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Radar Interferometry, Science, and Missions

October 26, 2006

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Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and Space Administration

Jet Propulsion Laboratory
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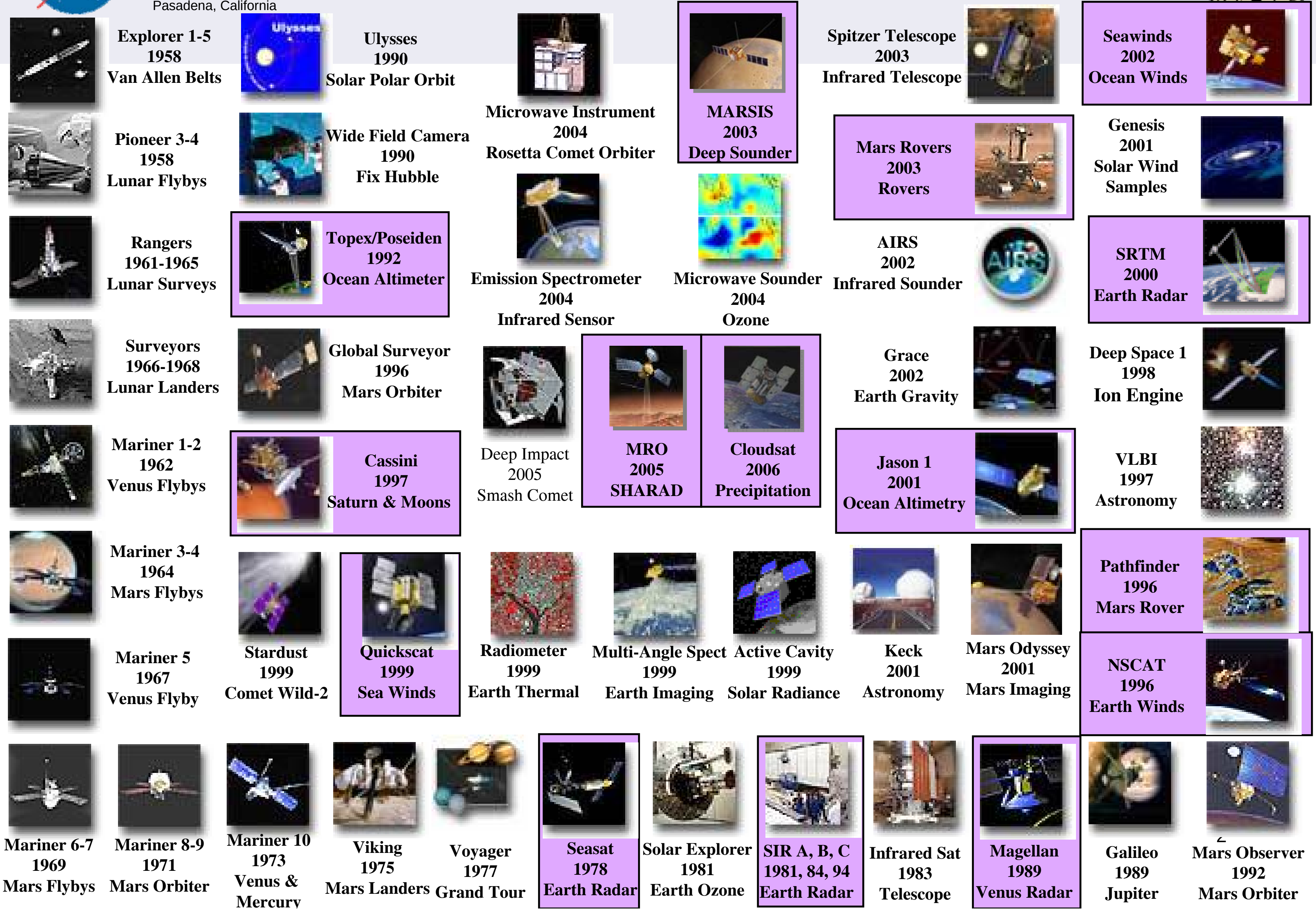
Gallery of JPL Missions



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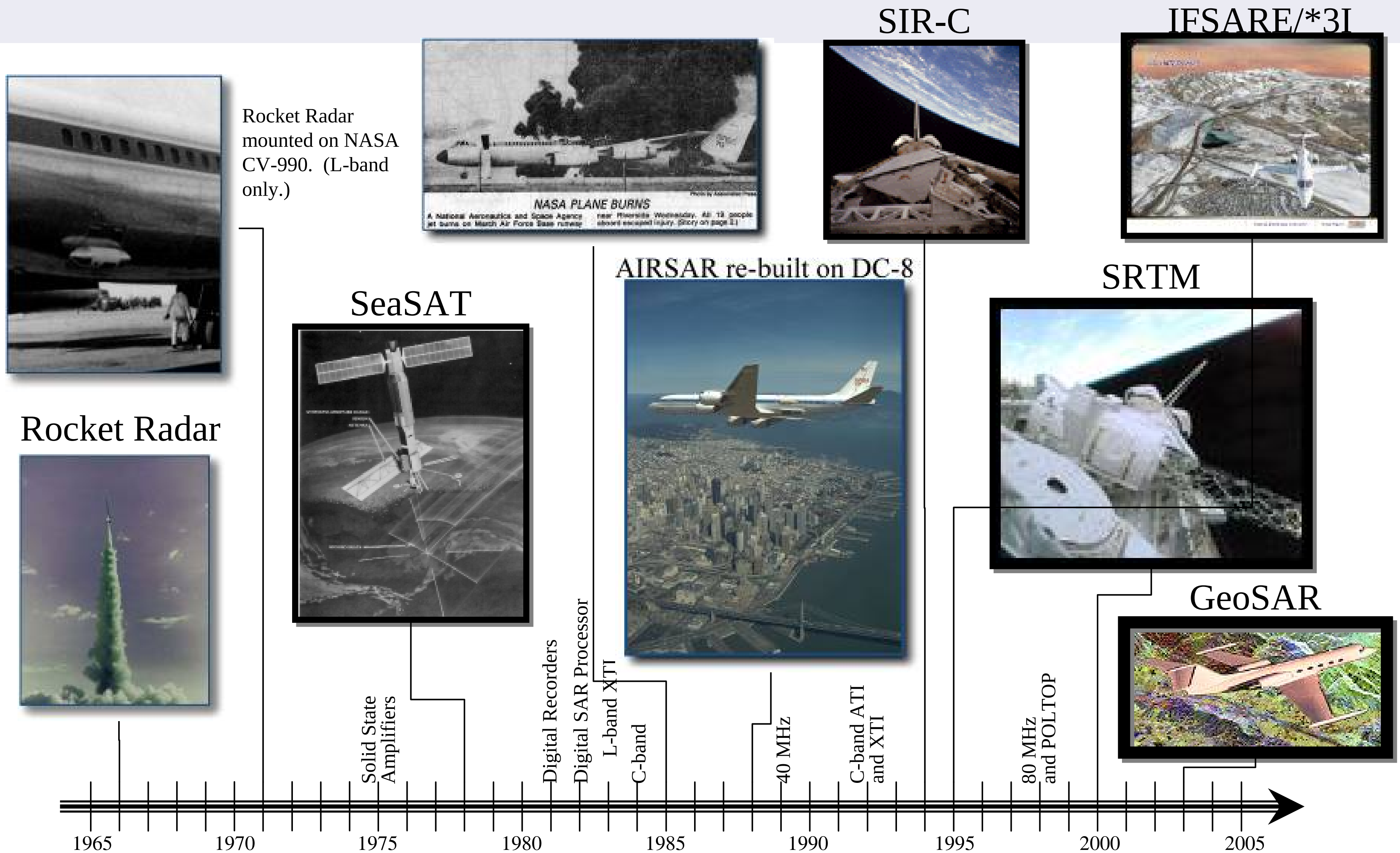
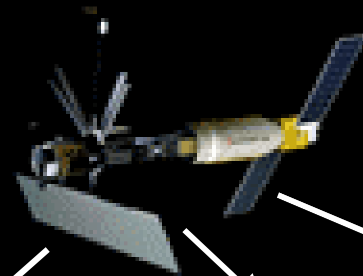
Coupled Airborne and Spaceborne Radar Programs

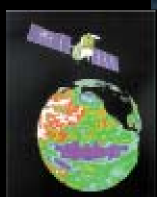


How it began in Space … The Legacy of SeaSat



ALTIMETER

TOPEX / Poseidon (1992)



Jason-1 (2001)

Ocean Surface Topography Mission: (2008)

SCATTEROMETER

NSCAT (1996)

QuikSCAT (1998)

SeaWinds (2002)

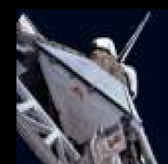
Ocean Vector Wind Measurement: (20??)

RADIOMETER

Sea Surface Salinity: Aquarius (2009)

Soil Moisture & Phase: HYDROS (20??)

