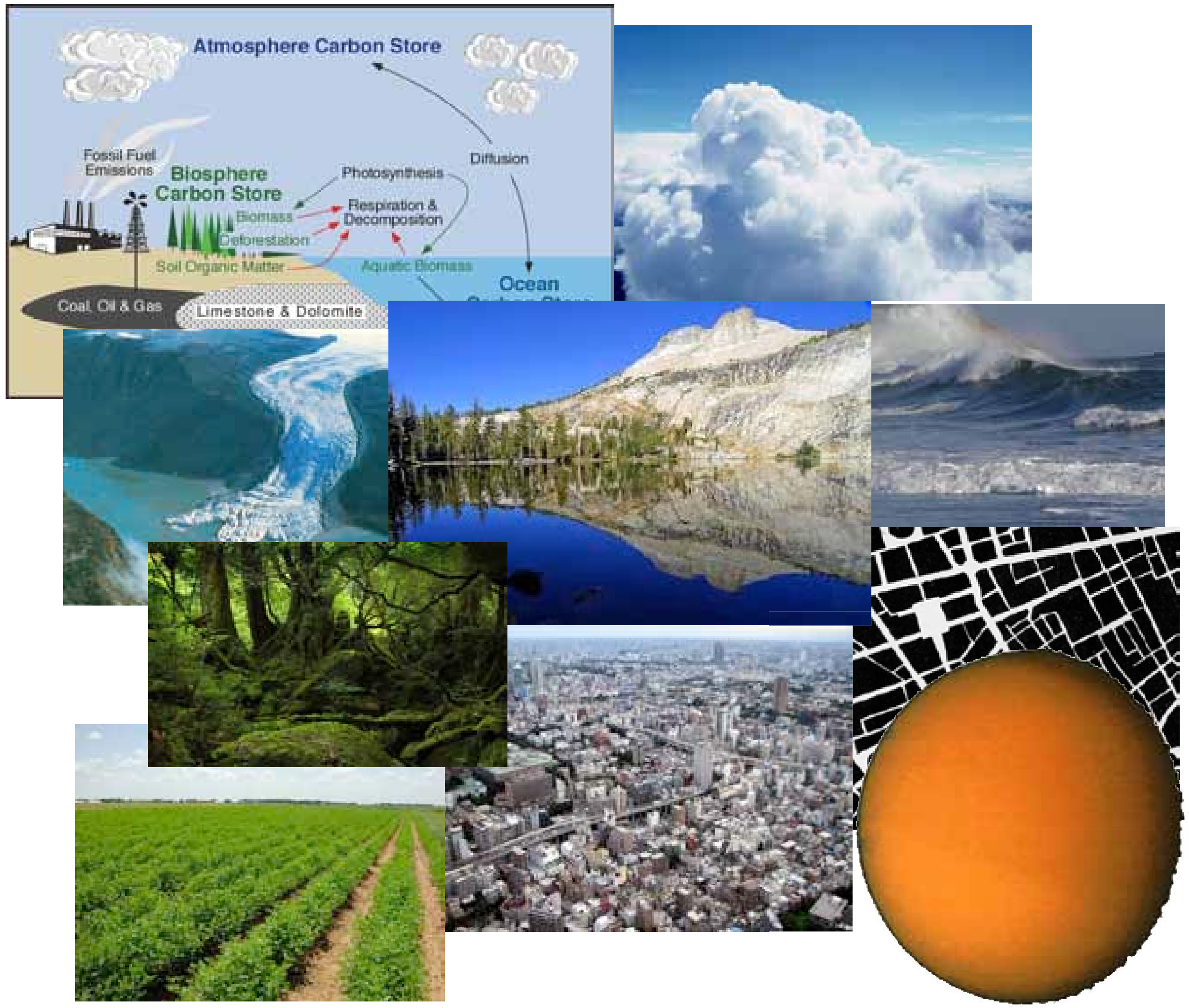
What do we want to measure with radar?

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



Grail
Sep 2011
Moon Gravity
Juno
August 2011
Jupiter
NuSTAR
June 2012
High Energy X-ray
Mars Science Lab
August 2012
Curiosity Rover
Aquarius/SAC-D
June 2011
Sea Salinity
Gallery of JPL Missions
Also: Galex 2003 MMM 2008 Diviner 2009 Kepler 2009 Herschel 2009
Explorer 1-5
1958
Van Allen Belts
Ulysses
1990
Solar Polar Orbit
Microwave Instrument
2004
Rosetta Comet Orbiter
MARSIS
2003
Deep Sounder
Spitzer Telescope
2003
Infrared Telescope
Seawinds
2002
Ocean Winds
Pioneer 3-4
1958
Lunar Flybys
Wide Field Camera
1990
Fix Hubble
Mars Rovers
2003
Rovers
Genesis
2001
Solar Wind
Samples
Rangers
1961-1965
Lunar Surveys
Topex/Poseiden
1992
Ocean Altimeter
Emission Spectrometer
2004
Infrared Sensor
Microwave Sounder
2004
Ozone
AIRS
2002
Infrared Sounder
SRTM
2000
Earth Radar
Surveyors
1966-1968
Lunar Landers
Global Surveyor
1996
Mars Orbiter
Grace
2002
Earth Gravity
Deep Space 1
1998
Ion Engine
Mariner 1-2
1962
Venus Flybys
Cassini
1997
Saturn & Moons
Deep Impact
2005
Smash Comet
EPOXI
MRO
2005
SHARAD
Cloudsat
2006
Precipitation
Jason 1
2001
Ocean Altimetry
VLBI
1997
Astronomy
Mariner 3-4
1964
Mars Flybys
Pathfinder
1996
Mars Rover
Mariner 5
1967
Venus Flyby
Stardust
1999
Comet Wild-2
Quickscat
1999
Sea Winds
Radiometer
1999
Earth Thermal
Multi-Angle Spect
1999
Earth Imaging
Active Cavity
1999
Solar Radiance
Keck
2001
Astronomy
Mars Odyssey
2001
Mars Imaging
NSCAT
1996
Earth Winds
Mariner 6-7
1969
Mars Flybys
Mariner 8-9
1971
Mars Orbiter
Mariner 10
1973
Venus / Merc
Viking
1975
Mars Landers
Voyager
1977
Grand Tour
Seasat
1978
Earth Radar
Solar Explorer
1981
Earth Ozone
SIR A, B, C
1981, 84, 94
Earth Radar
Infrared Sat
1983
Telescope
Magellan
1989
Venus Radar
Galileo
1989
Jupiter
Mars Observer
1992
Mars Orbiter

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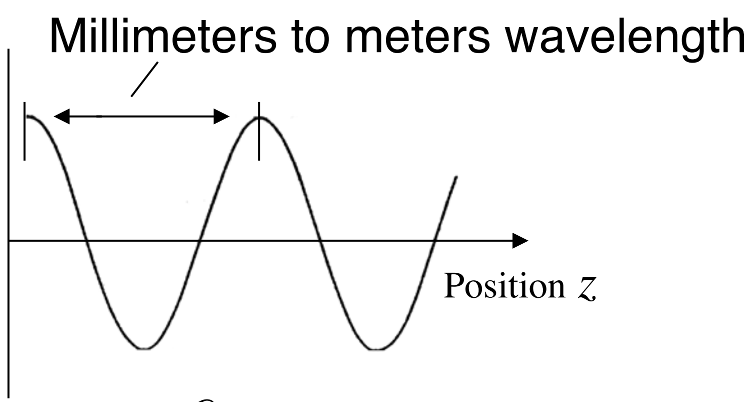
Radar and Light Waves



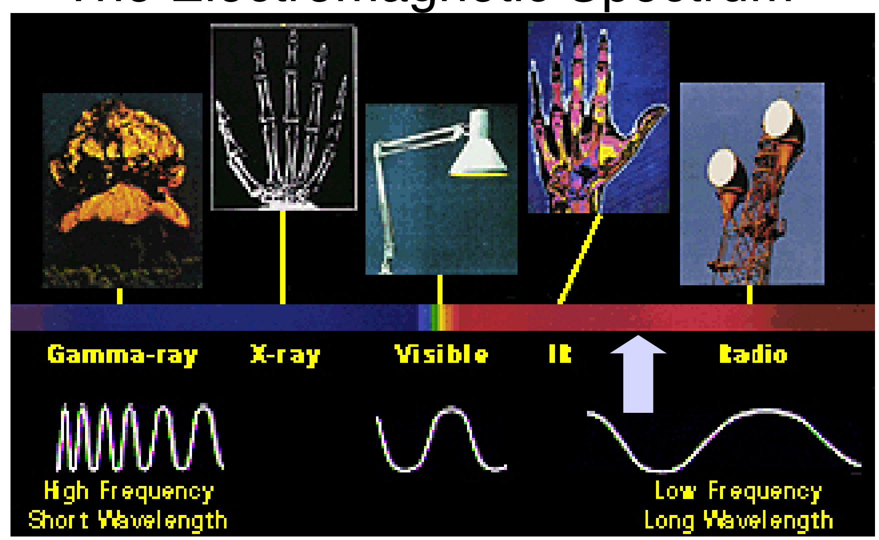
$$\lambda = \frac{c}{f}$$

- 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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Classic Radar Remote Sensing

- Invert the signal measurement to infer reflectivity using the "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

- Use reflectivity to infer geophysical parameter using models or ground measurements

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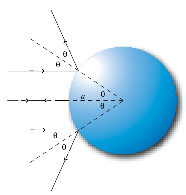
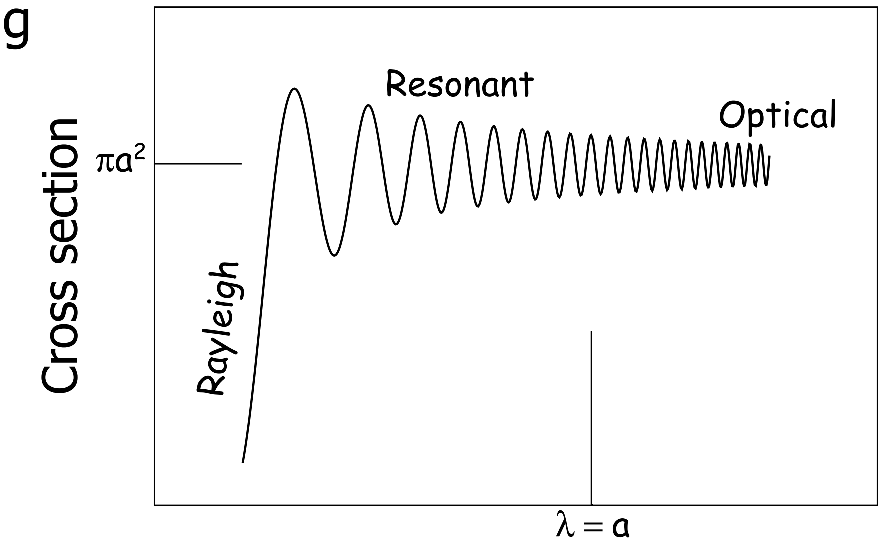
Surface and Volume Scattering Models for Radar

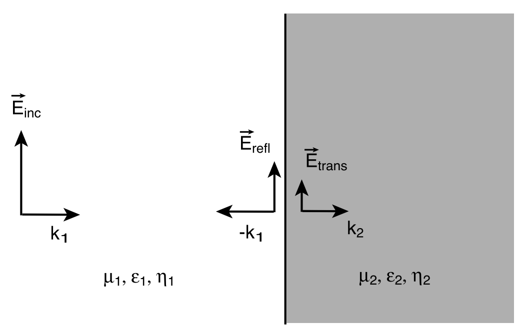
We can model simple scattering from particles or surfaces…

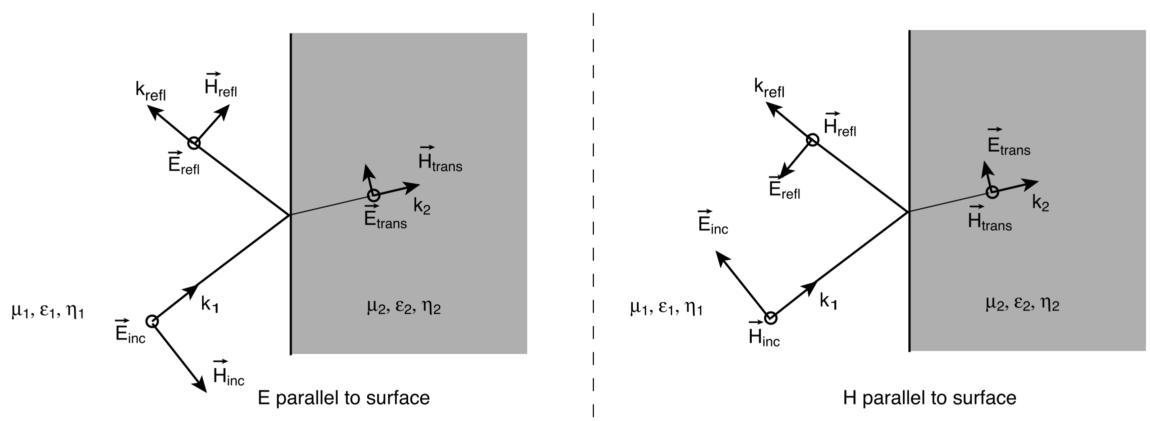
Cross section of a large sphere is its projected area





Cross section of a large flat facet goes as area squared





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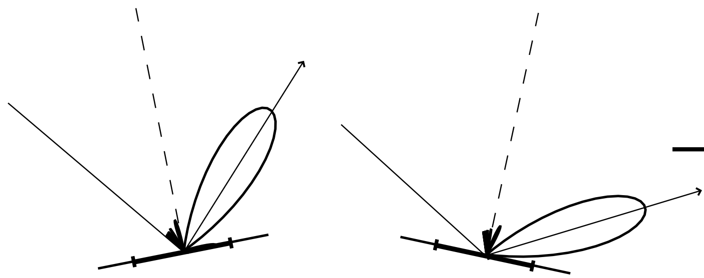
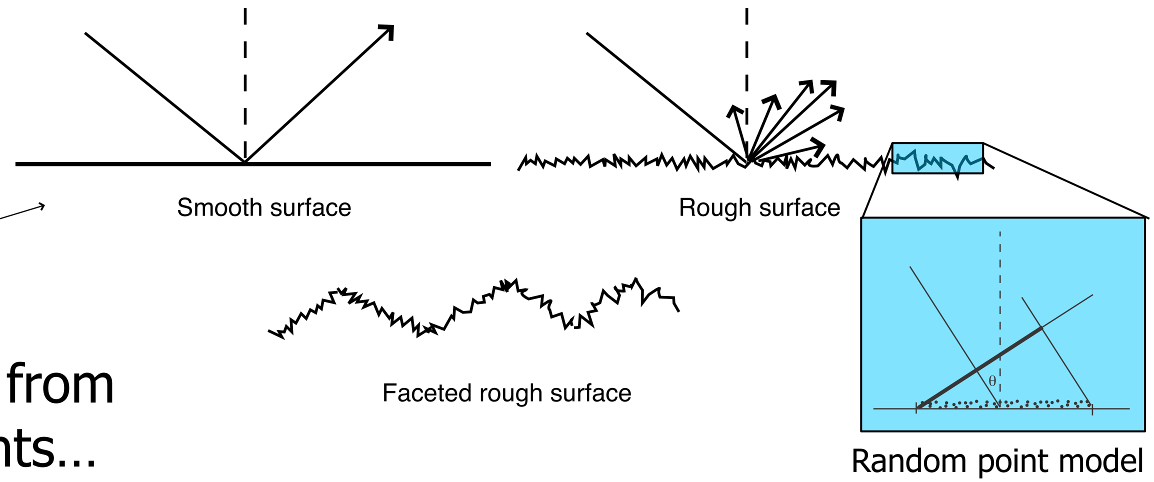
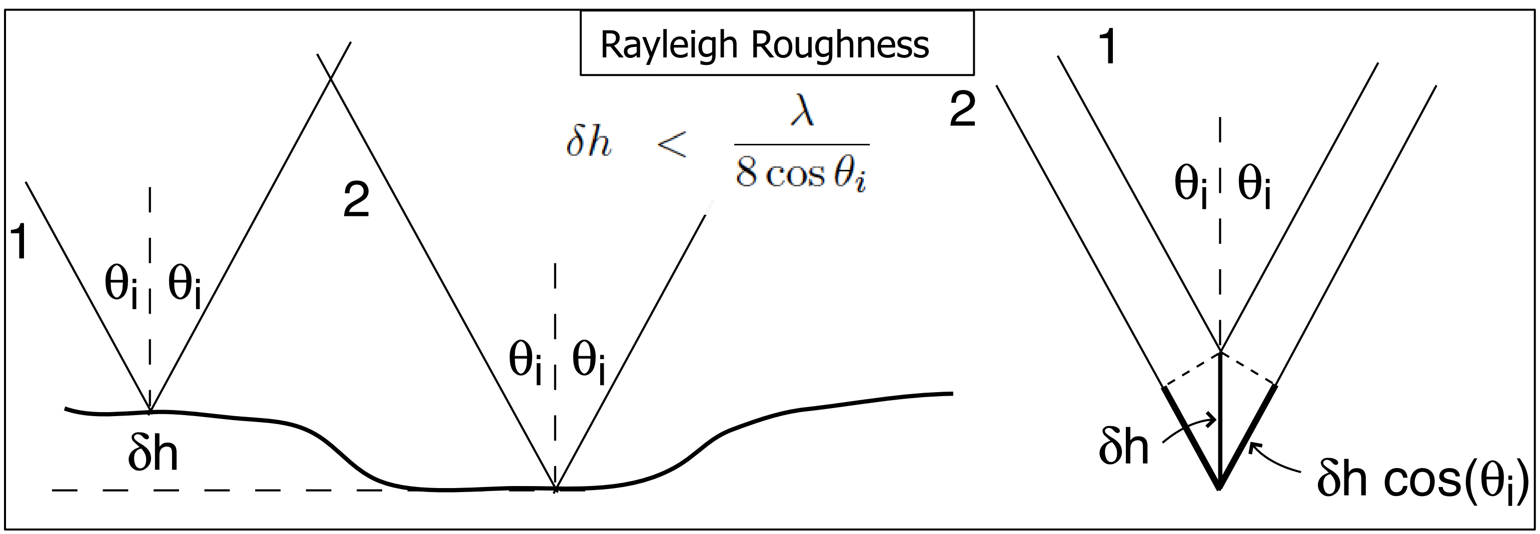
Surface and Volume Scattering Models for Radar





And we can develop intuition from combinations of these elements…



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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

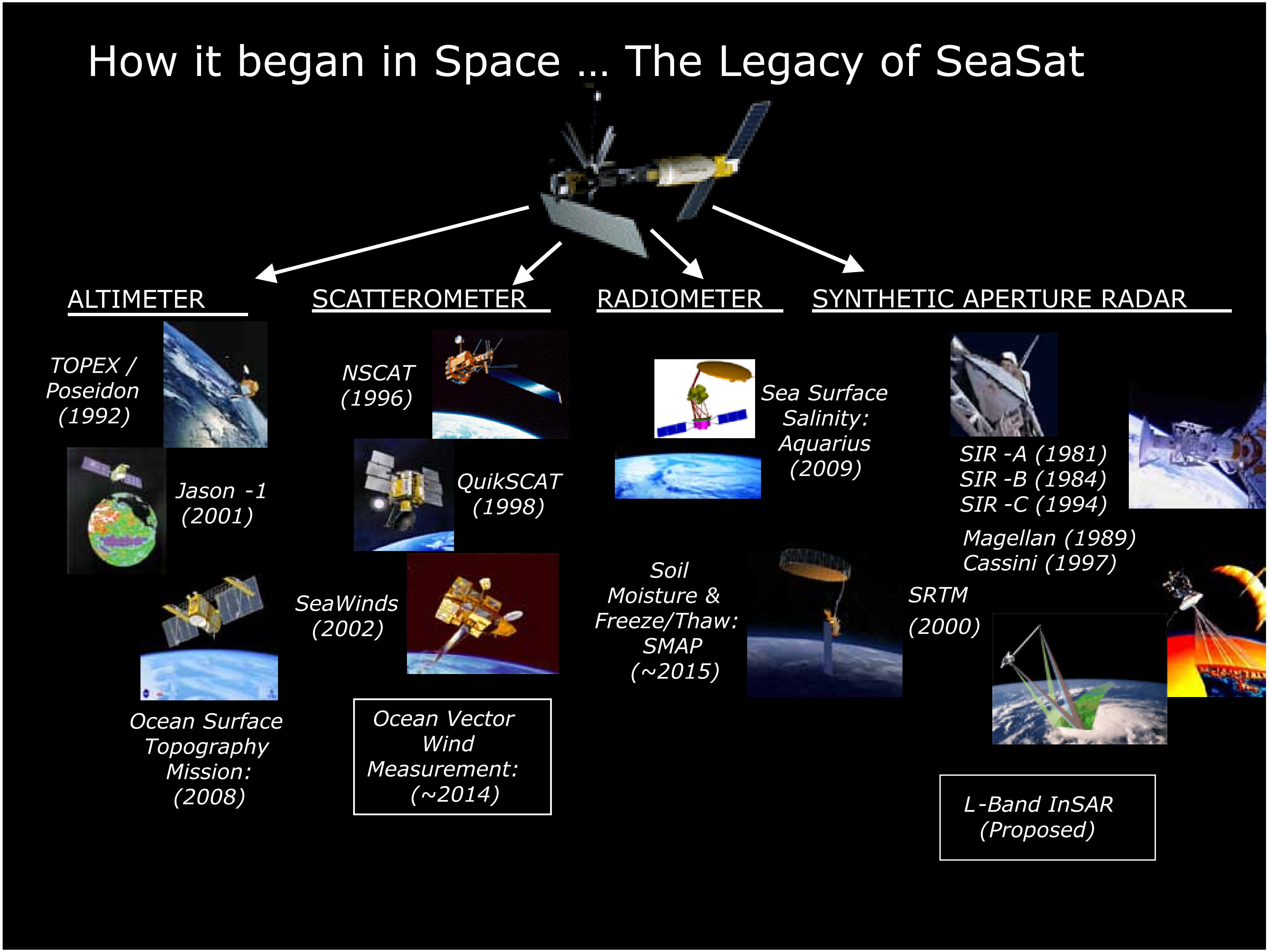
Sounders/Profilers measure the reflected power over range

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

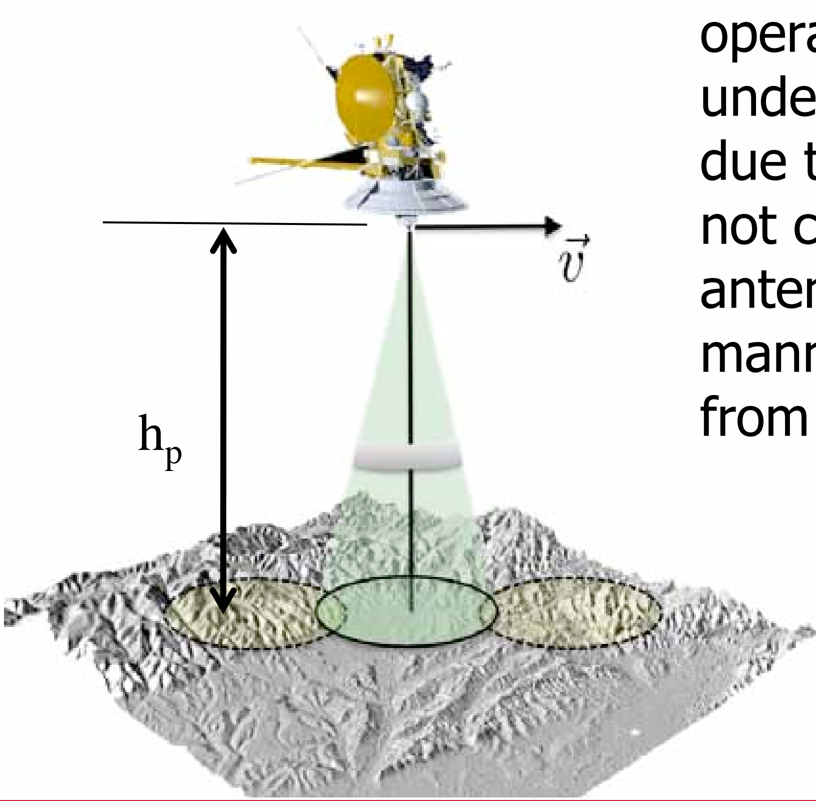
Polarimeters generate backscatter measurements from multiple polarizations. Polarimetric information helps distinguish surface roughness from surface composition effects on the backscatter

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.


How it began in Space … The Legacy of SeaSat
ALTIMETER
SCATTEROMETER
RADIOMETER
SYNTHETIC APERTURE RADAR
TOPEX / Poseidon (1992)
Jason -1 (2001)
Ocean Surface Topography Mission: (2008)
NSCAT (1996)
QuikSCAT (1998)
SeaWinds (2002)
Ocean Vector Wind Measurement: (~2014)
Sea Surface Salinity: Aquarius (2009)
Soil Moisture & Freeze/Thaw: SMAP (~2015)
SIR -A (1981)
SIR -B (1984)
SIR -C (1994)
Magellan (1989)
Cassini (1997)
SRTM (2000)
L-Band InSAR (Proposed)

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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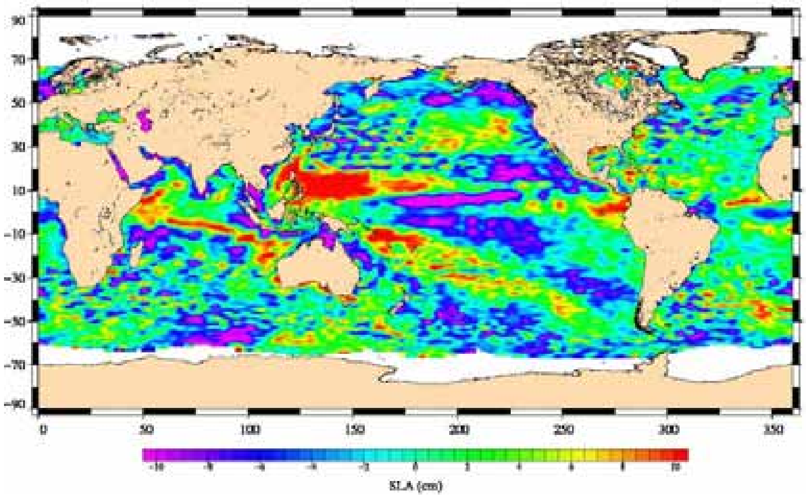
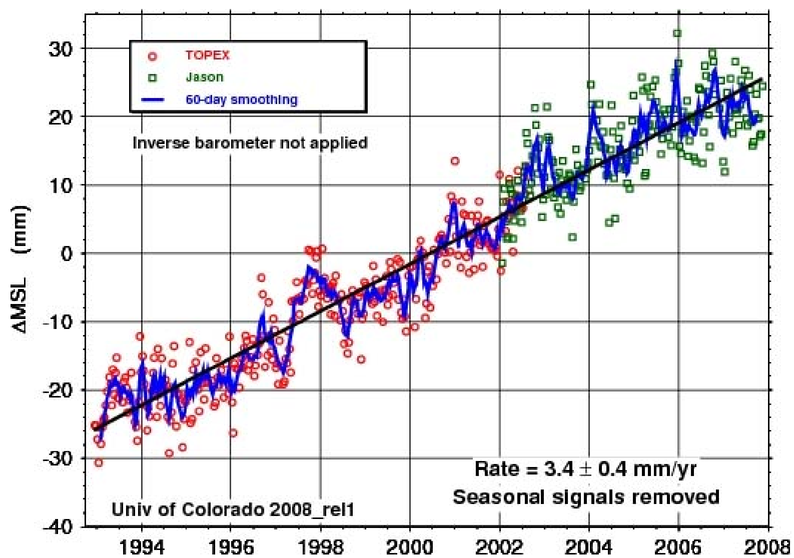
TOPEX-Jason 1-OSTM Altimetry



Less than a month after launch, the NASA-French space agency Ocean Surface Topography Mission (OSTM)/Jason 2 oceanography satellite produced its first complete maps of global ocean surface topography, surface wave height and wind speed



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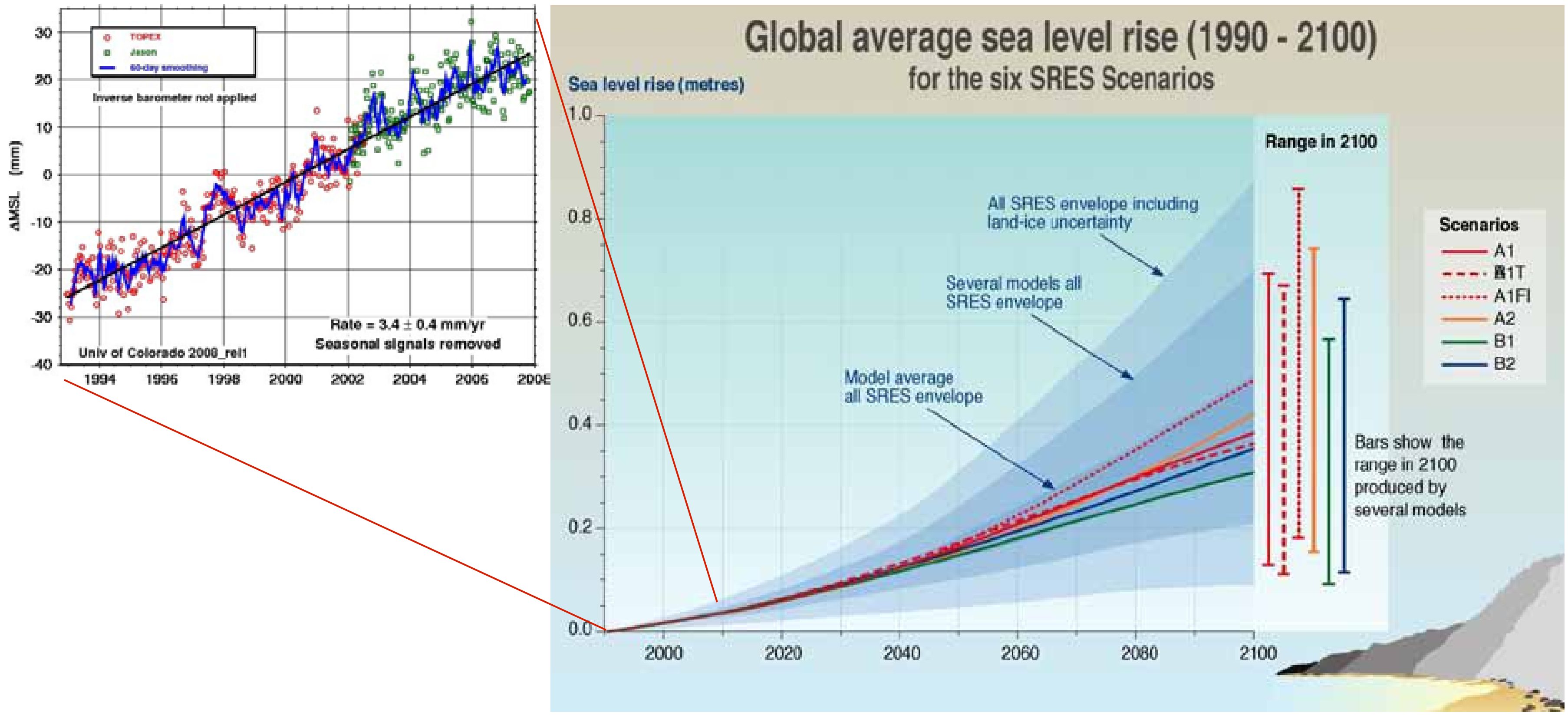
Projecting Sea Level Rise



"The projections do not include uncertainties in climate-carbon cycle feedbacks nor the full effects of changes in ice sheet flow, therefore the upper values of the ranges are not to be considered upper bounds for sea level rise."

IPCC (2007)

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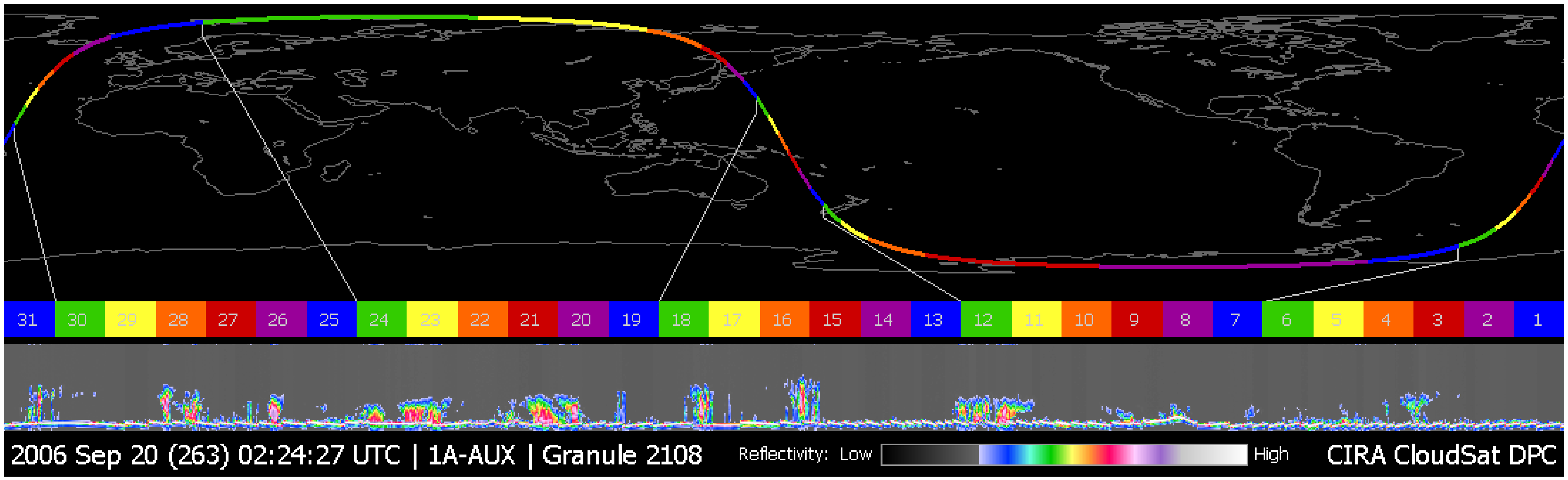
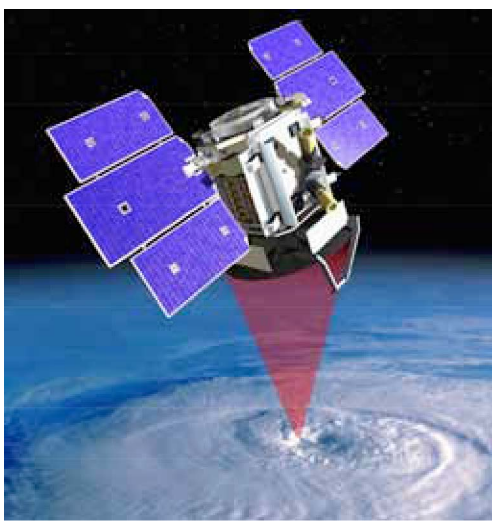
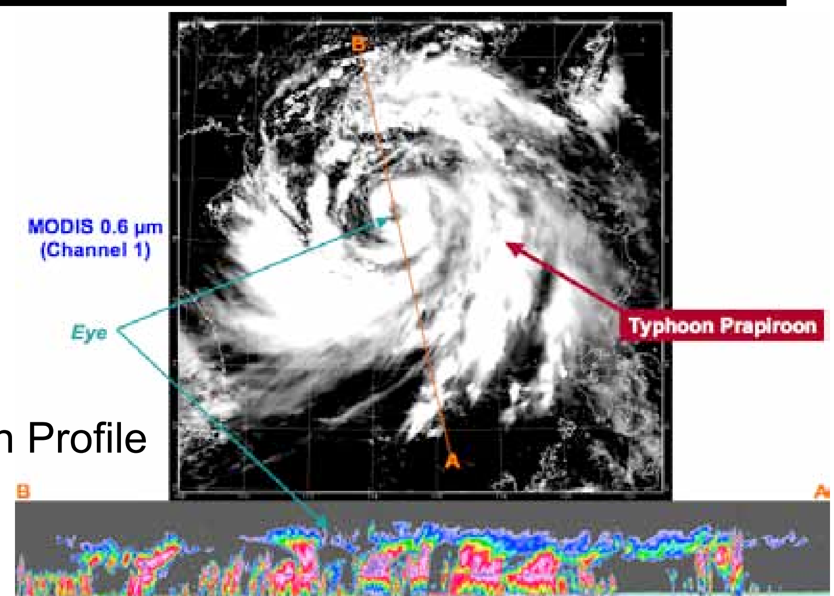
CloudSat – 94 GHz Profiling Cloud Radar



Typical Orbital Profile



Typhoon Profile



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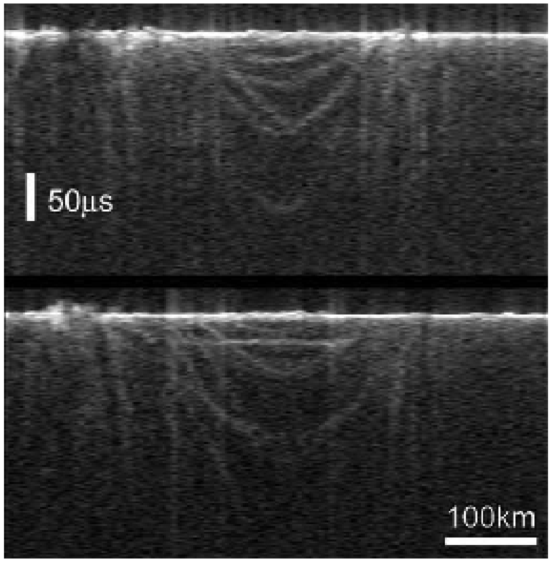
Mars Advanced Radar for Subsurface and Ionospheric Sounding on ESA Mars Express