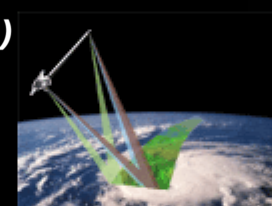
SYNTHETIC APERTURE RADAR



SIR-A (1981)
SIR-B (1984)
SIR-C (1994)

Magellan (1989)
Cassini (1997)

SRTM (2000)



L-Band InSAR (Proposed)

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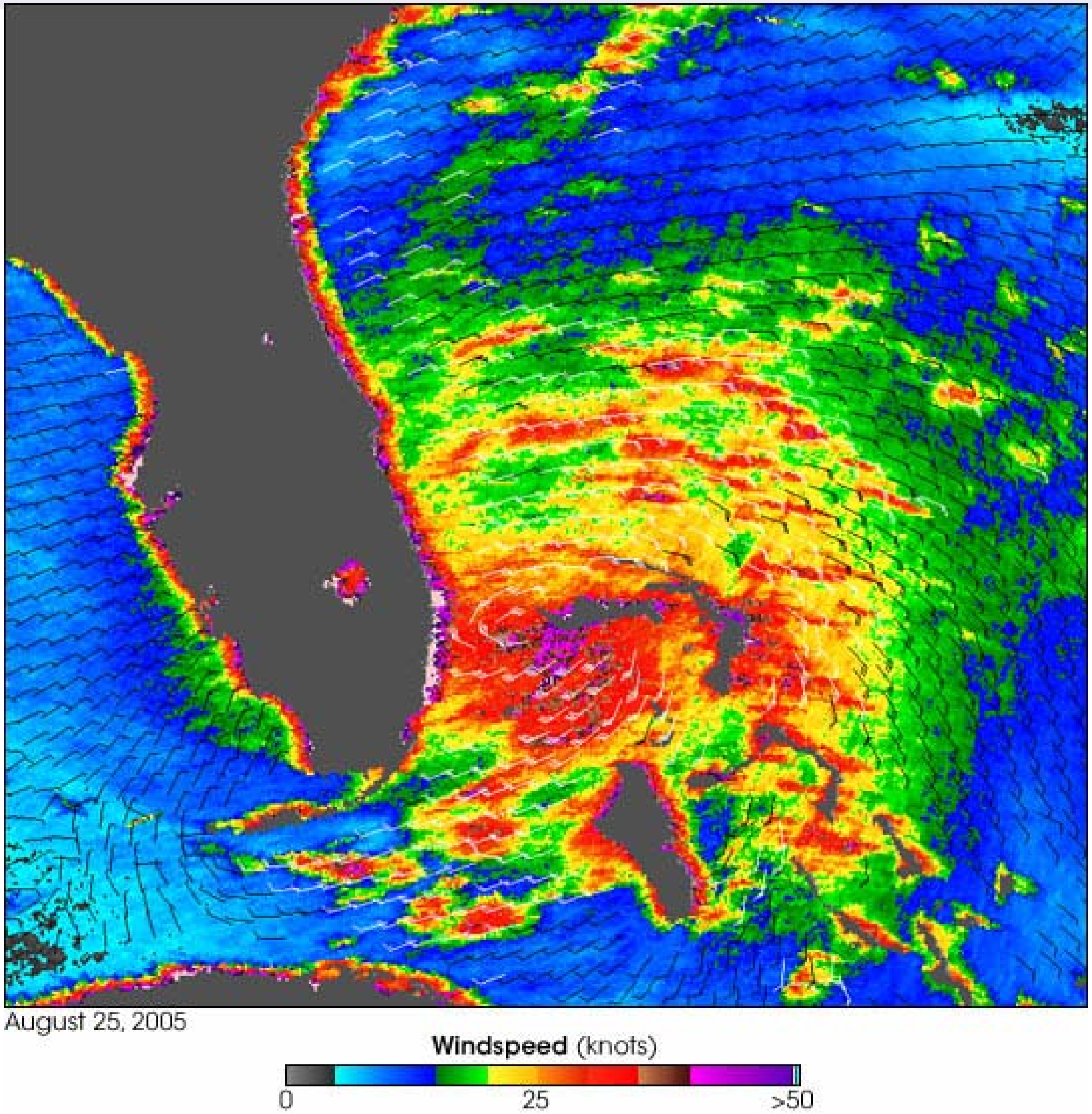
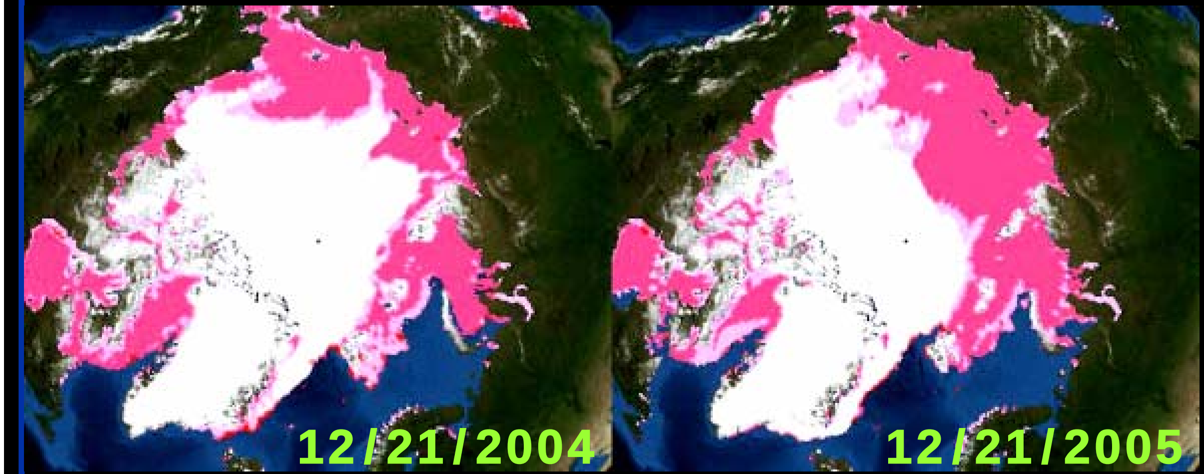
Radar scatterometer sees hurricane Katrina near Florida



QuikSCAT Revealed Texas-Size Loss in Arctic Perennial Sea Ice



On major news networks and 1000 radio stations in all 50 states and in many countries over the world

- AGU GRL Paper L17501, Sep. 2006
- AGU Highlight, EOS, 87, Sep. 2006
- NASA/JPL/AGU Press Release

- Section 334: Nghiem (First author) Neumann (co-author)
- Others: Chao (328), Li (387), Perovich (Army), Clemente-Colón and Street (Navy/USCG/NOAA)

NBC Nightly News

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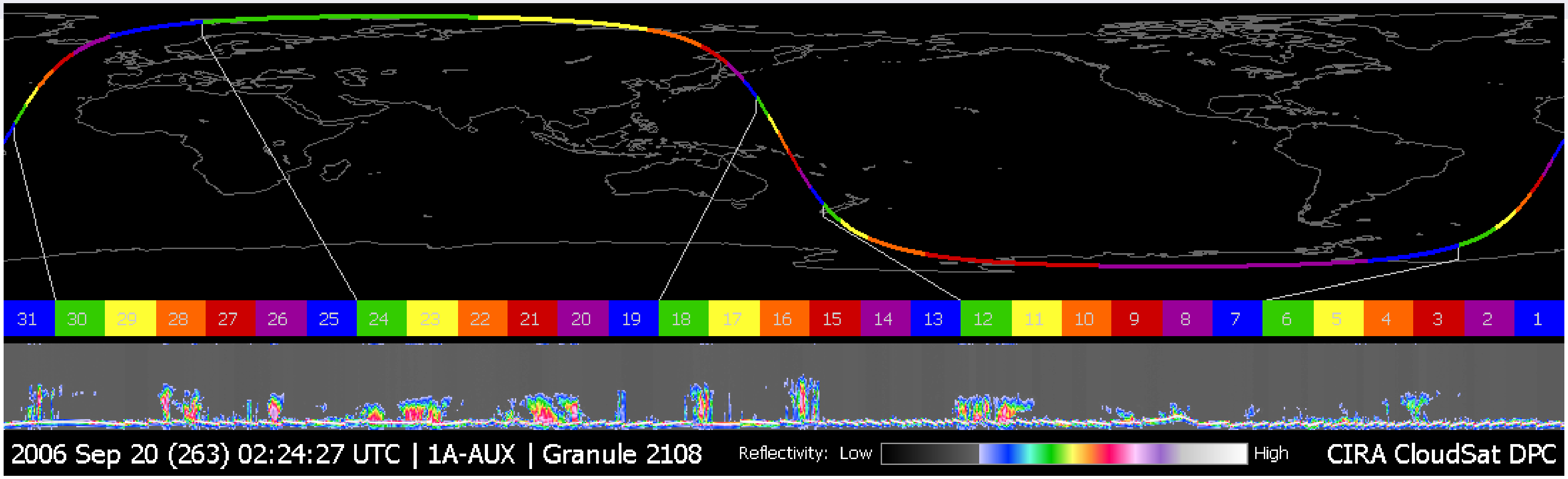
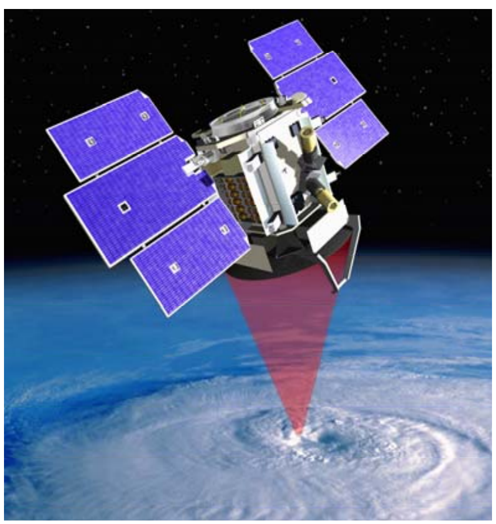
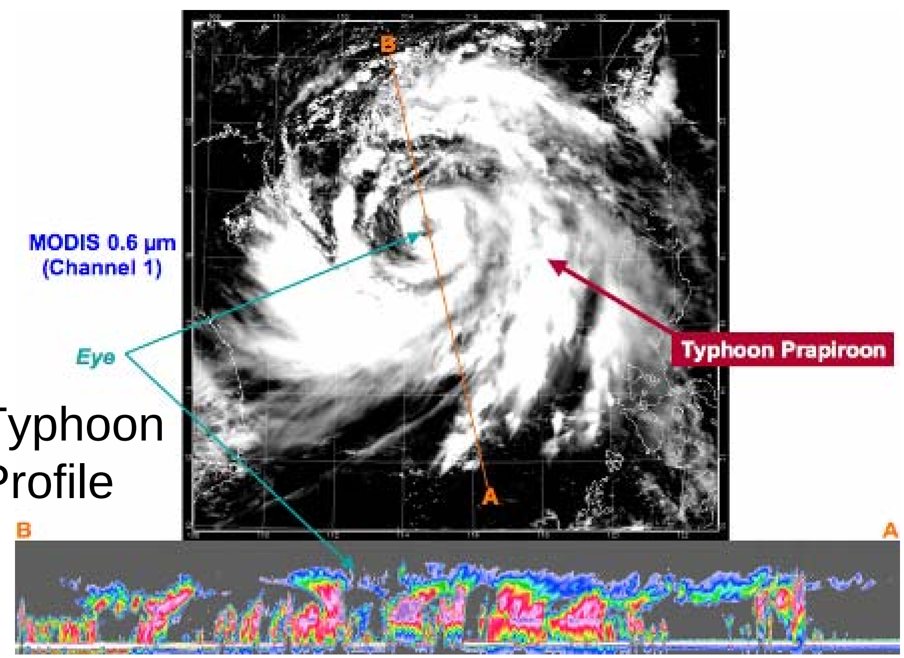
CloudSat - On-orbit Quick-look Data