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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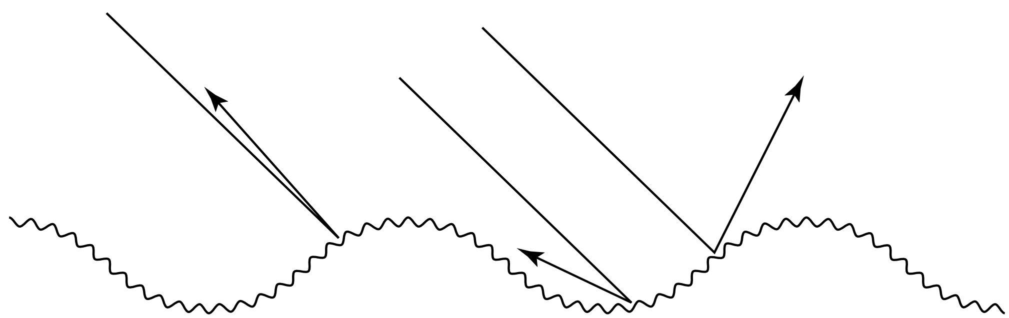
Scatterometry for Ocean Winds

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

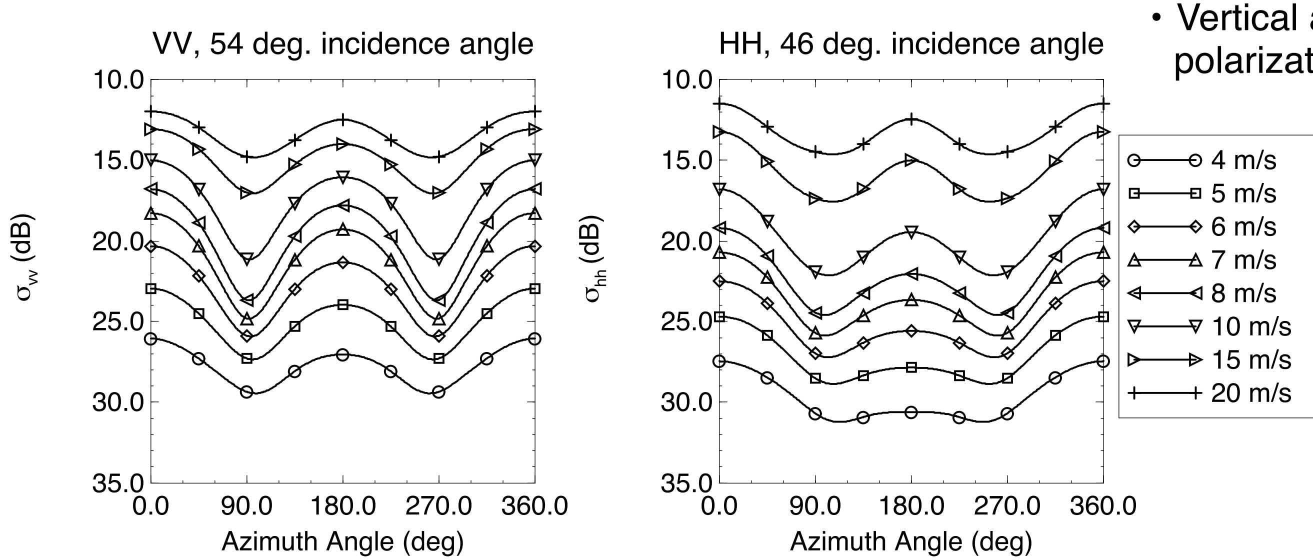
For a given polarization, incidence angle, and wind speed:

$$\sigma_0 = A_0 + A_1 \cos(\chi) + A_2 \cos(2\chi)$$

– Where χ 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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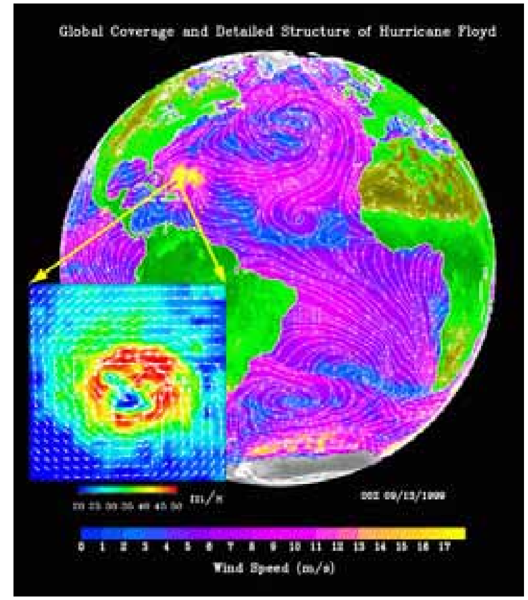
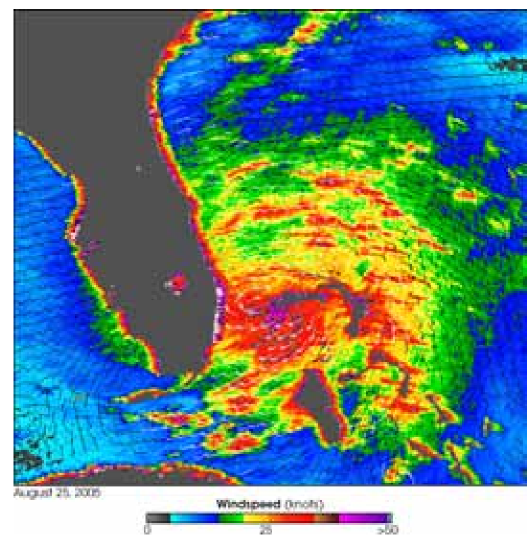
Scatterometers for Ocean Wind

- 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

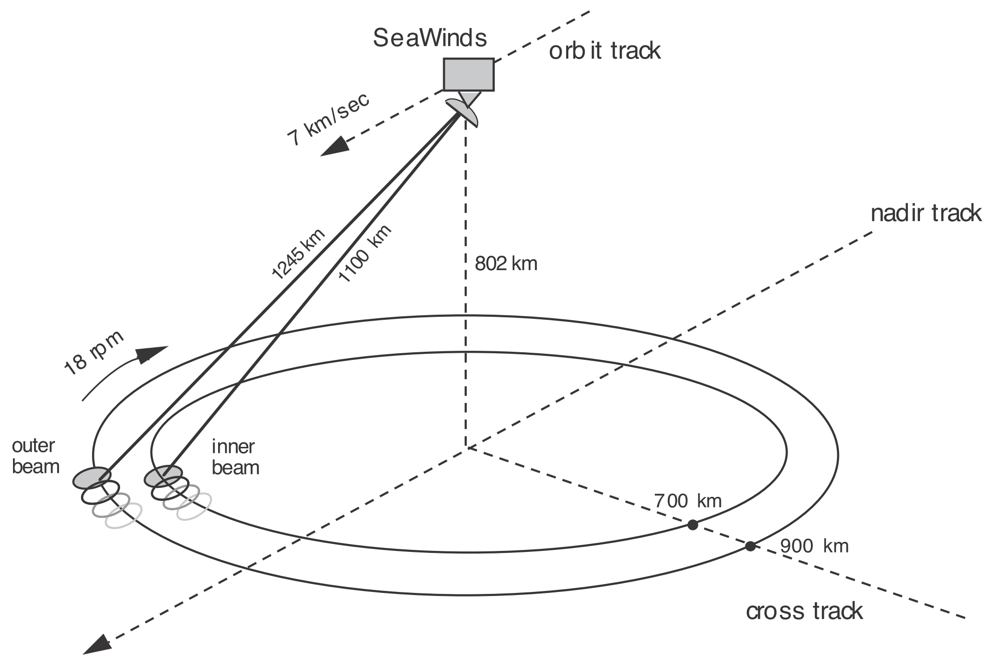
Beam geometry and polarization

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

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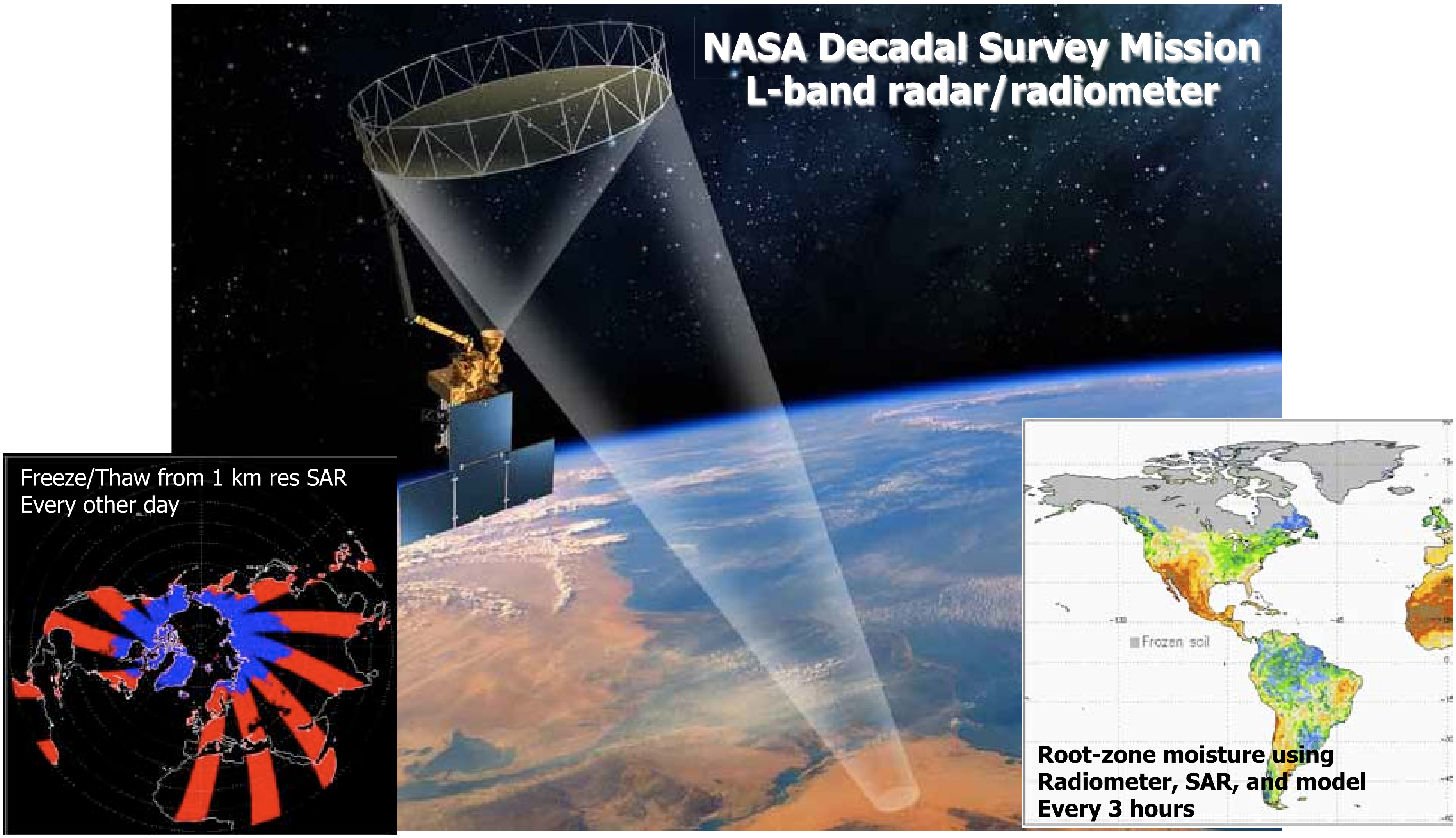
Soil Moisture Active/Passive (SMAP)



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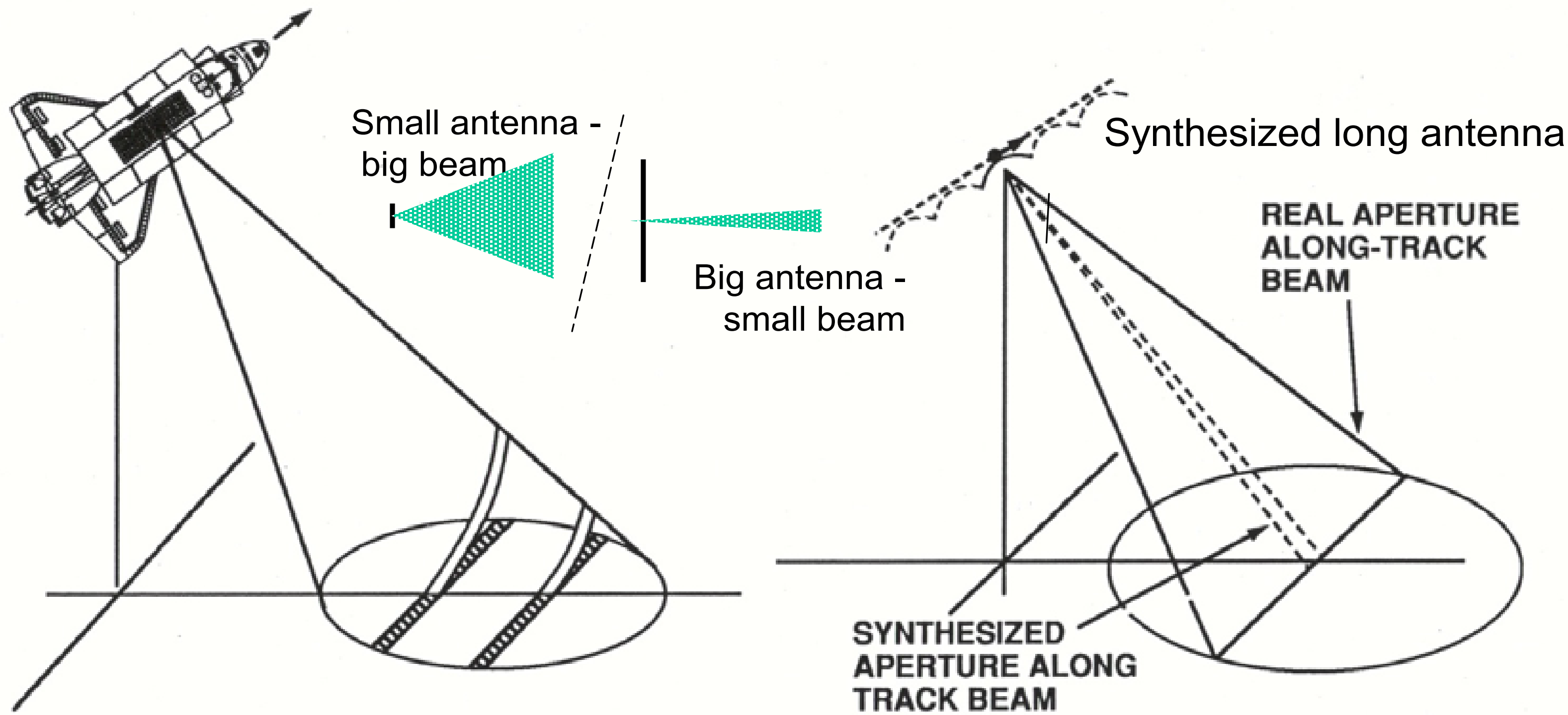
Imaging Radar



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

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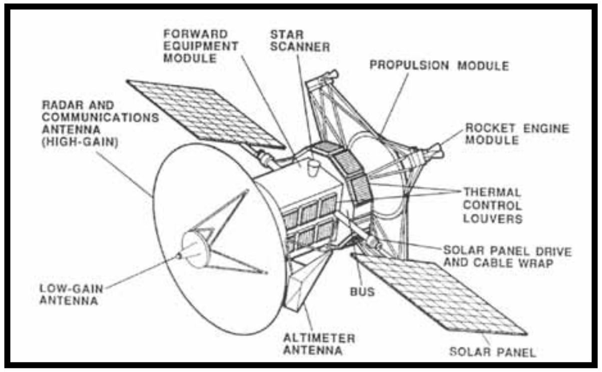
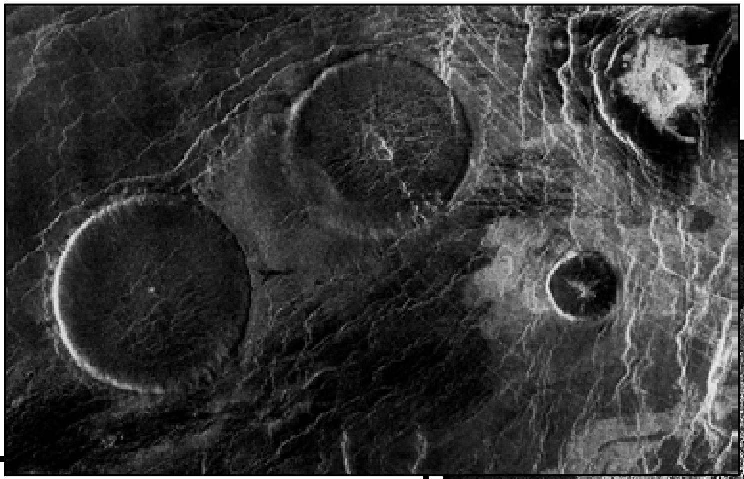
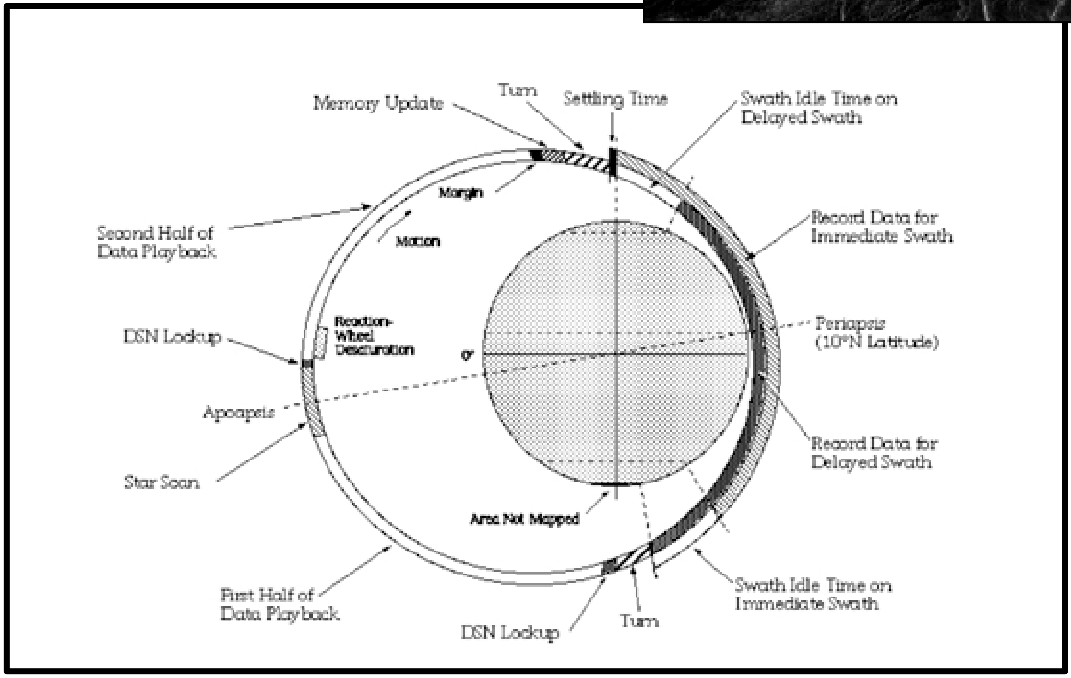
Magellan Mission to Venus







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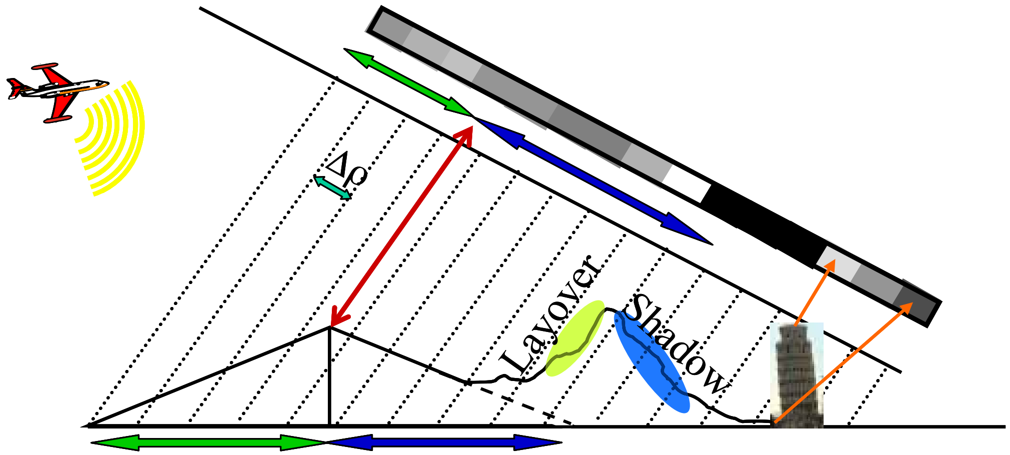
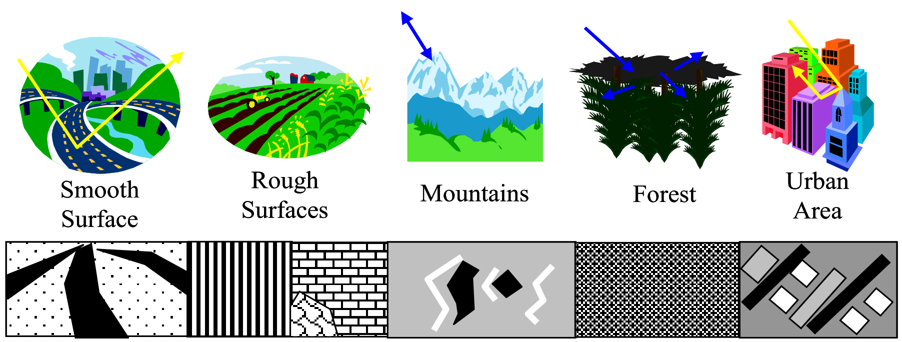
Radar Imaging Properties



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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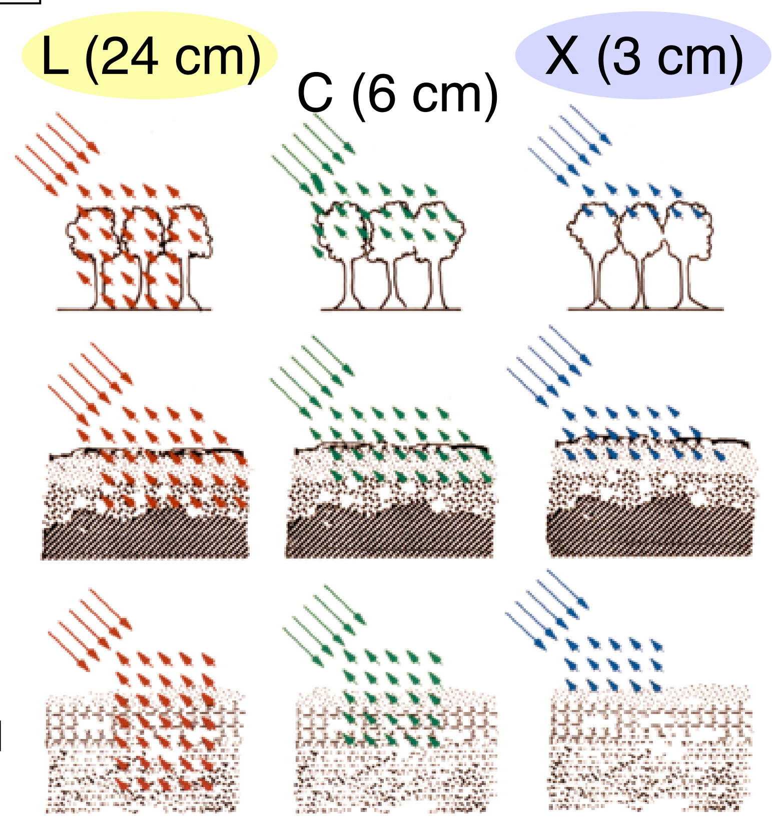
Wavelength - A Measure of Surface Scale

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



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

Dry soils: Surface looks rough to X-band but not L-band

Ice: Surface and layering look rough to X-band but not L-band

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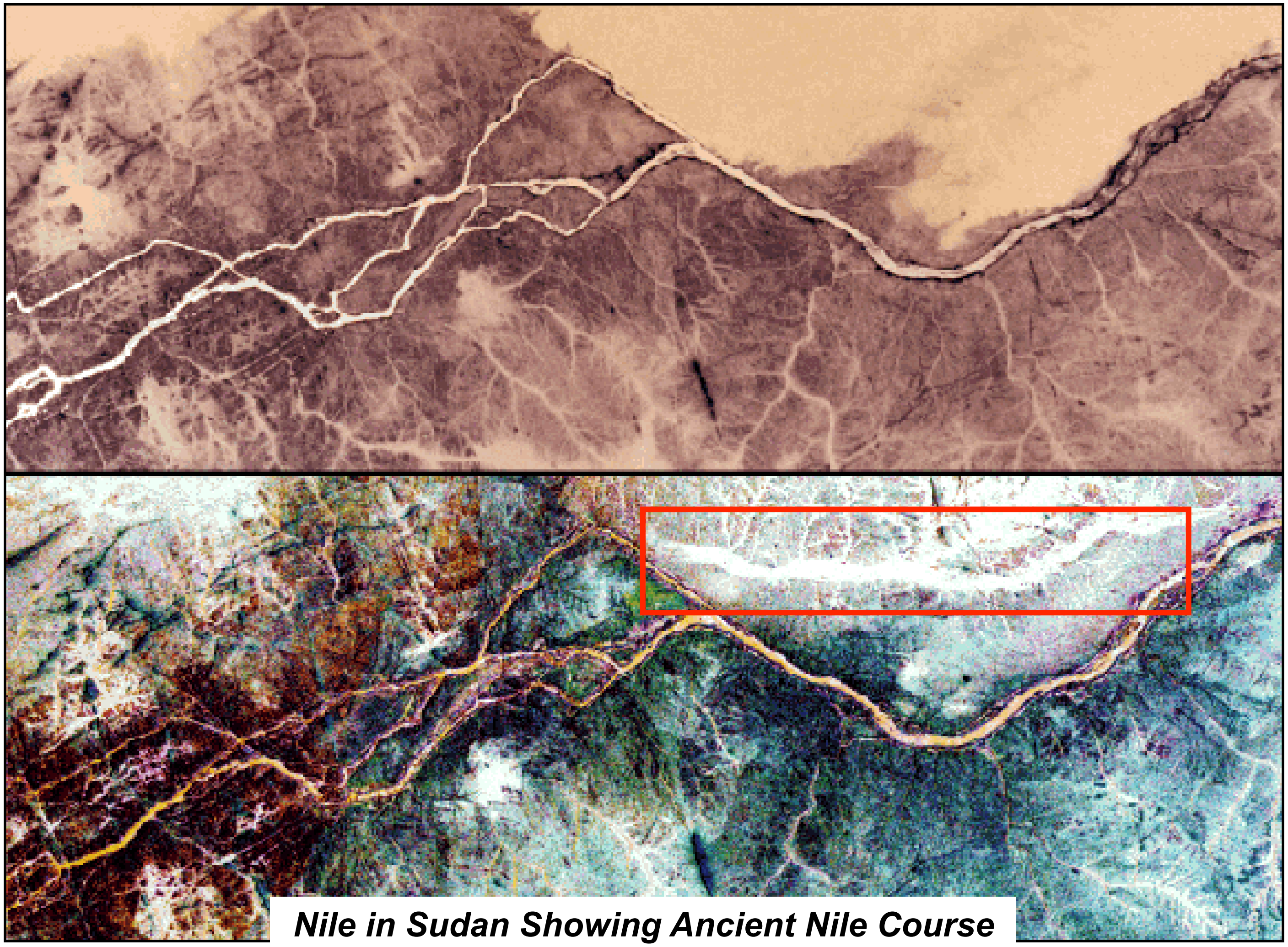
Visible (Upper) and Radar (Lower)



Nile in Sudan Showing Ancient Nile Course

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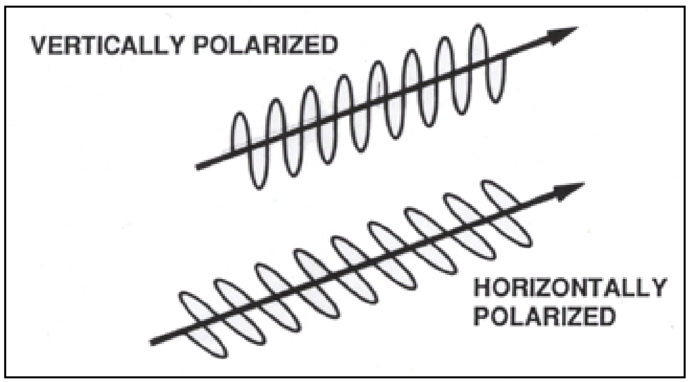
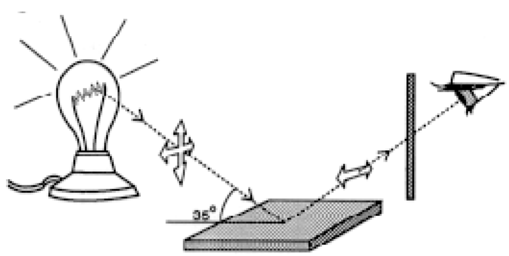
Polarization - A Measure of Surface Orientations and Properties

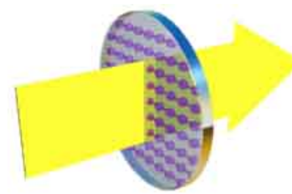
Wave Polarization



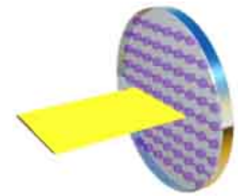


Mostly horizontal polarization is reflected from a flat surface.

Polarization Filters

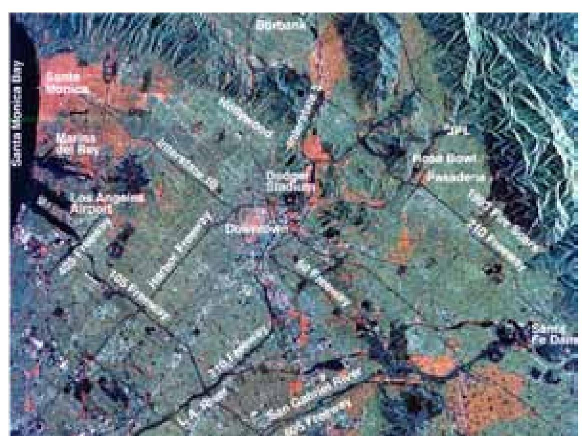


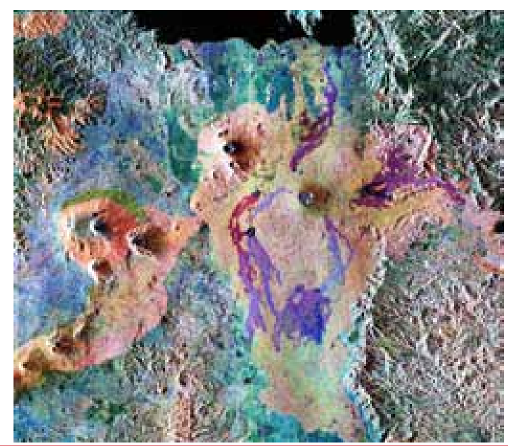
Vertical polarization passes through horizontally arranged absorbers.



Horizontal polarization does not pass through horizontally arranged absorbers.

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





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San Joaquin Valley, California

Applications: soil moisture estimation, vegetation classification

LHH-Red LHV – Green LVV – Blue

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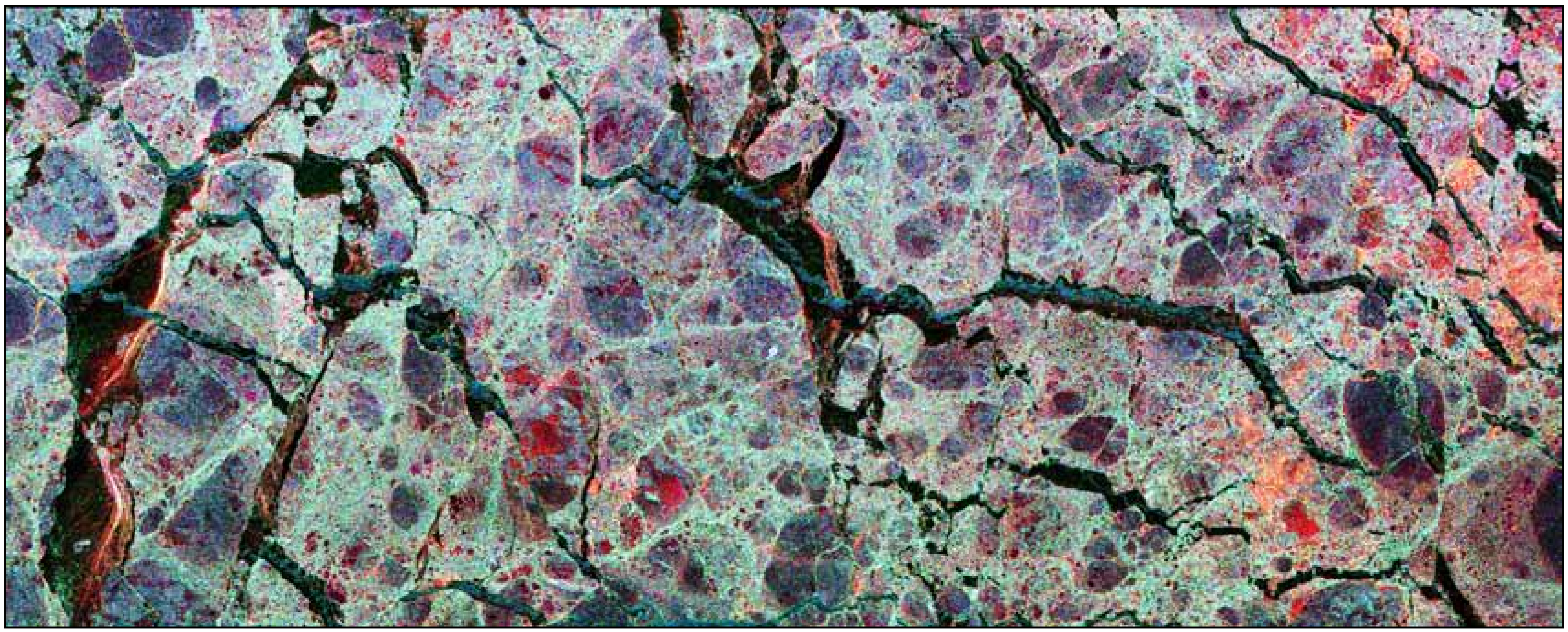
SIR-C/X-SAR Views Sea Ice

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



Red: CHH Green: LHV Blue: LHH

Weddell Sea, Antarctica

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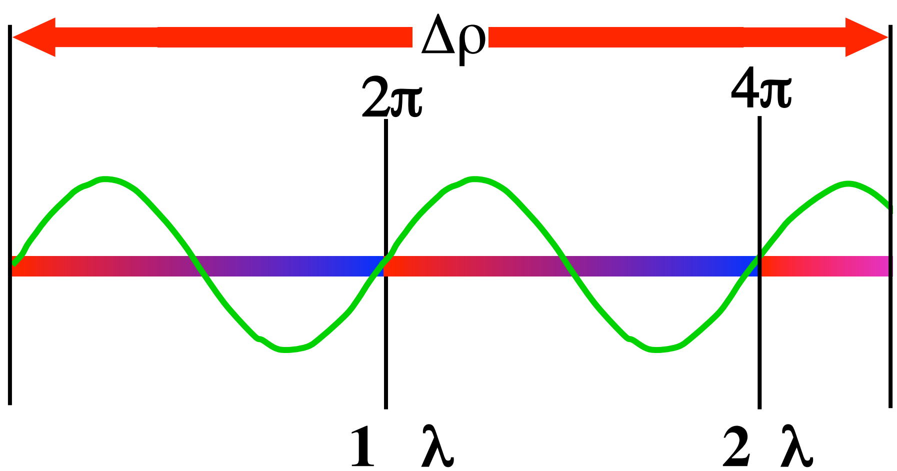
Phase and Radar Interferometry

- 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



$$\phi = \underbrace{2\pi}_{\text{Radians per wavelength}} \; \underbrace{\frac{\Delta\rho}{\lambda}}_{\text{Number of wavelengths}}$$

- 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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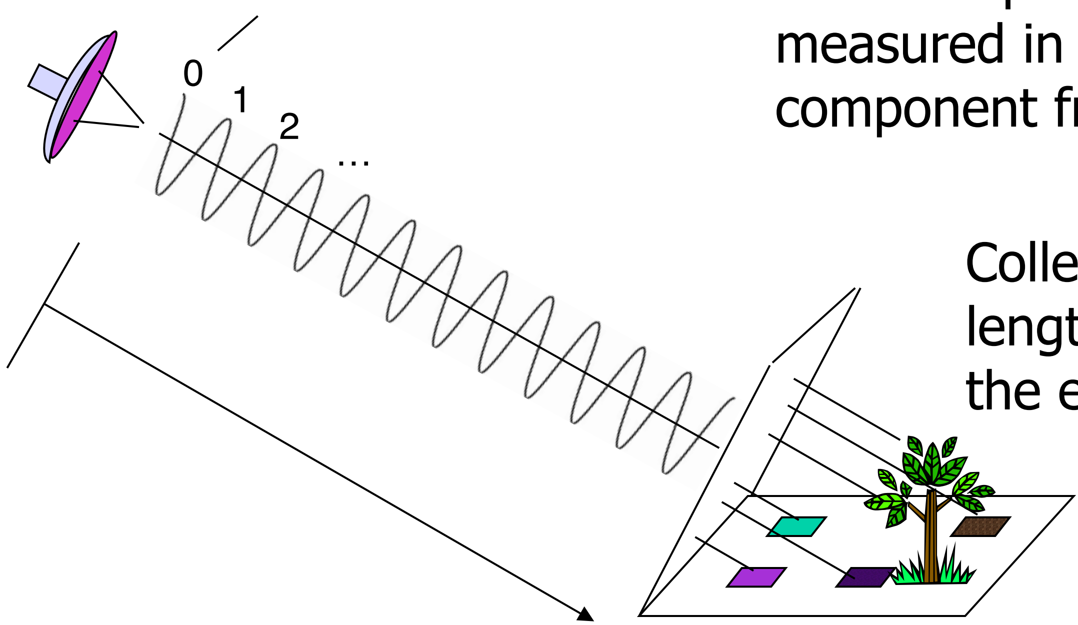
Phase - A Measure of the Range and Surface Complexity