Typical Orbital Profile





Typhoon Profile

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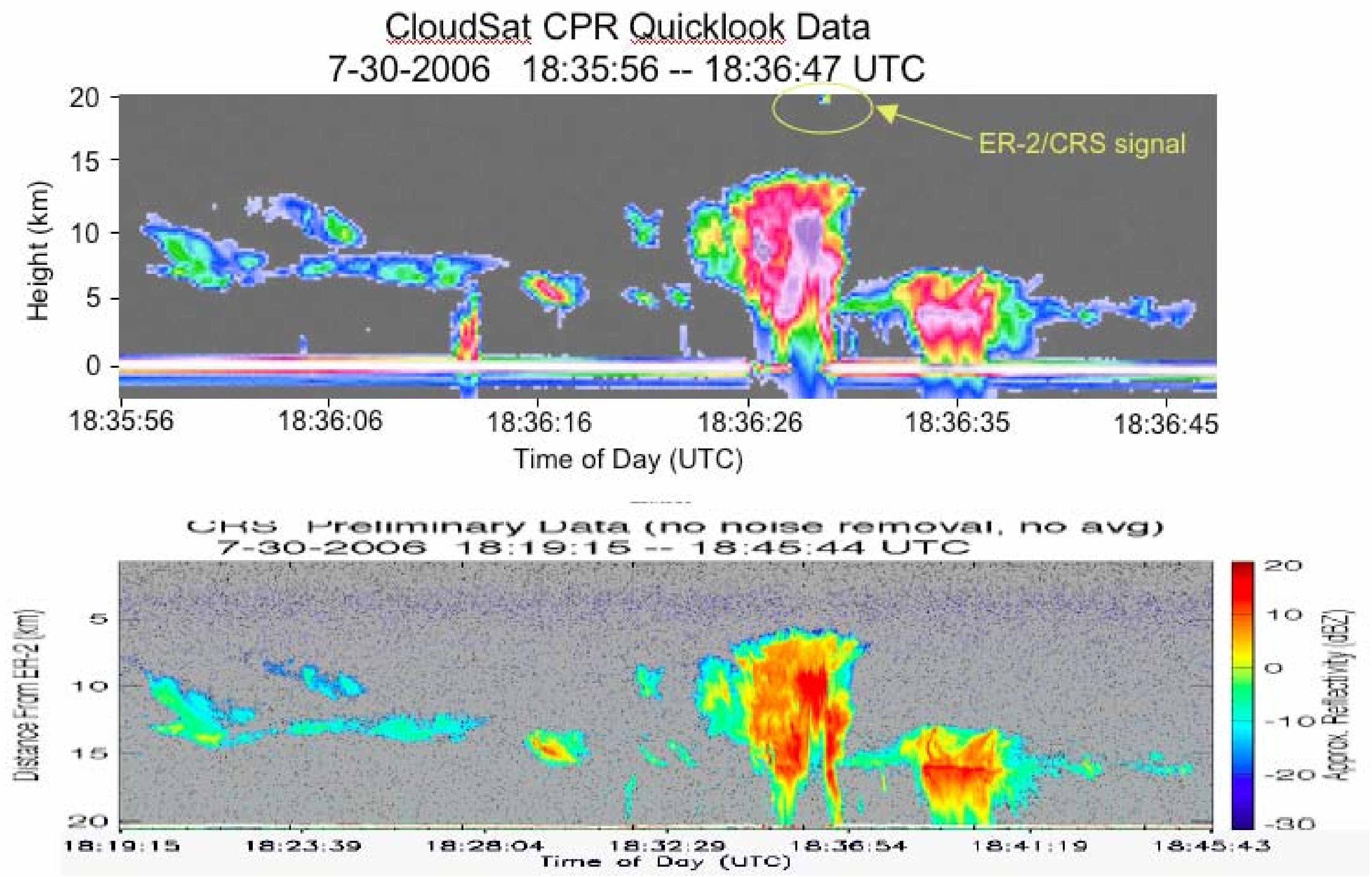
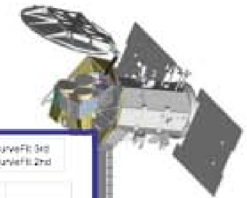
CloudSat CPR Power Returns vs Underflying ER-2 cloud radar (CRS) Reflectivity Measurements

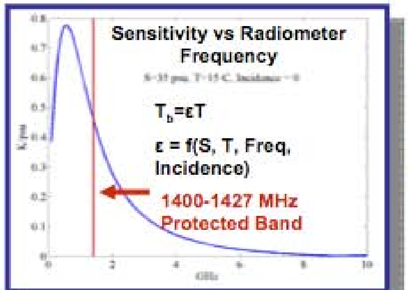


Aquarius: Ocean Surface Salinity

AQUARIUS/SAC-D

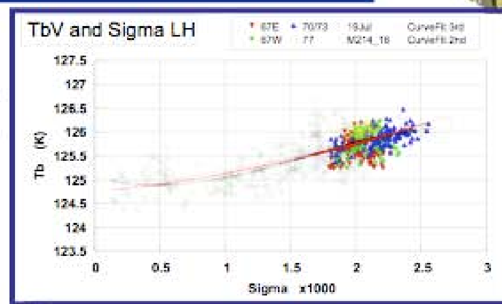
Aquarius Instrument for Sea Surface Salinity Measurements





L-band (1.413 GHz) Radiometer for Measurement Sensitivity

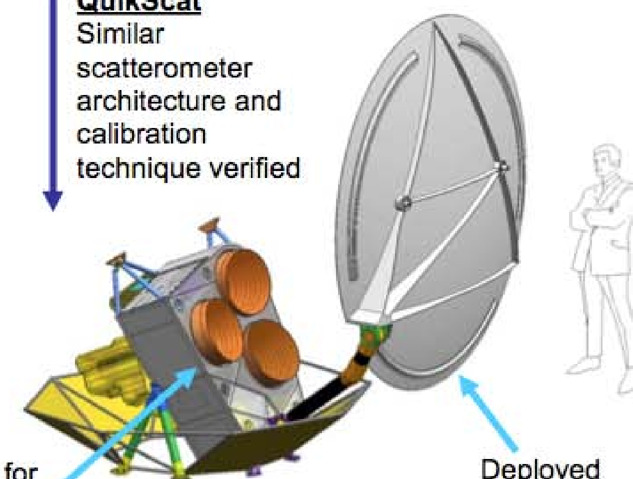
L-band (1.26 GHz) Scatterometer for Sea Surface Roughness Correction



Ultra-stable Radiometer IIP
Aquarius radiometer stability verified

Airborne Passive Active L/S-band (PALS) Instrument
Measurement technique verified

QuikScat
Similar scatterometer architecture and calibration technique verified



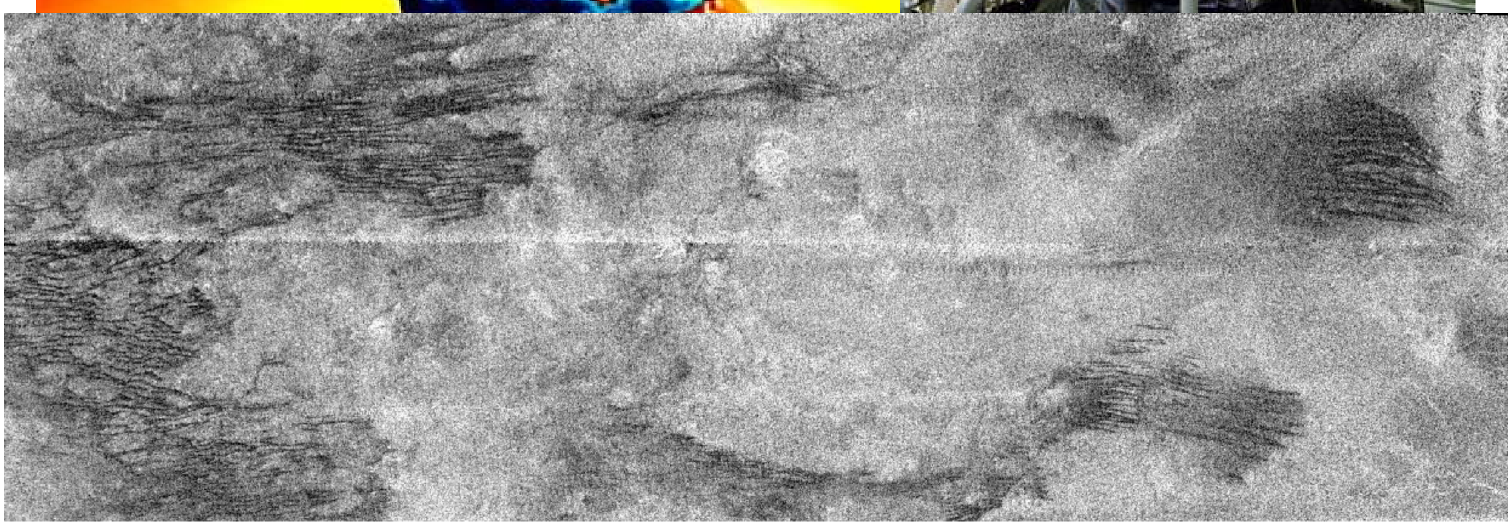
Three Feed Horns for Larger Area Coverage

Deployed 2.5m Reflector

- 400 kg and 450 W
- 3-year operational life

Aquarius radiometer and scatterometer data will be used to retrieve sea surface salinity using proven techniques

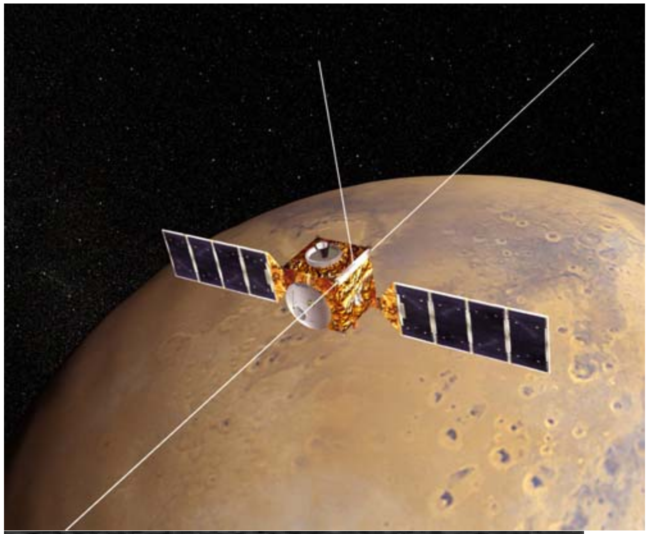
Titan SAR aboard Cassini Saturn orbiter

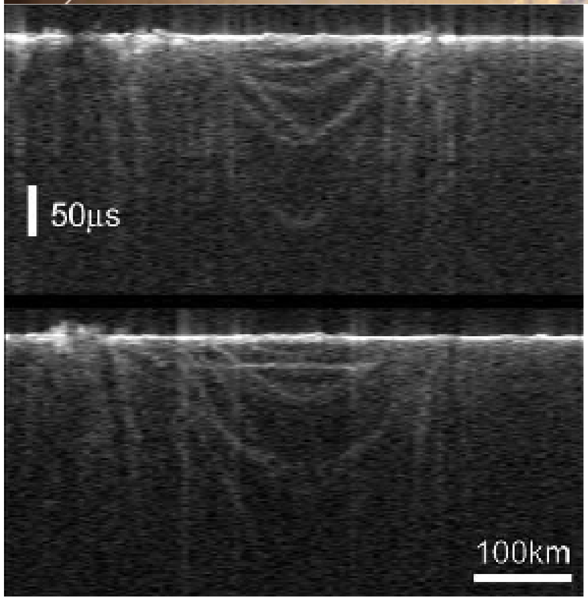


Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) on ESA Mars Express

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".**



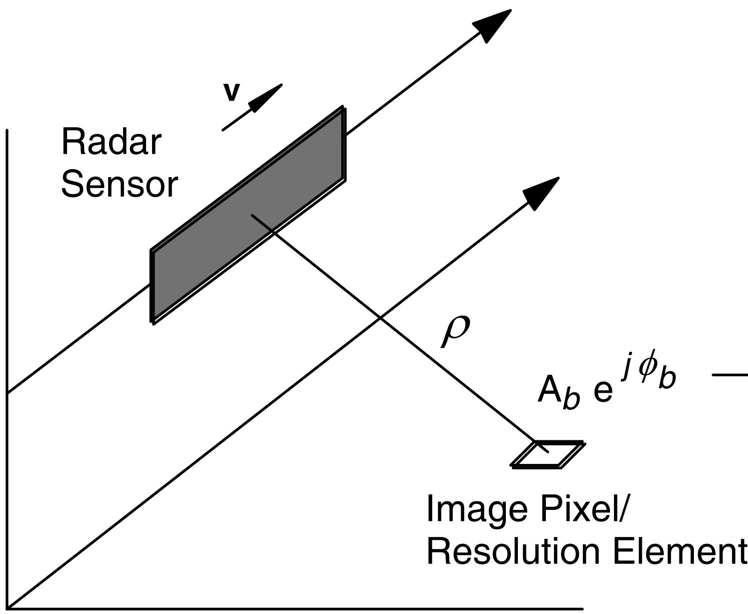


Technology Areas

- **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**

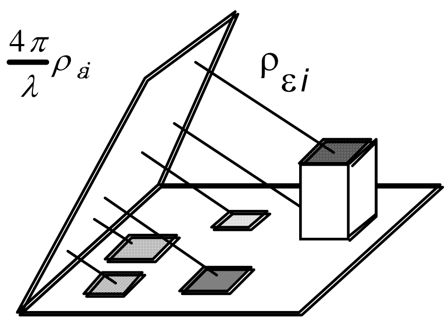
RADAR COHERENT BACKSCATTER

Pixels in a radar image are a complex phasor representation of the coherent backscatter from the resolution element on the ground and the propagation phase delay



$$A_b\, e^{j\phi_b} \longrightarrow \sum_i A_{\varepsilon i} e^{j\phi_{\varepsilon i}} e^{-j\frac{4\pi}{\lambda}\rho_{\varepsilon i}}$$

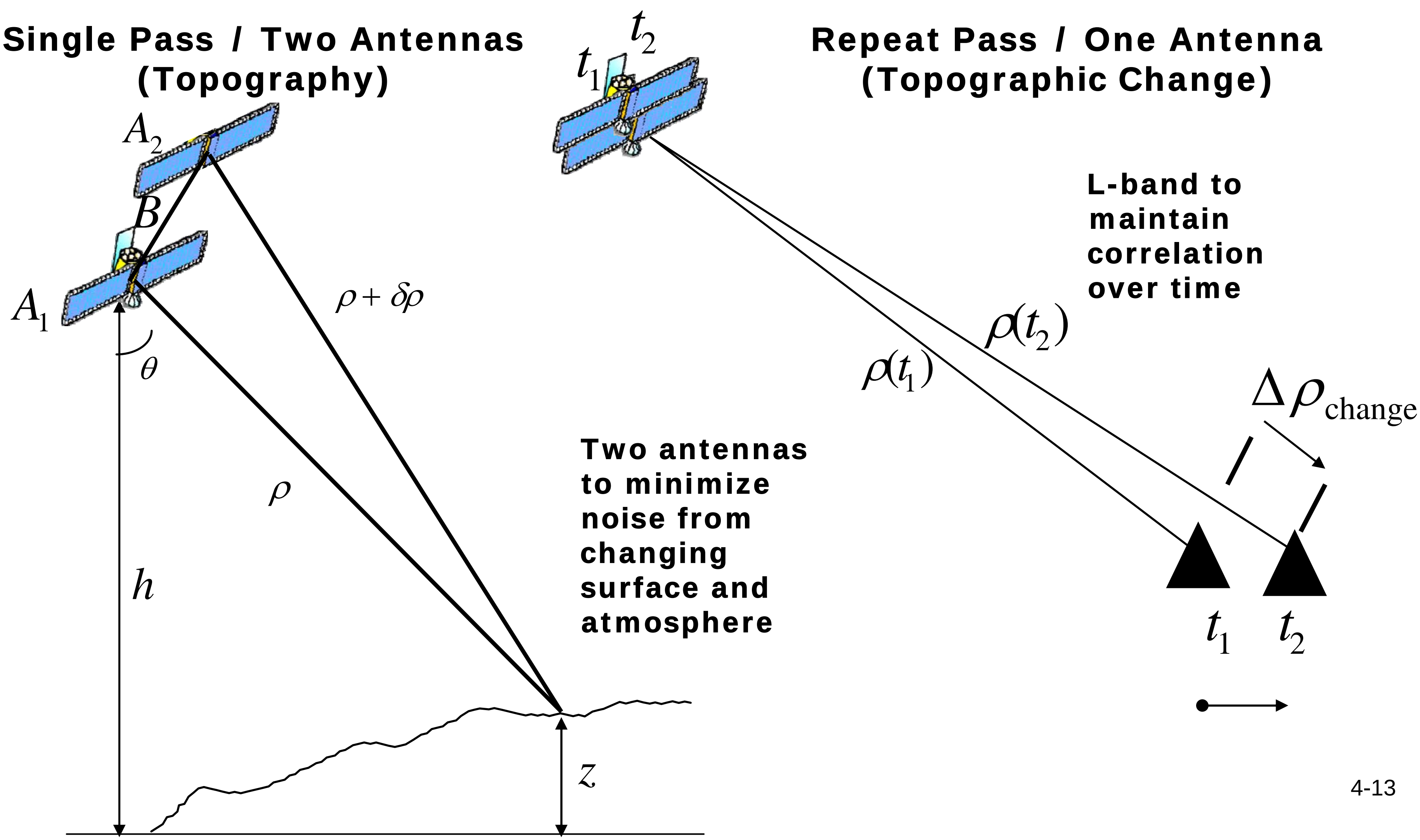
Image Pixel/Resolution Element



Propagation Phase Delay $\phi = -j\dfrac{4\pi}{\lambda}\rho$

Backscatter phase delay is coherent sum of contributions from all elemental scatterers in the resolution element with backscatter $A_{\varepsilon i} e^{j\phi_{\varepsilon i}}$ and their differential path delays $\rho_{\varepsilon i}$