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



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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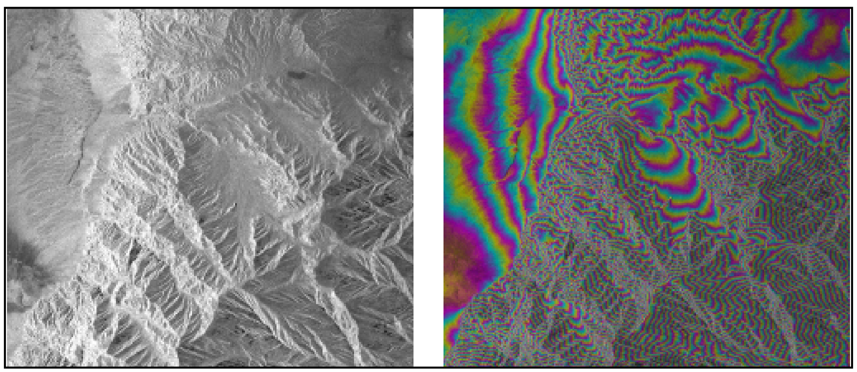
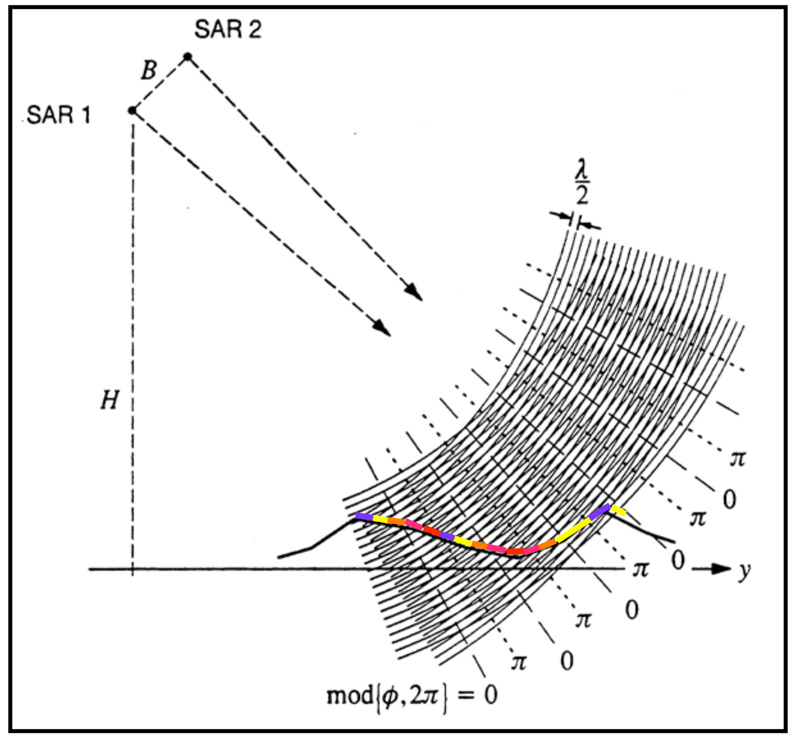
Radar Interferometry

- 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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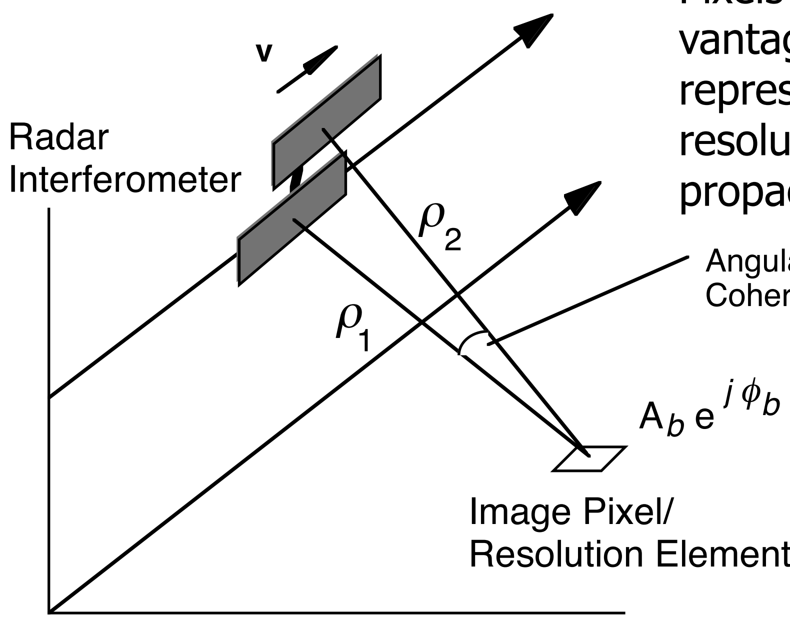
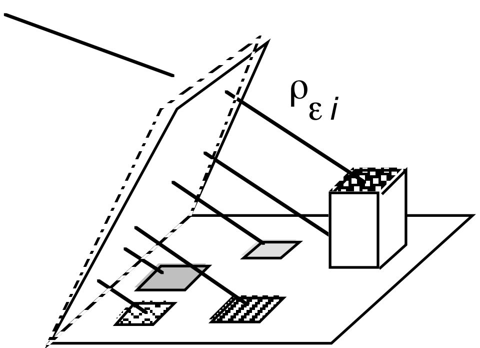
Interferometric Phase Characteristics



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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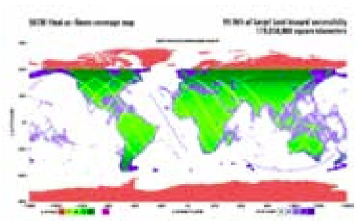
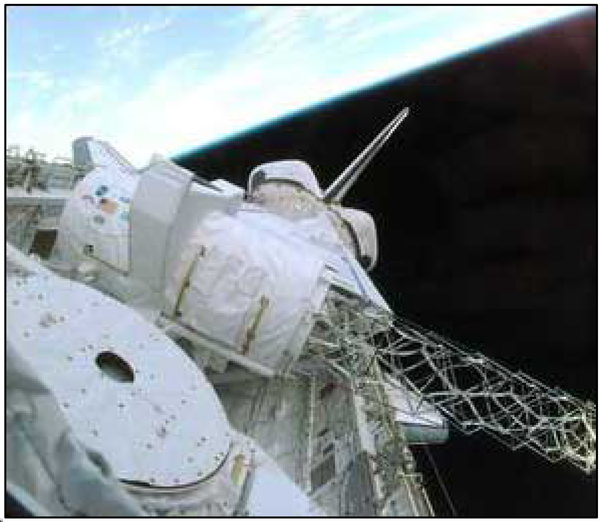
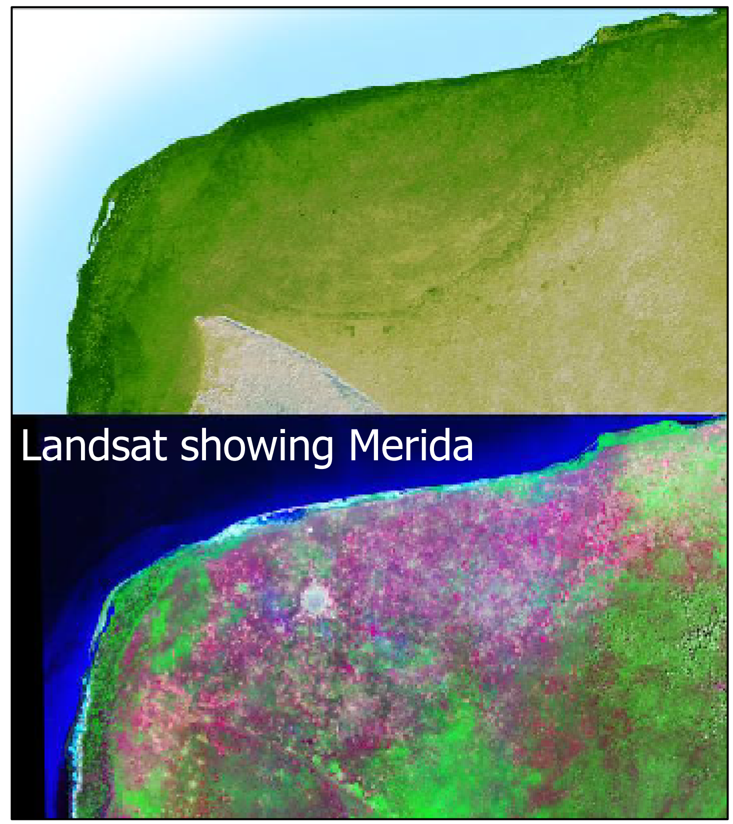
Shuttle Radar Topography Mission (SRTM)





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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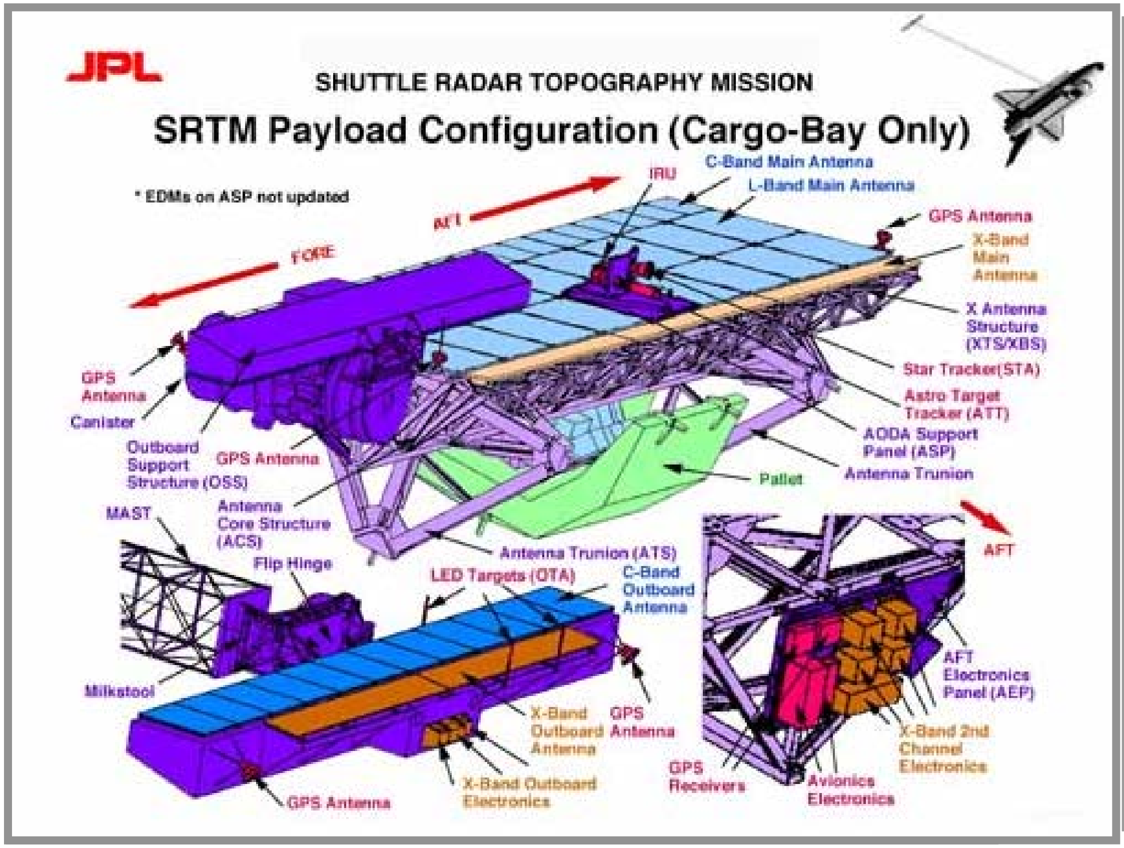
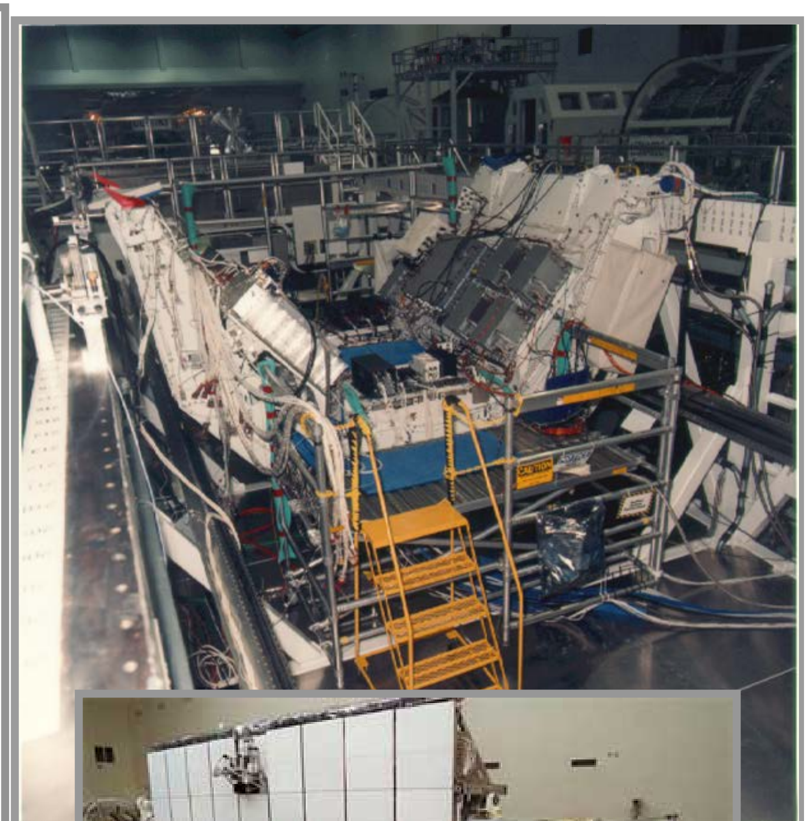
Shuttle Radar Topography Mission Hardware and Electronics





Mast Length: 60 m
Mast + Cannister Mass: 1000 kg
Total Payload Mass: 13,600 kg
Total Data Volume over 10 days: 12.3 TB
Number of tapes for recording: 300

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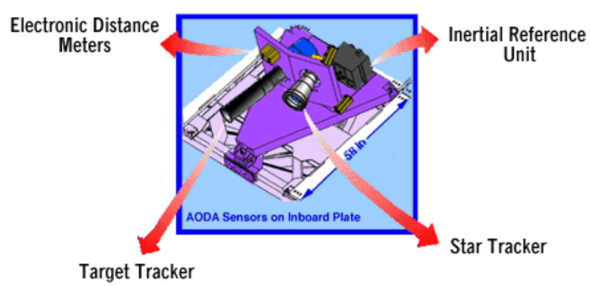
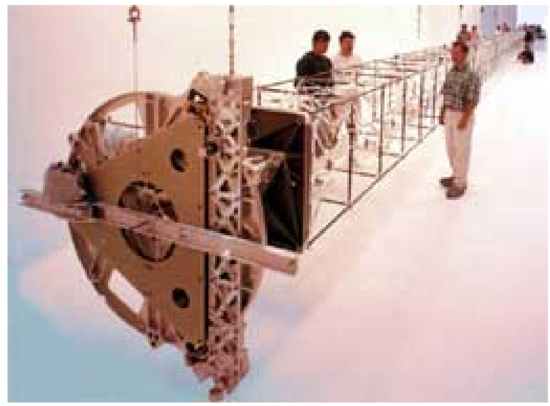
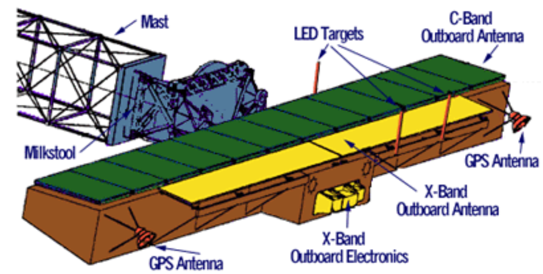
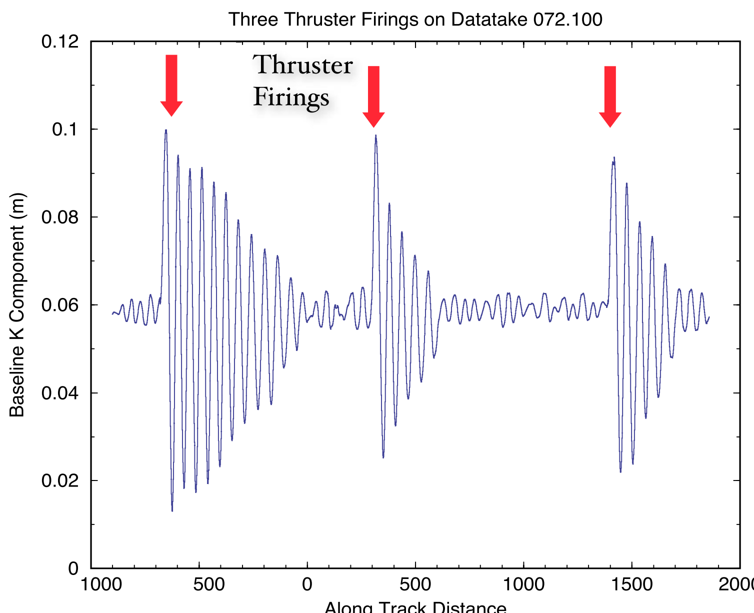
Shuttle Radar Topography Mission
Mast Characteristics