Interferometry Basics



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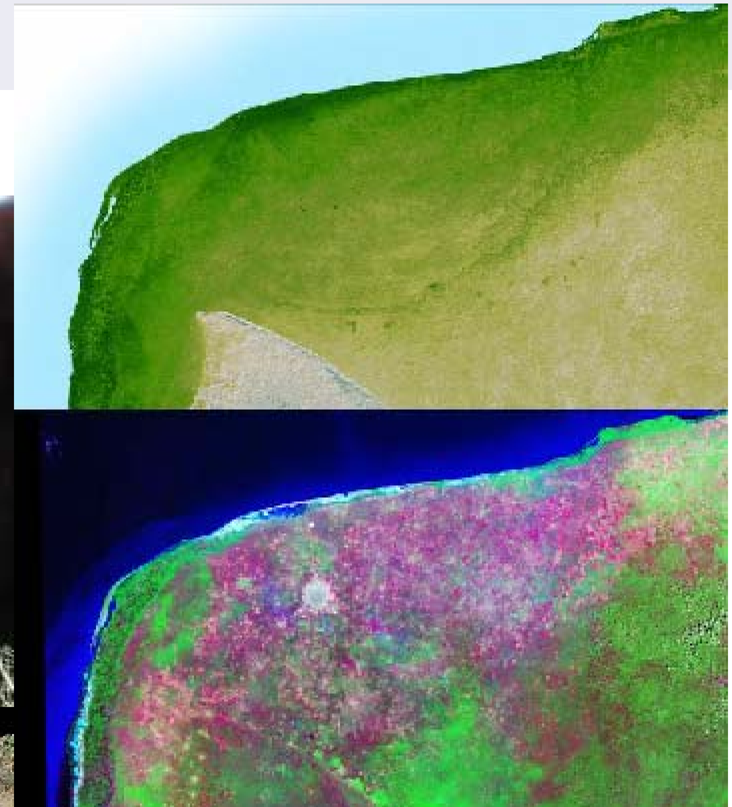
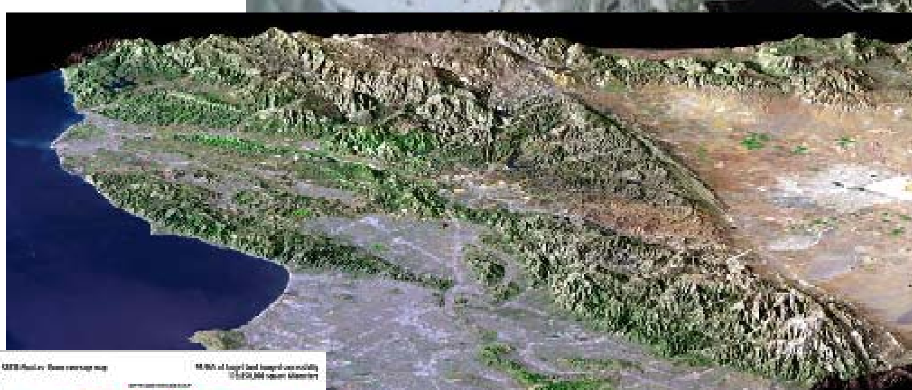
Shuttle Radar Topography Mission (SRTM)

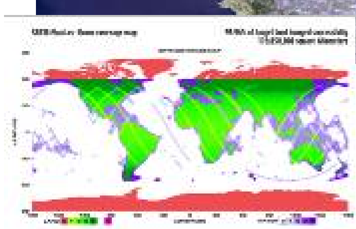
- Mapped 80% of Earth
- 30 m horizontal data points
- 10 m vertical accuracy



SRTM image of Yucatan showing Chicxulub Crater, site of K-T extinction impact. Bottom image is from Landsat showing Merida

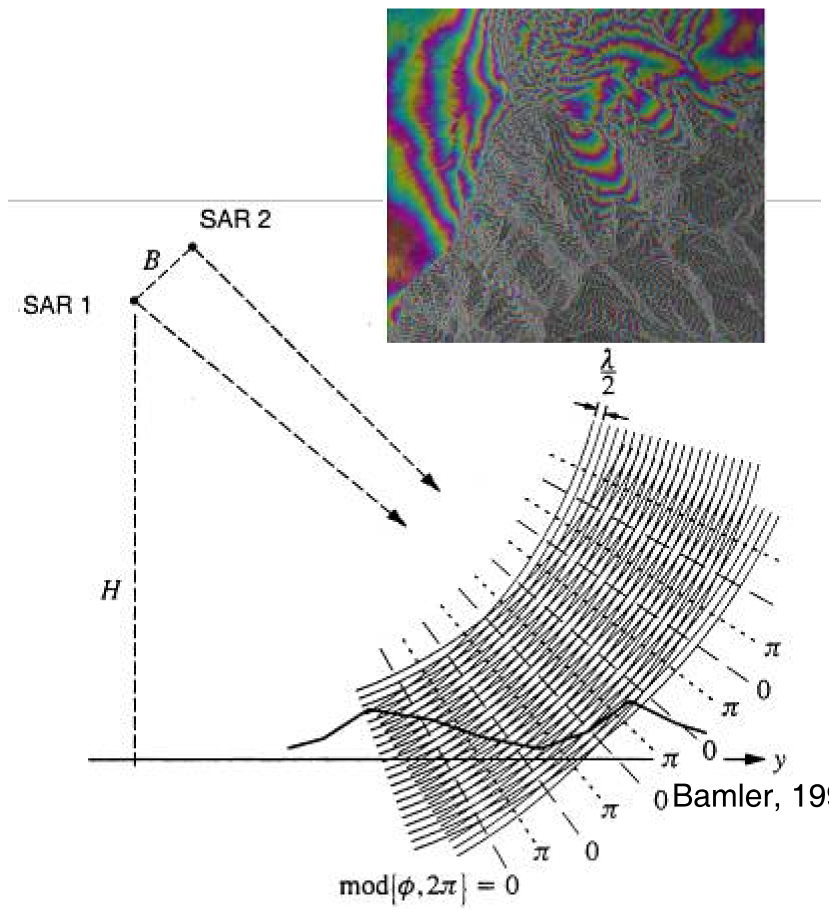


3-dimensional SRTM view of Los Angeles (with Landsat data) showing San Andreas fault



Radar Interferometry

- When imaging a surface, the phase fronts from the two sources interfere.
- The surface topography slices the interference pattern.
- The random surface component of the phase nearly cancels because the SAR's are very closely spaced, so the surface looks the same.
- The measured phase differences record the topographic information