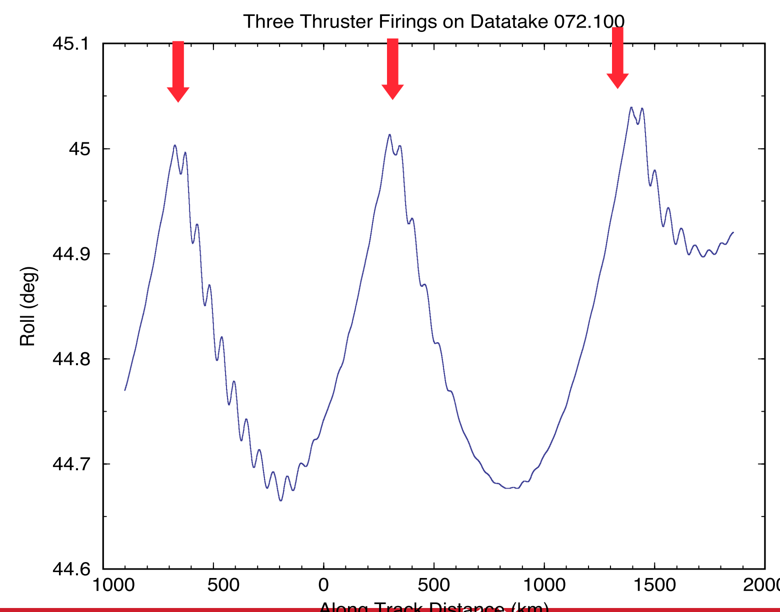




SRTM Boom Motion



SRTM Roll Angle



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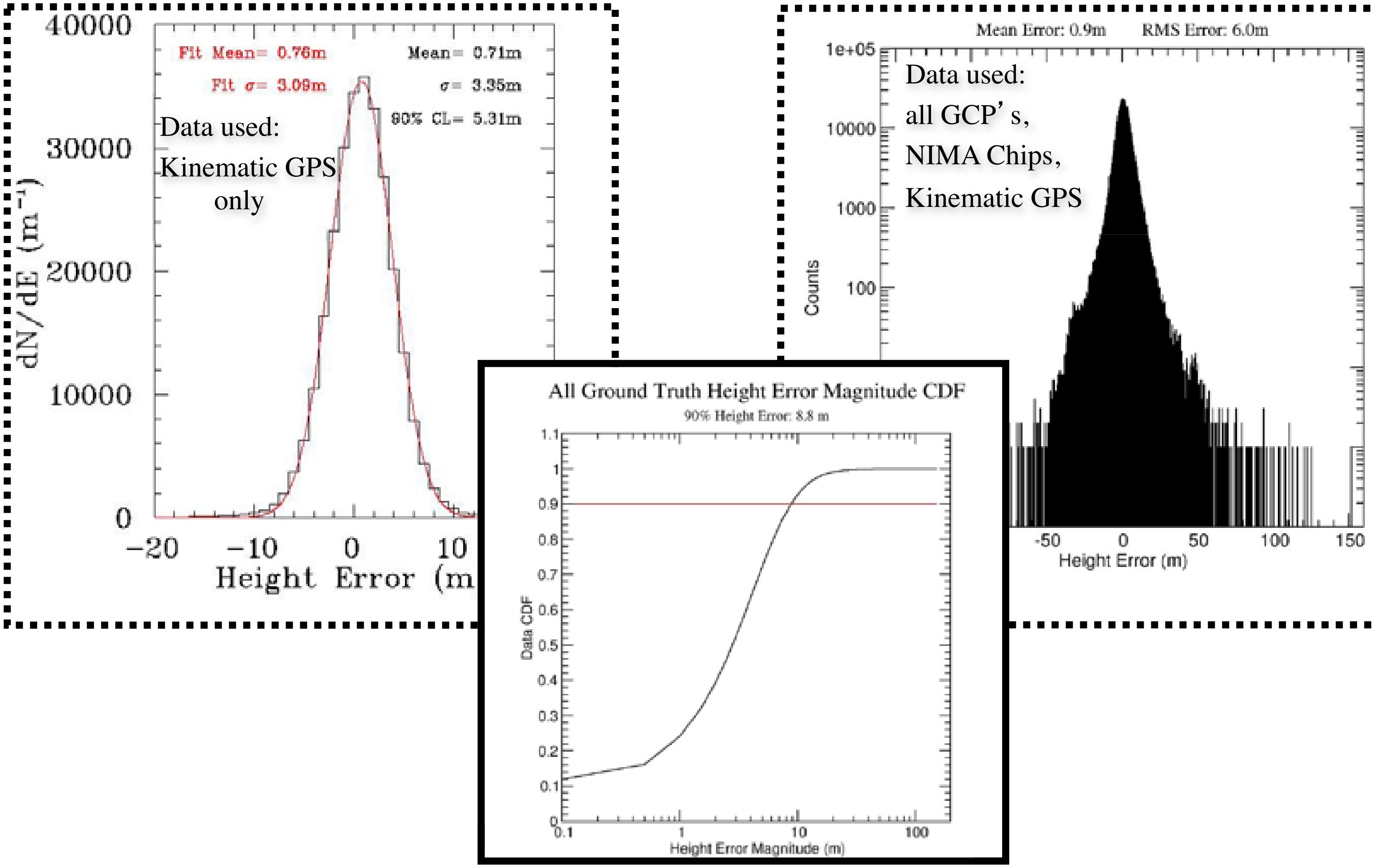
Shuttle Radar Topography Mission
Summary Height Error Histograms



- Both the absolute and relative SRTM height accuracy requirements are met.
- Both the absolute and relative SRTM horizontal accuracy requirements are met.

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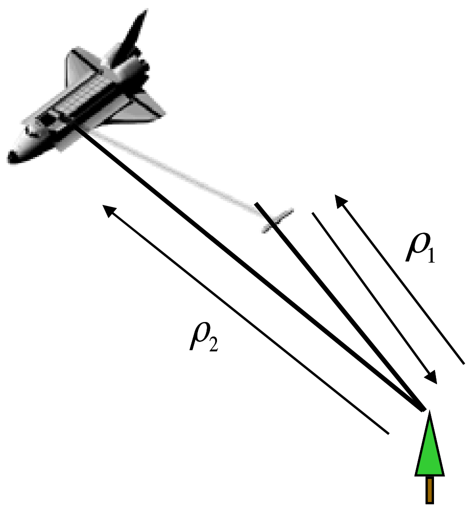
Data Collection Approaches

Single Pass

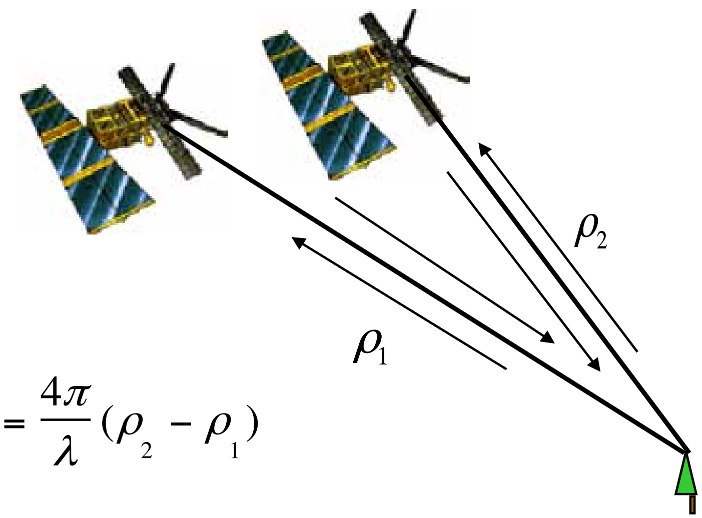
- **Interferometric radar data can be collected in a single pass interferometry (SPI) mode where both antennas are located on the same platform. One antenna transmits and both antennas receive the returned echoes**



$$\phi = \frac{2\pi}{\lambda}(\rho_2 - \rho_1)$$

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**



$$\phi = \frac{4\pi}{\lambda}(\rho_2 - \rho_1)$$

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

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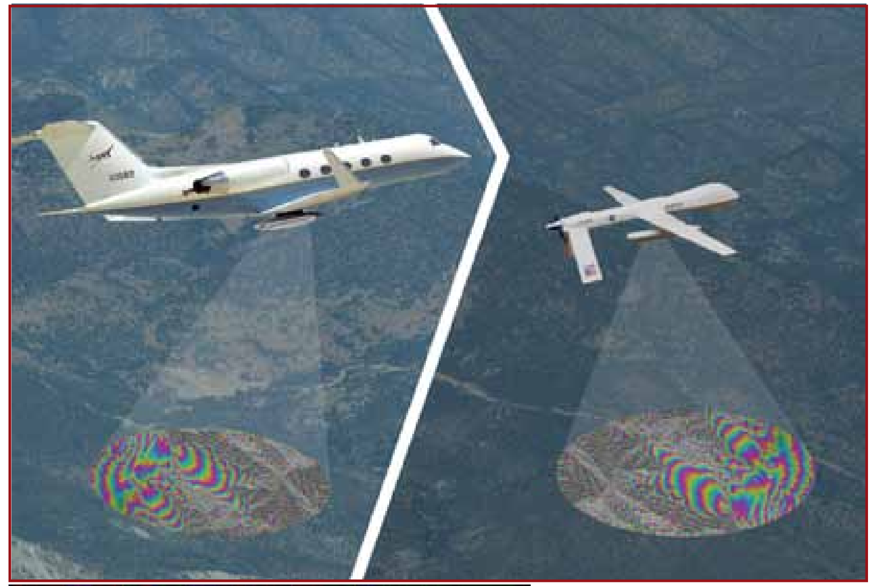
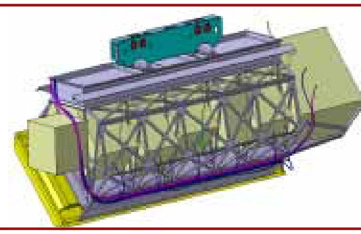
UAVSAR: NASA's New Airborne Radar Science and Technology Testbed

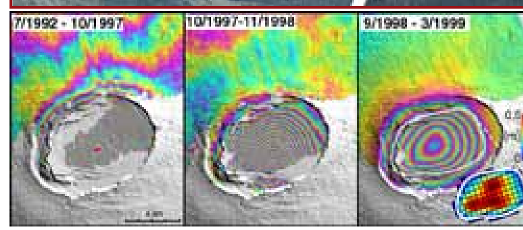
Salient Features

- Robust repeat pass interferometry for deformation measurements
- Fully polarimetric at L-Band (1.2 GHz,80 MHz BW)
- Initial tests on NASA's Gulfstream III
- Plan for transition to UAV platform
- Steerable electronically scanned array antenna
- Flight path controlled to be within a 10 m tube using real-time GPS and modified autopilot
- Autonomous radar operation in flight
- Flexible, light-weight, reconfigurable design





Instrument Pod Internal Layout



Volcanic Surface Deformation

Science

- Global and regional volcanic inflation, flooding, land and coastal erosion, fault strain, fire hazard, tectonic strain, precision topography
- Local continuous observation of deformation for prediction of eruption, landslide and flooding
- Provide crustal structure, high temporal resolution, regional deformation processes for increased predictability of earthquake and volcanic activity.

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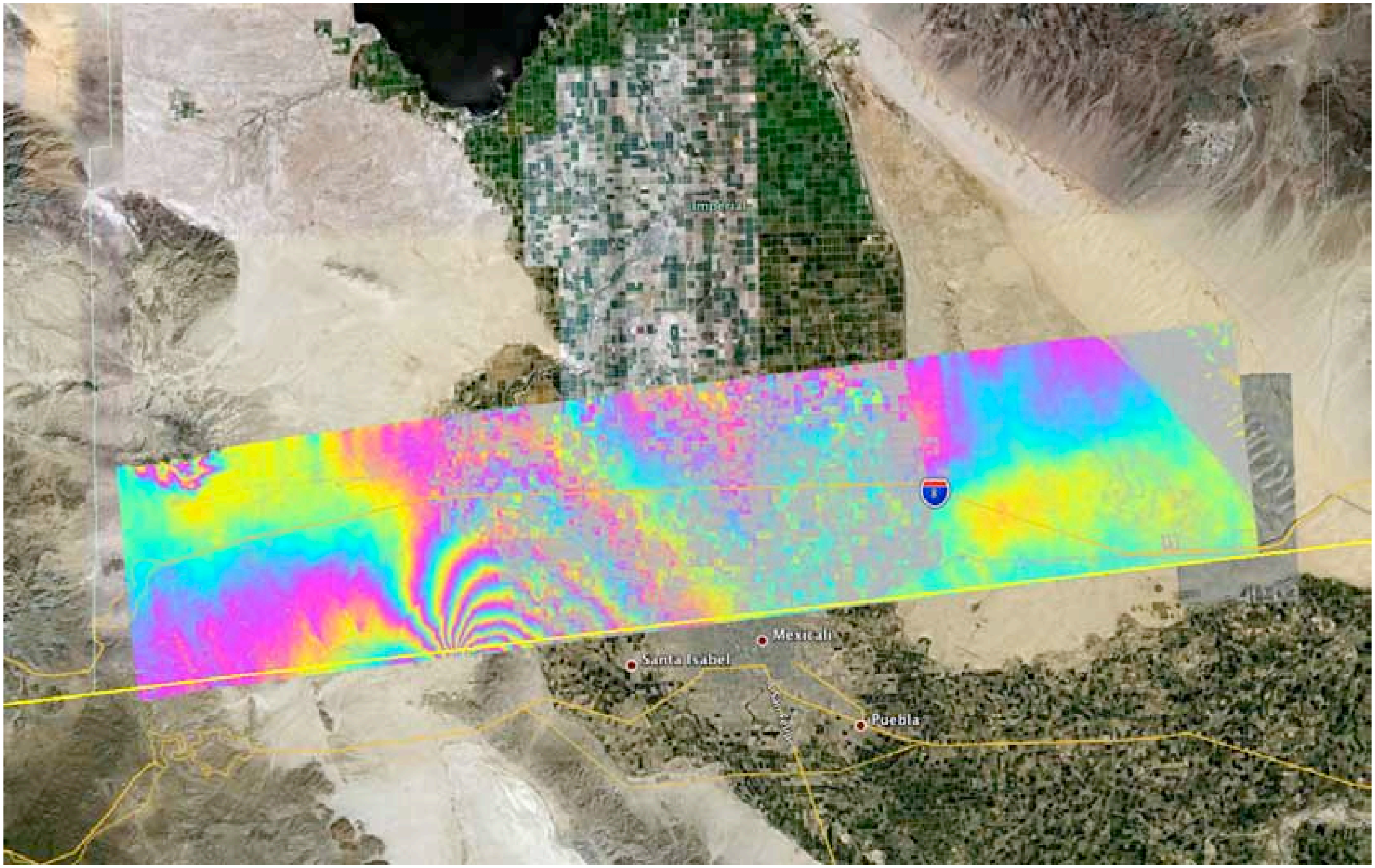
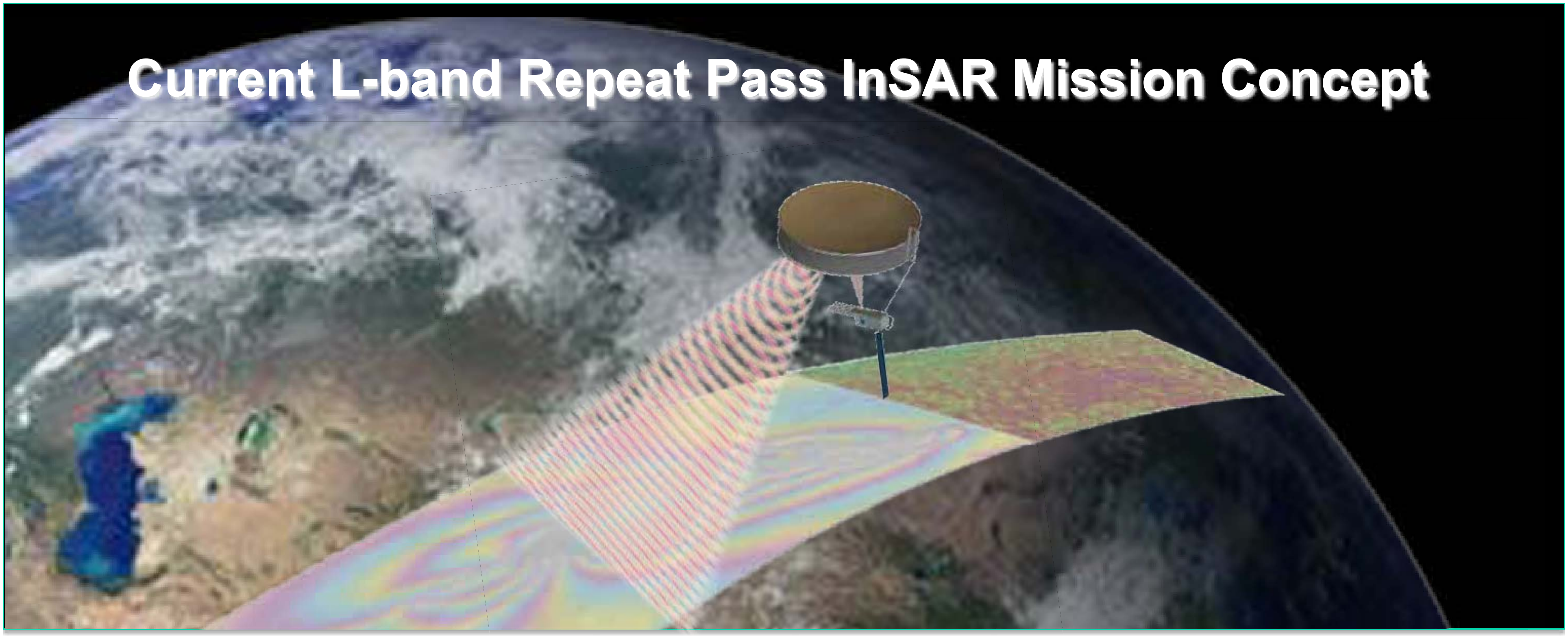
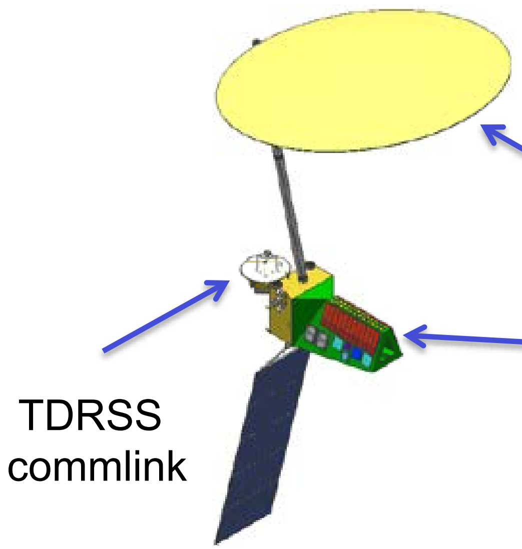
April 4, 2010 M 7.2 Baja California Earthquake

Airborne repeat-pass InSAR for geodetic imaging



Current L-band Repeat Pass InSAR Mission Concept





Radar designs for proposed mission being studied in pre-Phase A

L-band 5-80 MHz BW Quad-pol Radar
9-15 m mesh reflector
12-24 element transmit and receive array
12-24 dual-pol receive channels
180-360 km swath, full res, full-pol
Better than -25 dB NES0 at 20 MHz BW

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Radar Design to Meet Critical Requirements

Repeat Period requirement for Deformation science drives the Radar Swath

8M-day Repeat Period => 360/M-km Swath Width

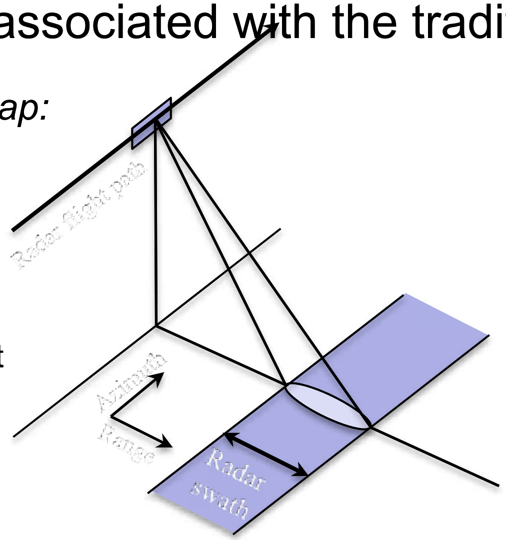
Sensitivity requirement for Biomass (cross-pol) measurement drives Antenna Size and Radar Power

Accuracy requirements for Deformation and Biomass drive Electronics & Mechanical Stability and Calibration

A new SweepSAR technique was adopted as a means to achieve much wider swath than conventional SAR strip-mapping, without the performance sacrifices associated with the traditional ScanSAR technique

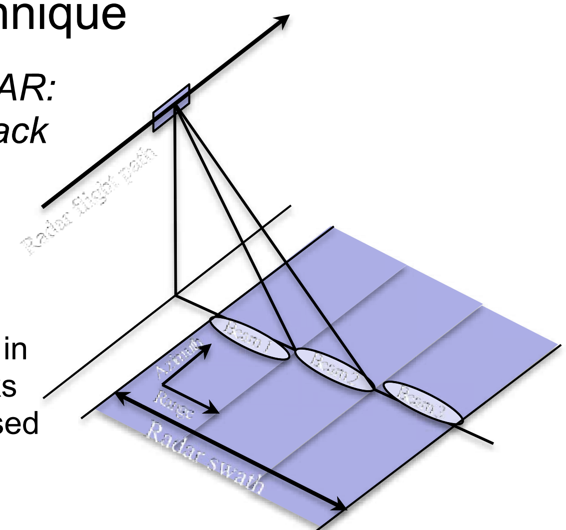
Conventional StripMap: <~70km Swath

Resulting ~40 day repeat does *NOT* meet proposed Deformation and Ice Science Requirements