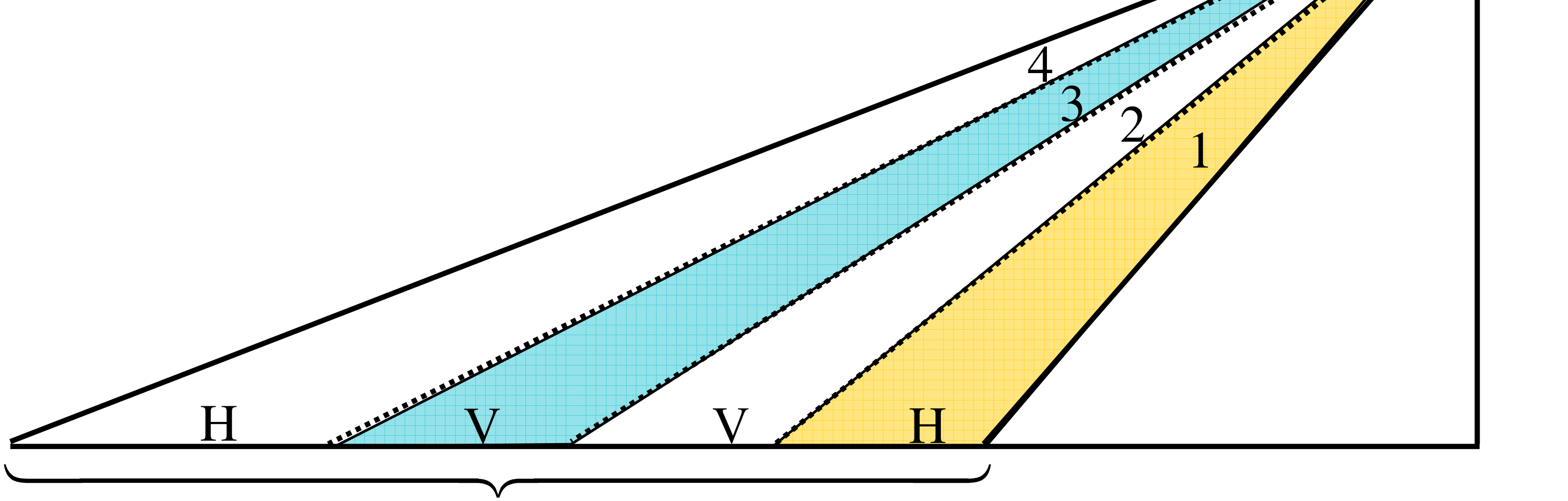


Bamler, 1999

SRTM Data Collection: ScanSAR

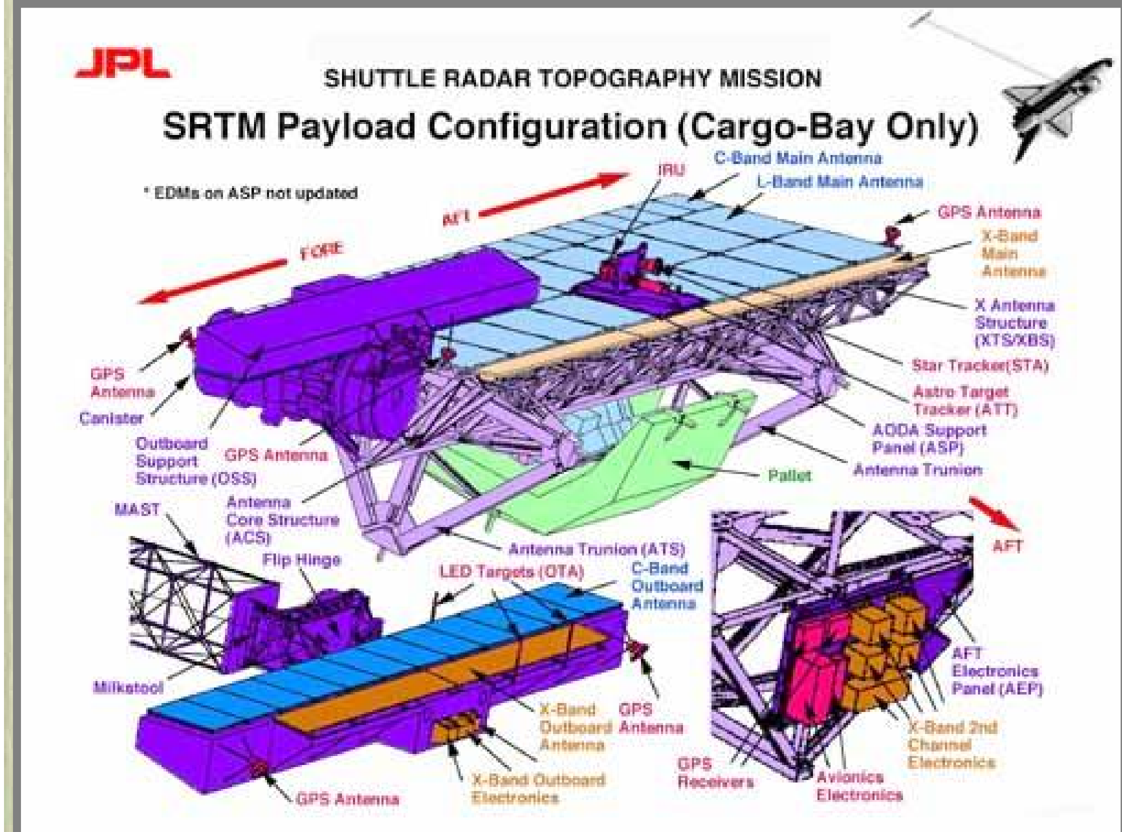
- **SRTM collected data in a SCANSAR mode**
  - **Electronic beam switching in bursts of pulses to cover more swath**
  - **Dual polarized independent channels allowed double width coverag**
  - **ScanSAR gave another factor of 2**

Data collected simultaneously on beams
1 and 3 and on beams 2 and 4.



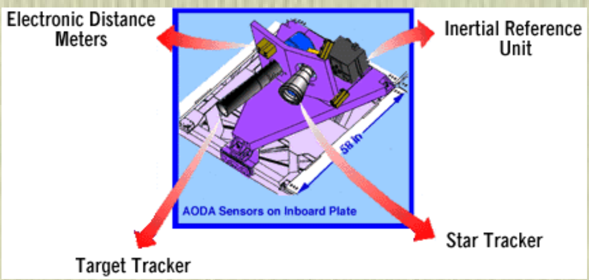
225 km swath width composed
of four subswaths

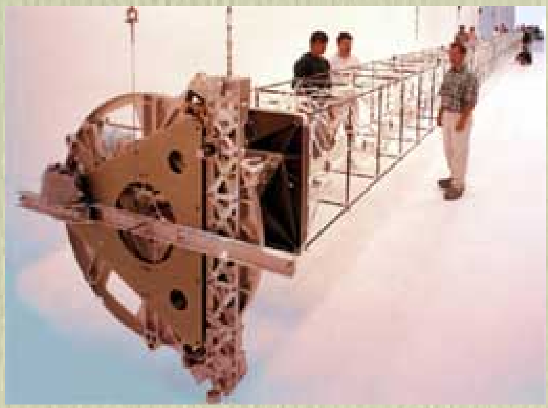
SRTM Hardware and Electronics

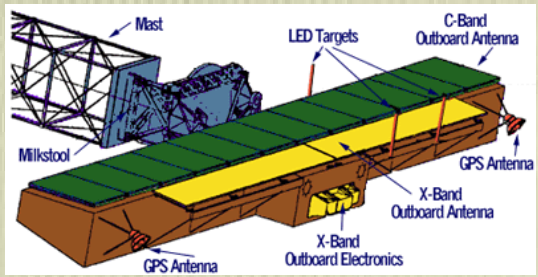


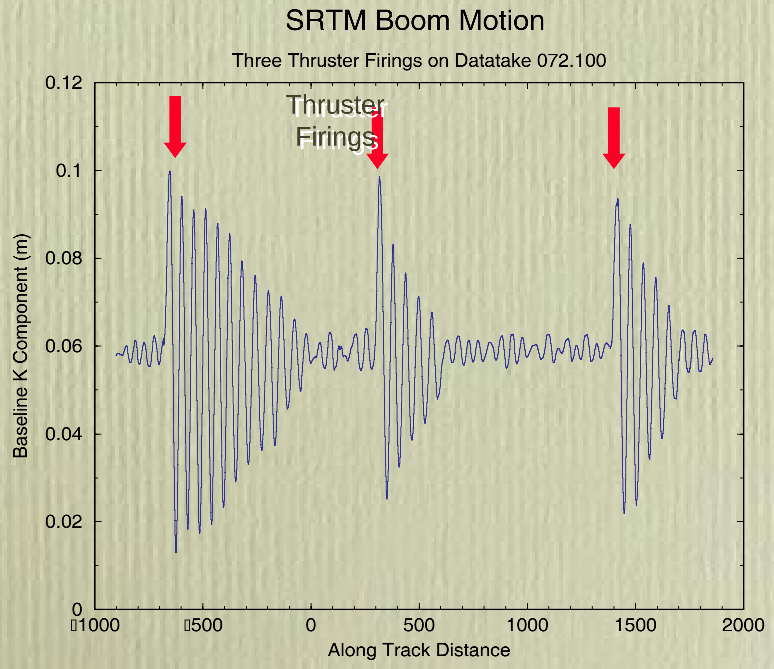
Mast Length: 60 m
Mast + Cannister Mass: 1000 kg
Total Payload Mass: 13,600 kg
Total Data Volume over 10 days: 12.3 TB
Number of tapes for recording: 300