Conventional ScanSAR: non-uniform along-track sampling

Resulting degradation in effective azimuth looks does *NOT* meet proposed Ecosystem Science Requirements



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New SweepSAR Technique to Meet Science Needs

- On Transmit, all Feed Array elements are illuminated *(maximum Transmit Power)*, creating the wide elevation beam
- On Receive, the Feed Array element echo signals are processed individually, taking advantage of the full Reflector area *(maximum Antenna Gain)*

Uses *digital beamforming* to provide wide measurement swath

DBF allows multiple simultaneous echoes in the swath to be resolved by angle of arrival

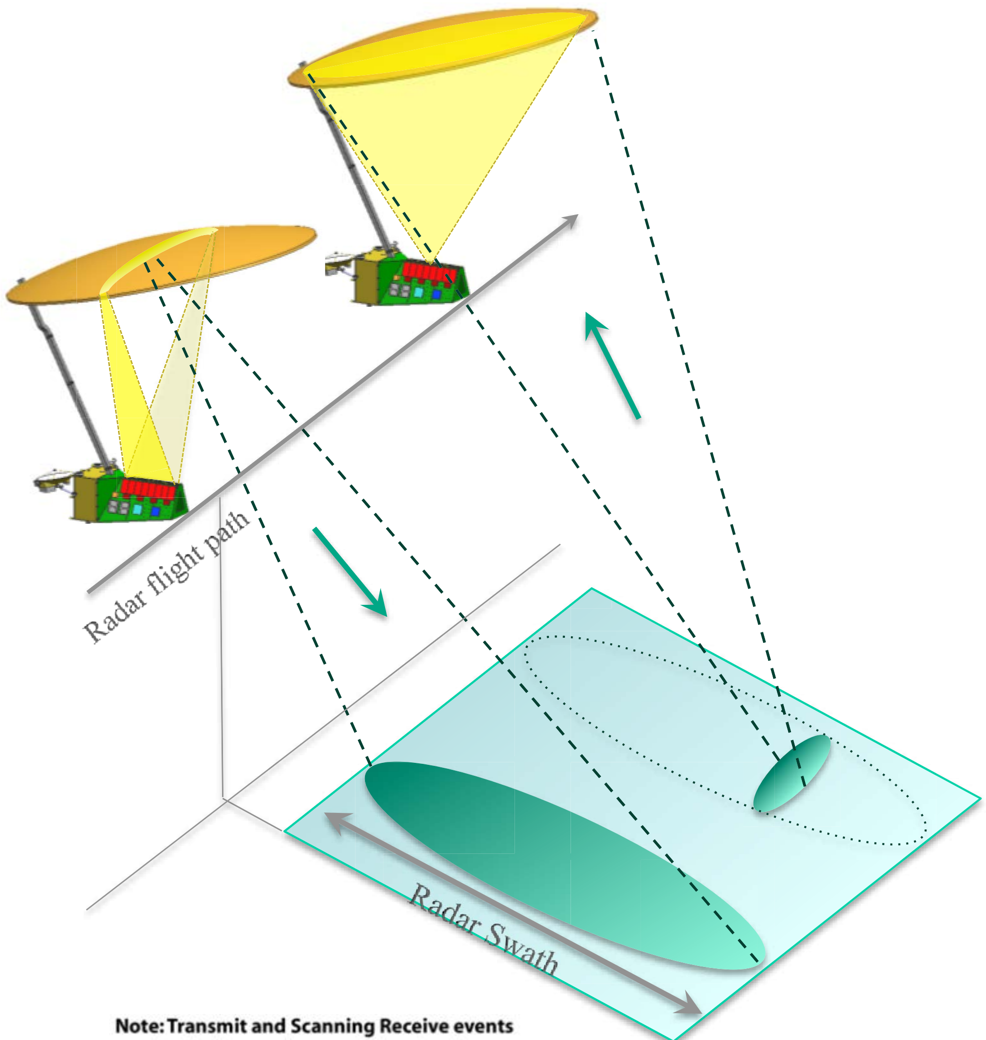
Uses large reflector to provide high aperture gain

Full-size azimuth aperture for both transmit and receive

Full-sized elevation aperture on receive

Only need data from feed array elements being illuminated by an echoes

These elements can be predicted *a priori*



Note: Transmit and Scanning Receive events overlap in time and space. Along-track offset shown is for clarity of presentation only.

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Animation of SweepSAR Concept

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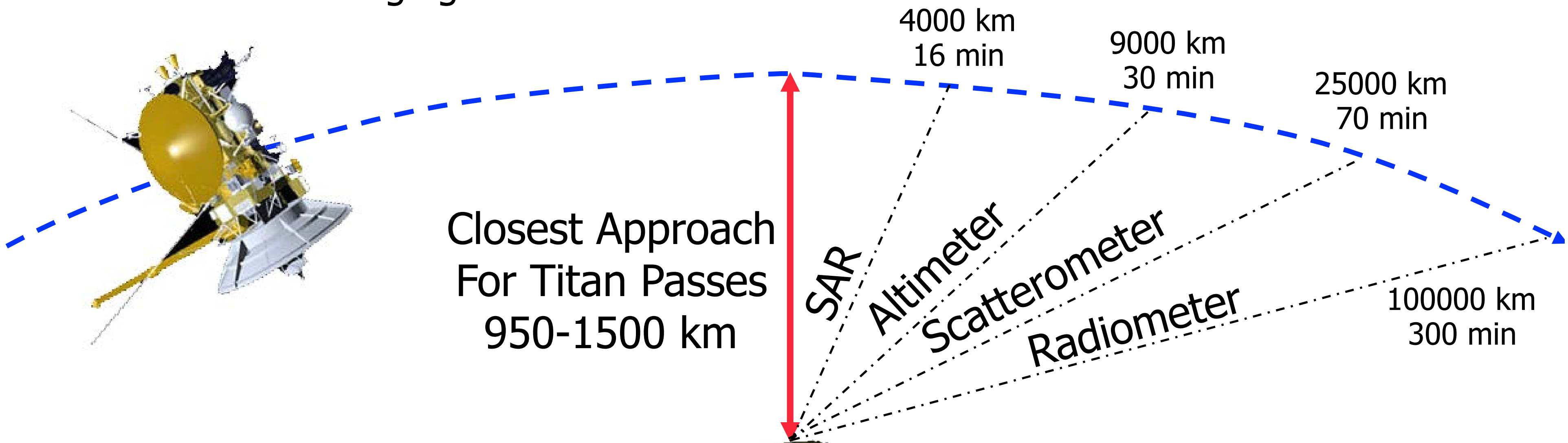
Titan Observation Geometry

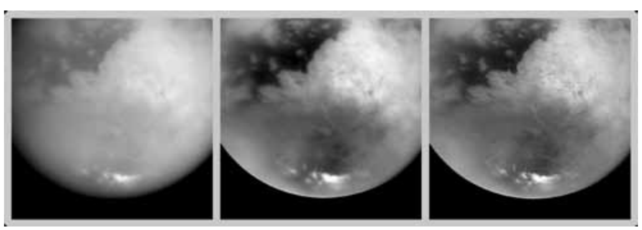
SAR imaging takes place from around ±16 minutes from closest approach with altitude Titan ranging from 4000 km to 1000 km.



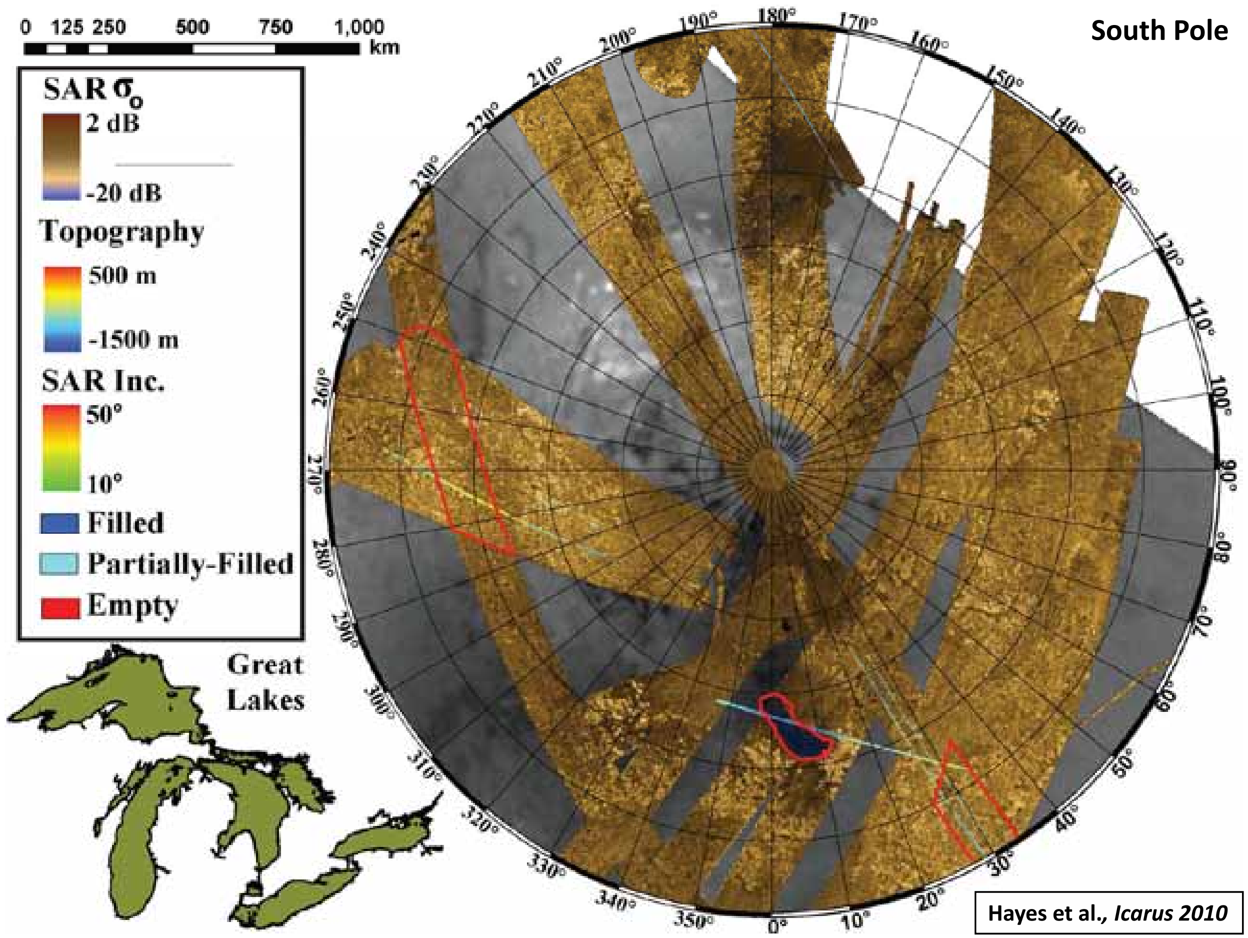
Titan:

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

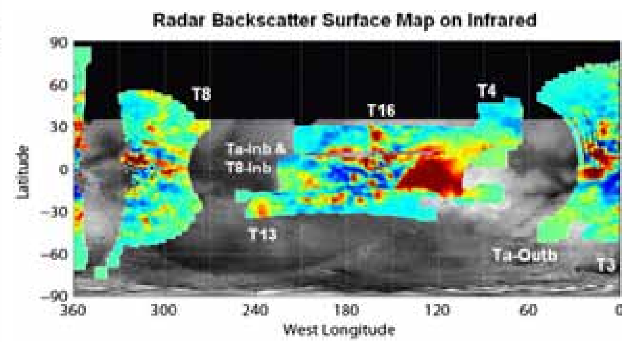
Infrared Images of Titan



Cassini Radar Results



(Courtesy S. Hensley)



Wye et al. (Icarus, 2007)

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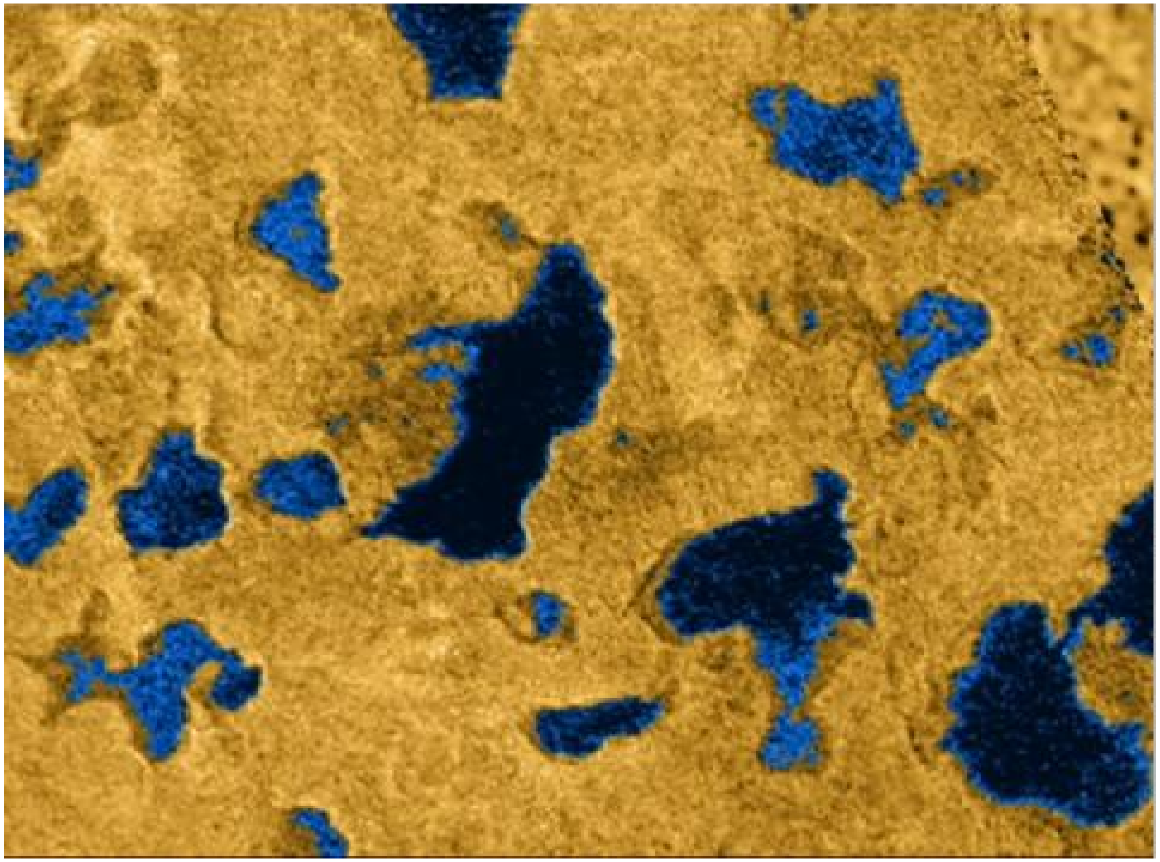
Lakes on Titan

- Although not suitable for swimming at 77°K, the Cassini radar detected the first liquid surfaces in the solar system not on Earth.
- These lakes are composed of liquid hydrocarbons like methane.



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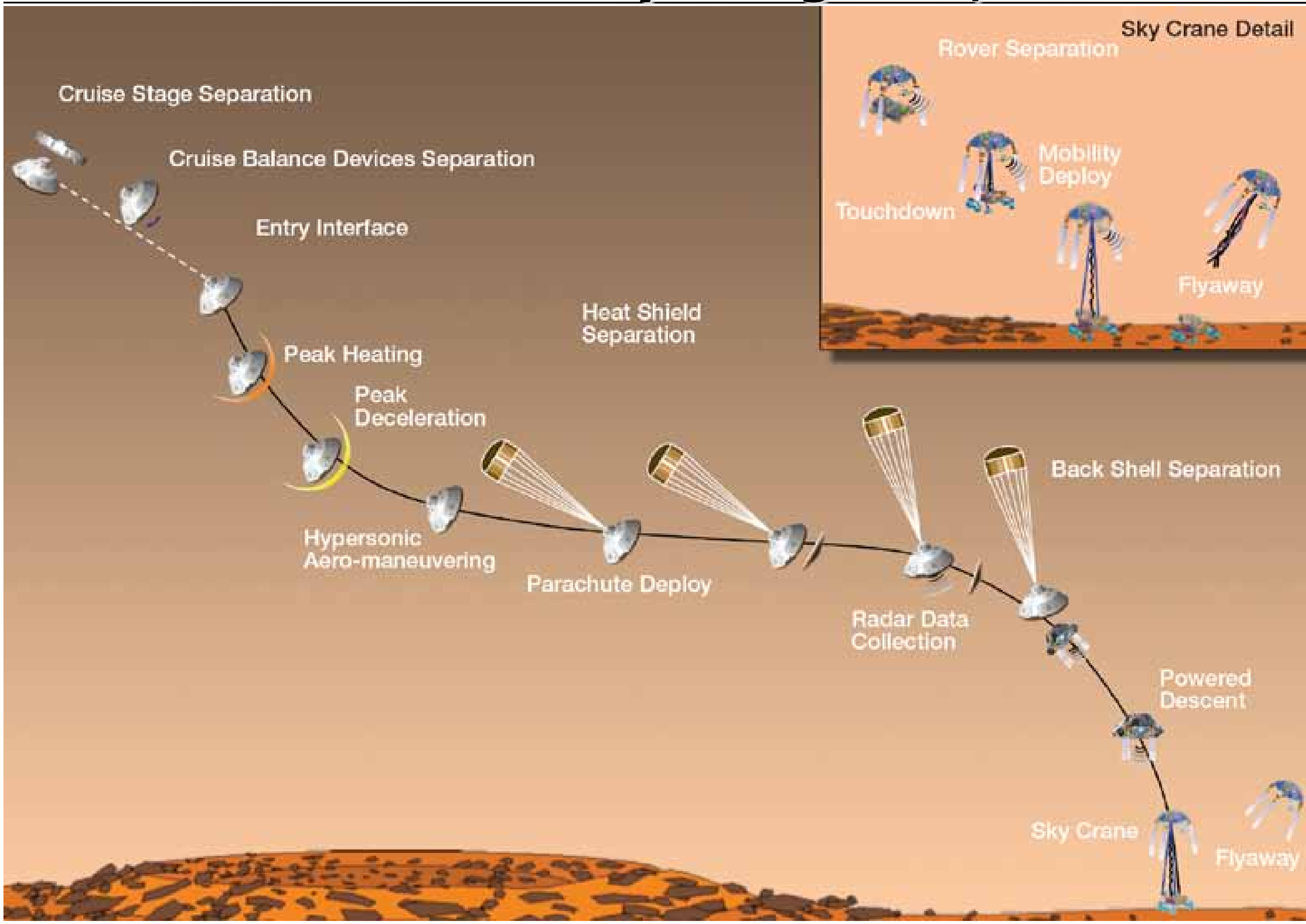
Timeline of Major Mission Events During Curiosity's August 5, 2012 Landing



Time Event Occurrence Received on Earth (PDT)

[10:24:33.8 PM] Atmospheric Entry

[10:28:53.0 PM] Parachute Deploy

[10:29:12.7 PM] Heat Shield Separation

[10:31:26.7 PM] Rover Separation (from Descent Stage)

[10:31:45.4 PM] Touchdown

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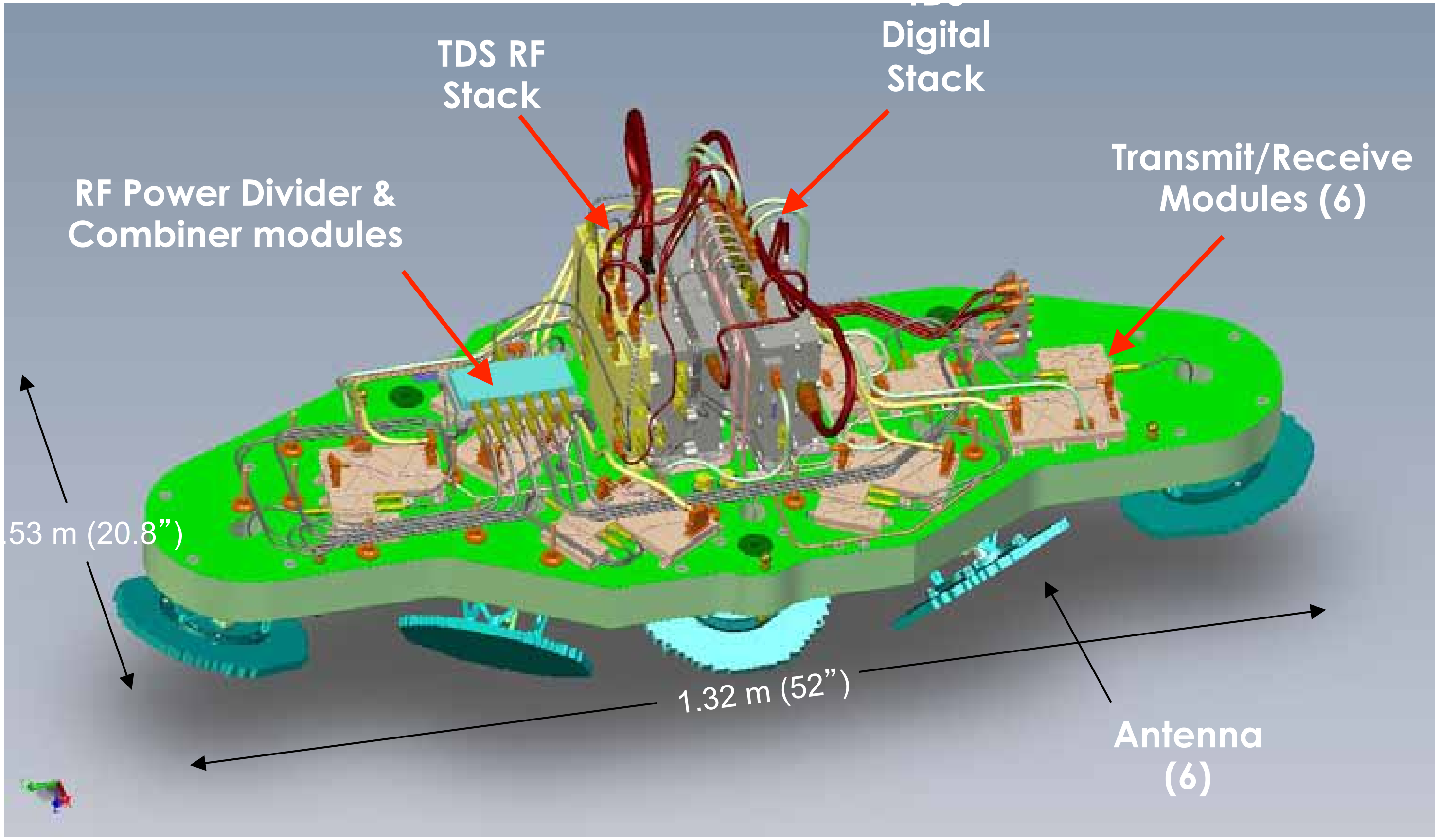
Terminal Descent Sensor (Radar) Physical Configuration



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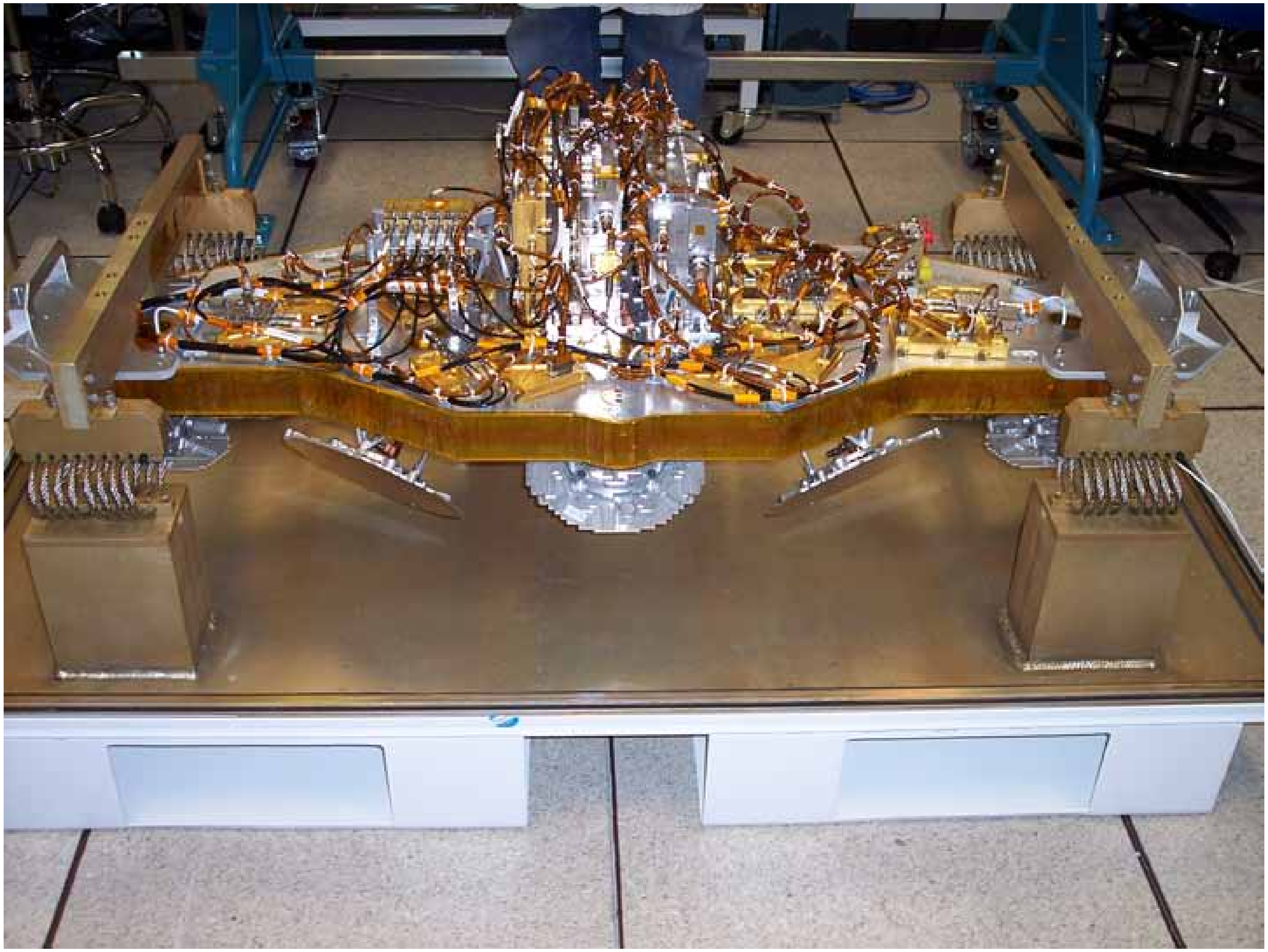
Terminal Descent Sensor (Radar) Flight Model



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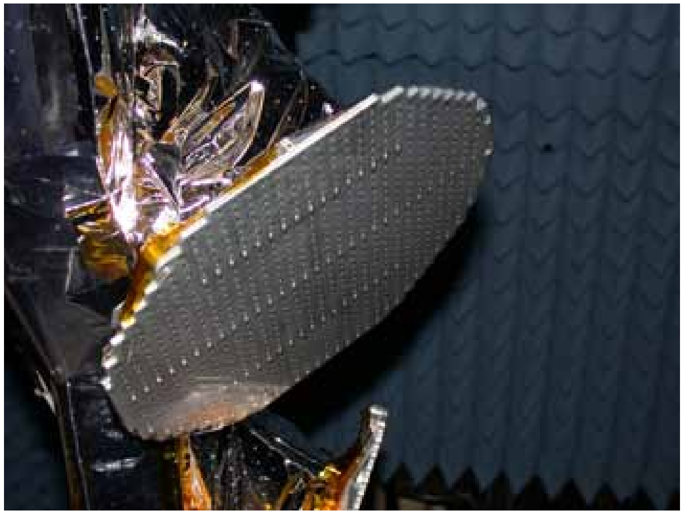
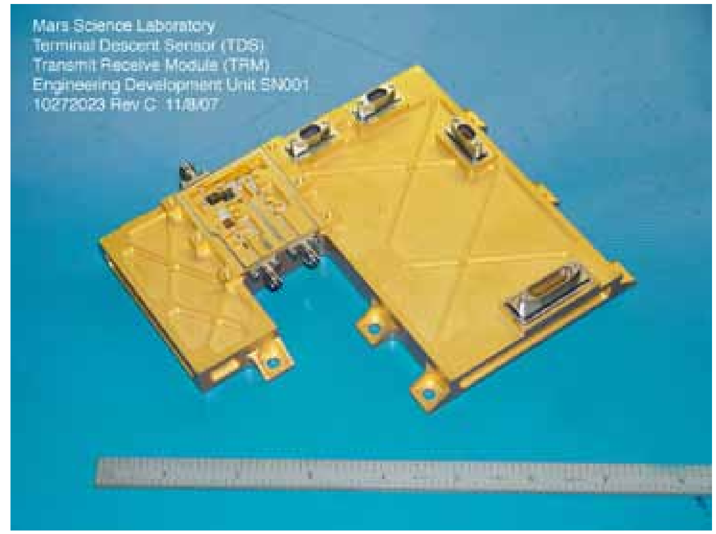
Key TDS Technologies

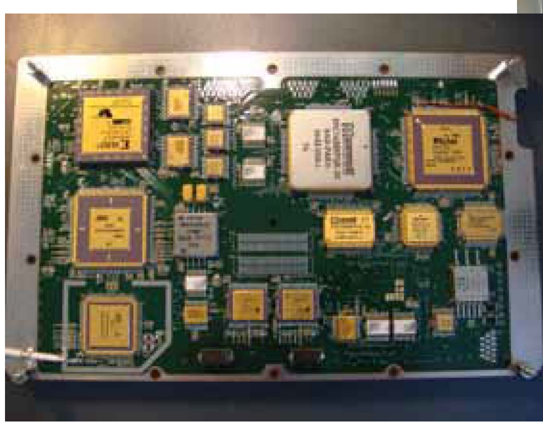


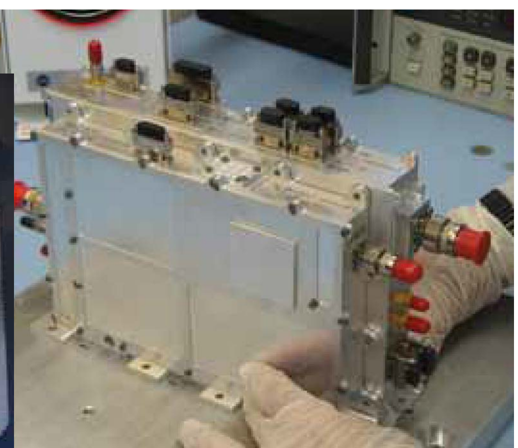
Antennas: six individual slotted waveguide antennas built by EMS-Atlanta (now Honeywell) – 22 cm diameter, 1 cm thick

Transmit / Receive Modules: Ka-band microelectronic hybrid circuits. 2W peak power, 7-9 dB noise figure, fast switching speeds (sub-10m minimum range)



Single Board Digital Subsystem: SPARC onboard computing, Xilinx-based onboard 10000x data reduction and processing, telemetry acquisition, and all radar timing





EM Radar of Radar on Descent Stage

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Assembling the Powered Descent Vehicle

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At Kennedy Space Center

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Extensive Field Testing of TDS Throughout Flight Envelope

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Some Animations

http://mars.jpl.nasa.gov/multimedia/videos/movies/mardisplit20120821/mardisplit20120821-1280.mov

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Some Animations

http://mars.jpl.nasa.gov/multimedia/videos/movies/msl20120810_mardi/msl20120810_mardi-1280.mov

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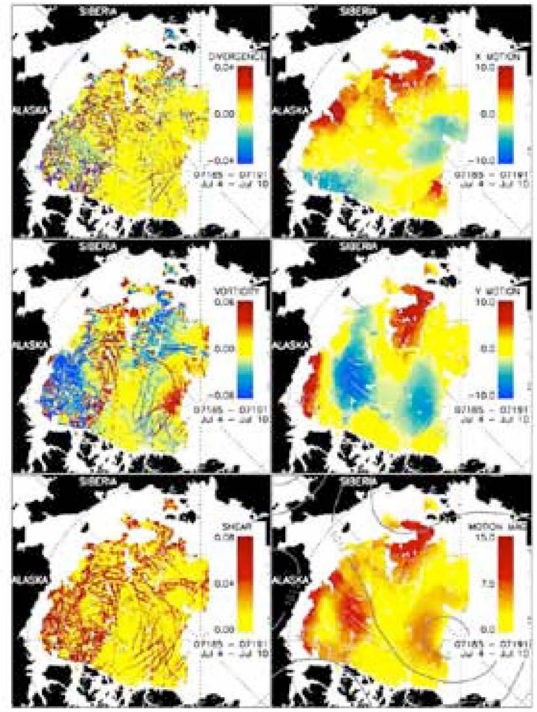
Radar, JPL, and Alaska

JPL enjoys a long history of collaboration with, and observations of, Alaska!

- The Radarsat Geophysical Processor System was developed by JPL in the 1990s and installed for operations at the Alaska SAR Facility
- Conducted joint study of digital elevation mapping of Alaska using JPL TOPSAR data ERS-1/2 tandem observations
- JPL AIRSAR and UAVSAR data are presently distributed from the ASF Distributed Active Archive Center
- JPL presently working with ASF personnel to reprocess historical SeaSAT SAR data
- Collaborative work includes calibration activities of numerous SAR data sets using corner reflectors installed at Delta Junction, AK, ionospheric effects on long-wavelength SAR with UAF (F. Meyer)



http://www.asf.alaska.edu/program/sdc/project/measures/measures_visualizations#

(Moxey et al. 2002)

Summary

- The NASA/JPL radar program is a broad-based, science-driven research and development effort.
- Science requirements lead to specific sensor and mission configurations offering first of a kind capabilities to the nation.
- Generation of the source of illumination by radar instruments allows a degree of control that is as close to reaching out and touching the object as possible in the context of remote sensing.

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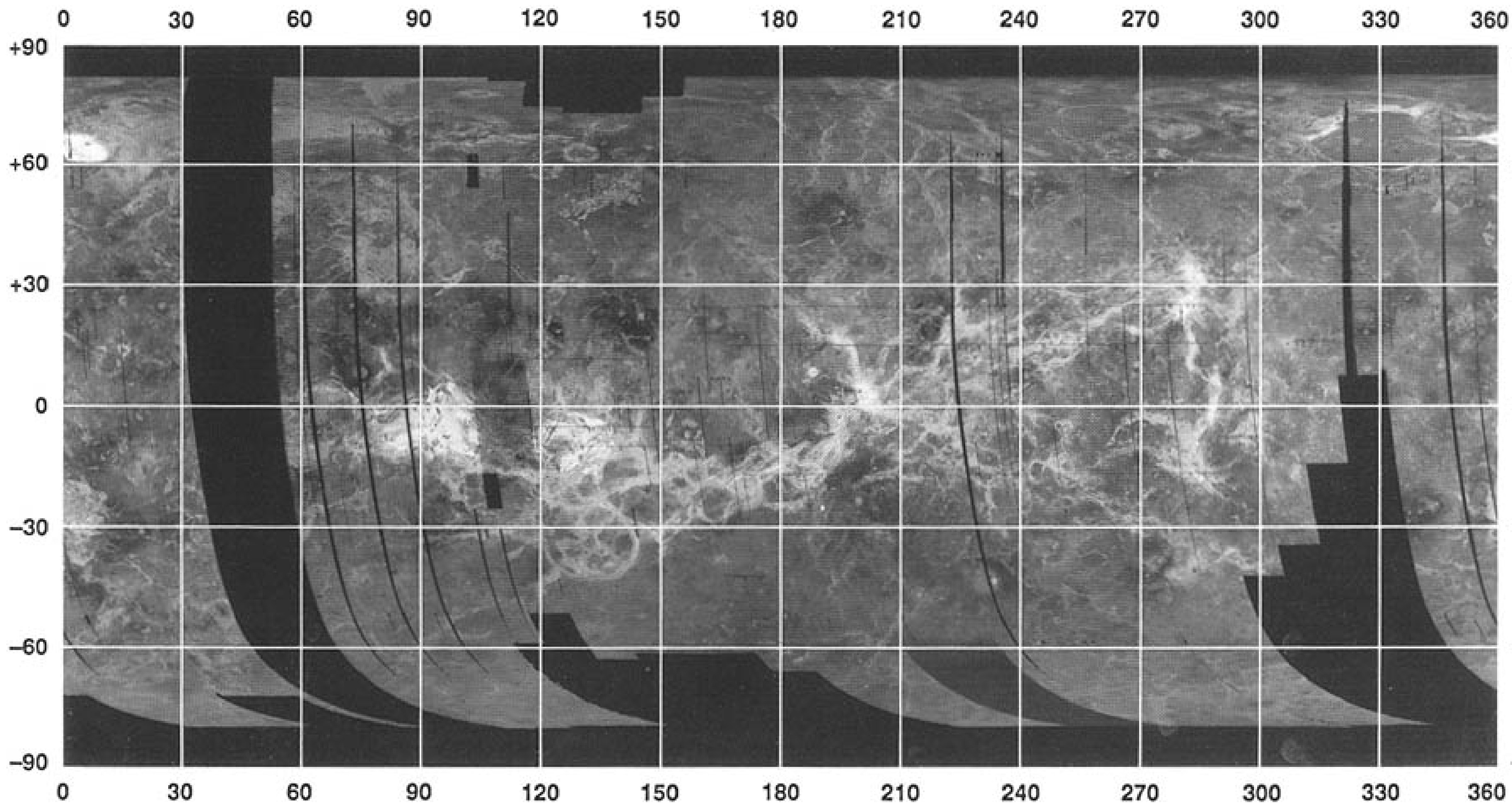
Magellan Map of the Surface of Venus

Composite image of one Cycle (about 2000 orbits) of Magellan imagery



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Coupled Airborne and Spaceborne Radar Programs