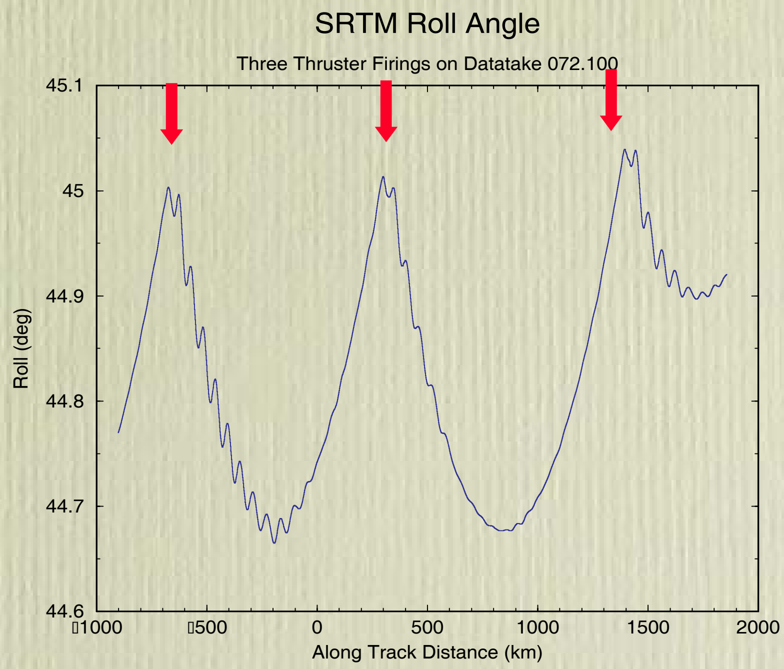
SRTM Mast Characteristics



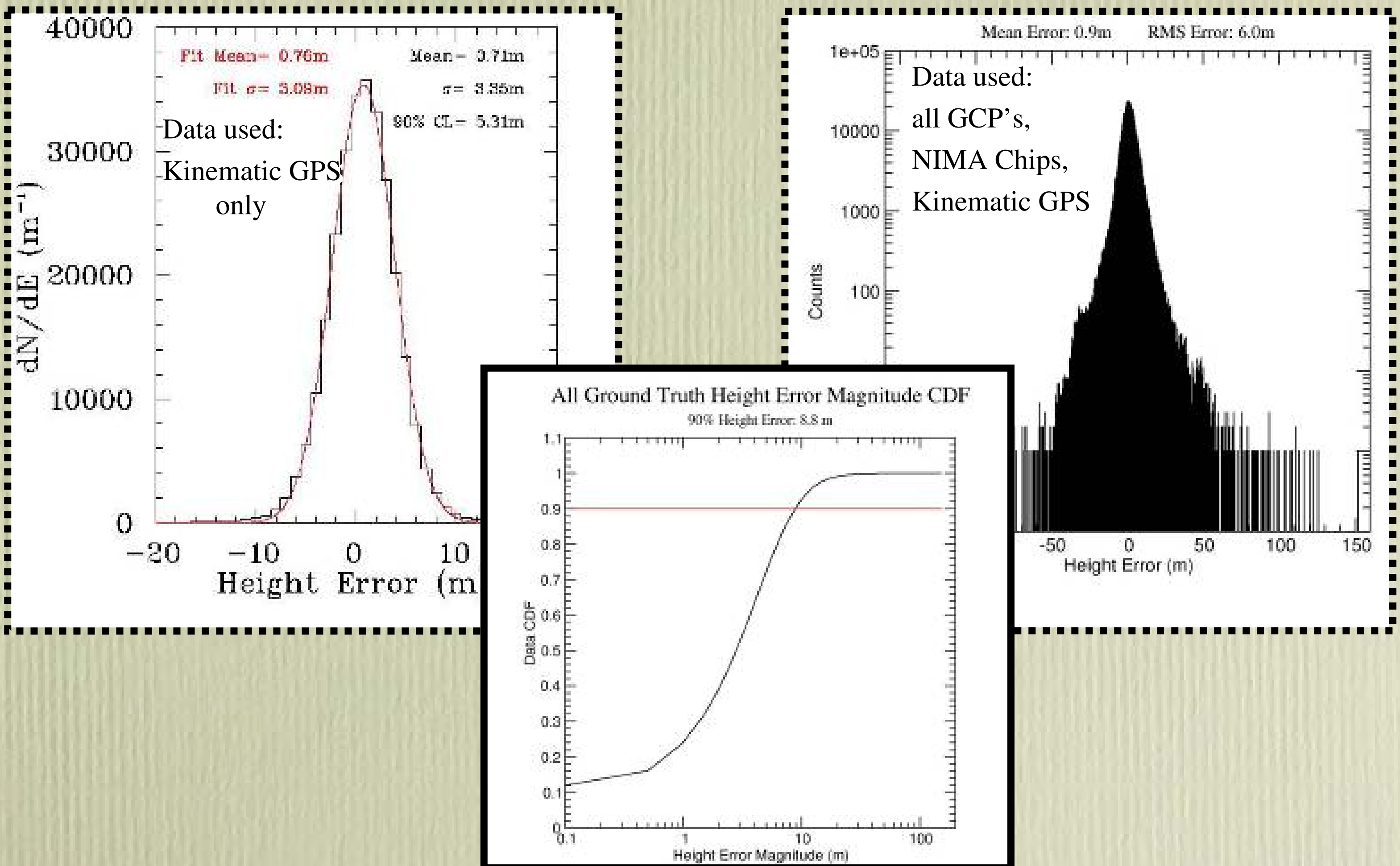






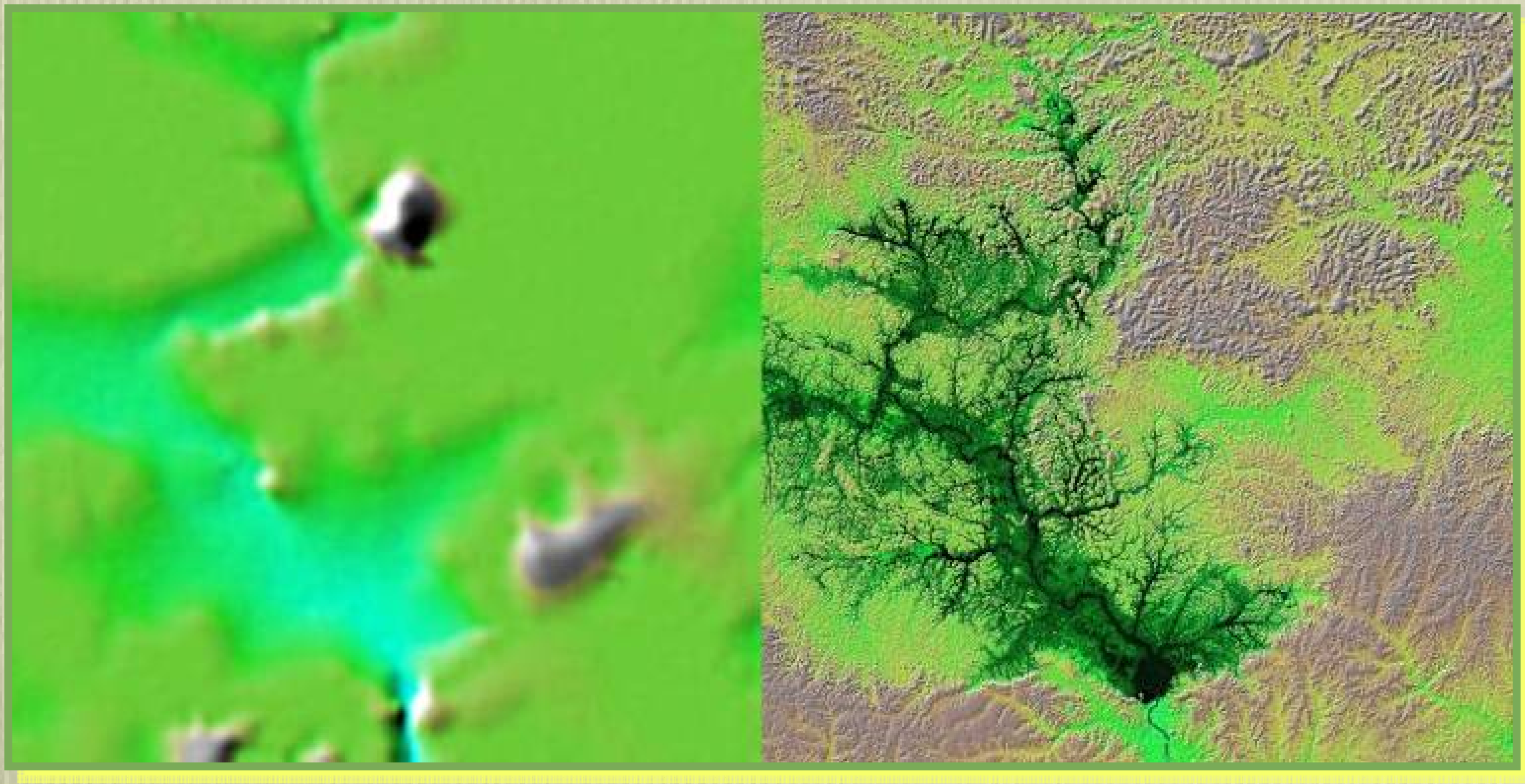


Summary Height Error Histograms



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

SRTM Resolution Improvement



GTOPO30 DEM SRTM DEM with radar image overlay

- Lake Balbina, Brazil

SRTM Global Production

The topographic data generated by SRTM will be a standard for global topographic data for some time to come and provides a valuable data set for accessing future changes to the Earth's topography.

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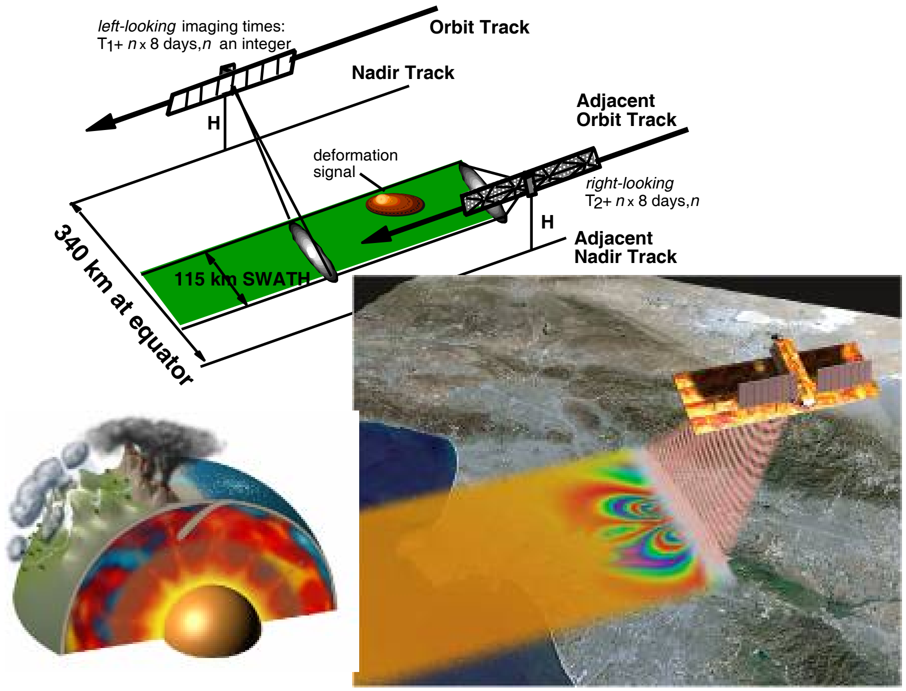
Surface Deformation Repeat Pass InSAR Mission

Mission/Goals

- **Generation of a discrete times series of deformation data for the Earth's deforming areas in vector image format**
  - **–100 m resolution, mm-scale relative statistical accuracy**
  - **–Imaging of Earthquakes, Volcanoes, and Ice Sheets: 1000 seismic events in 5 years**
- **NASA Earth Science strategic plans have called for measurements that can lead to understanding how the Earth's surface is being transformed**
- **NSF EarthScope Program calls for similar measurements to complement in situ arrays**



Technology Areas

- **Low-cost dedicated L-band radar**
- **Phase stable phased array or reflector**
- **ScanSAR interferometry algorithms and technology**
- **Interferometric calibration algorithms and verification**

Programmatics/Status

- **A future NASA SAR/InSAR mission has been recommended by numerous Science panels**
  - **–There is a need for L-band Measurements**
  - **–There is a need for wider swath coverage and more rapid repeat orbits**

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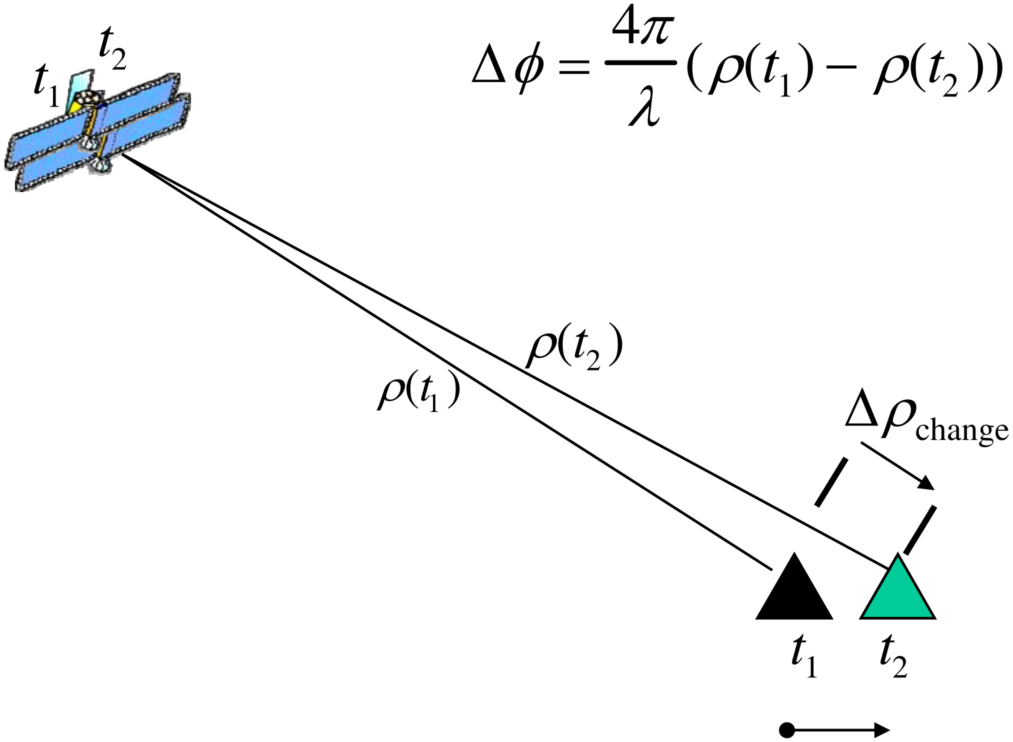
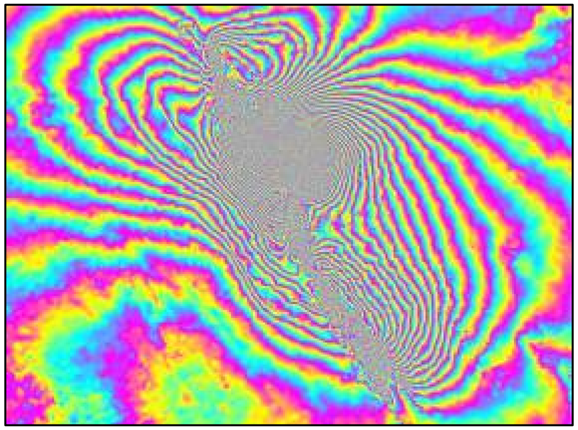
Deformation Interferometry

When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{\text{change}}$$

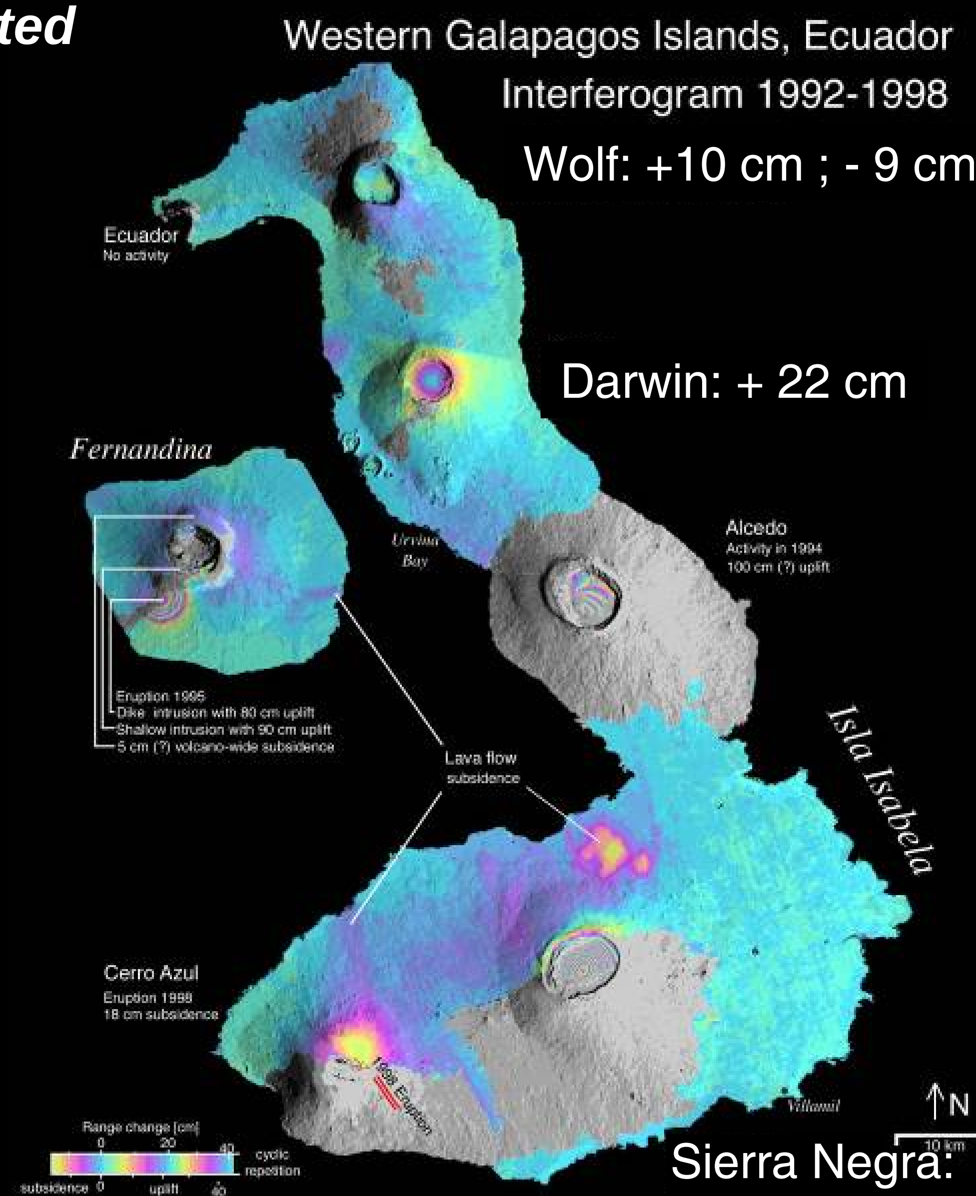




Surface Deformation of the 1999 Hector Mine Earthquake

InSAR Measures Unreported Volcanic Activity

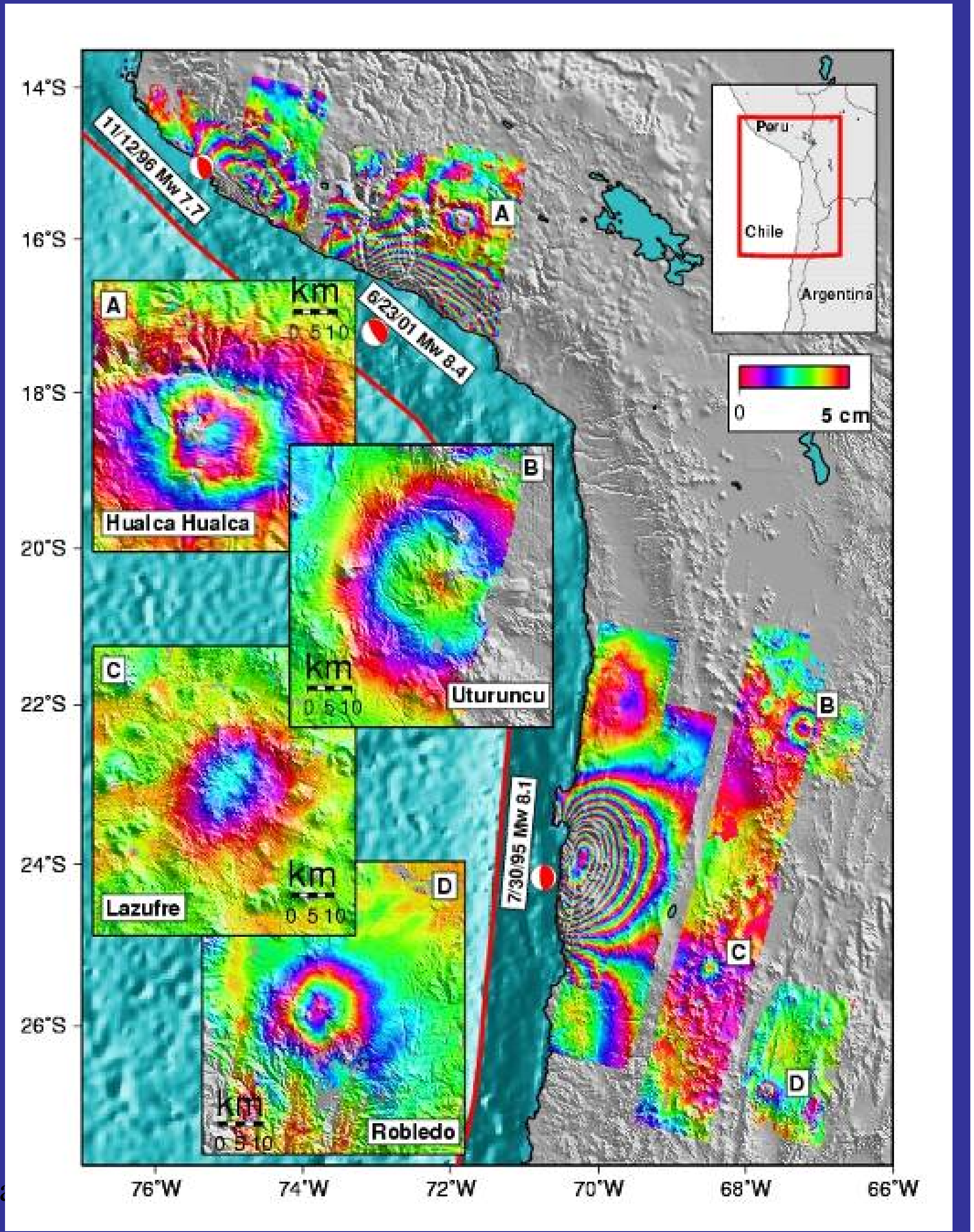
0.5 Billion people live near volcanoes, many of which are not monitored and have unknown surface deformation and hazard potential



Amelung and Jonsson

A glimpse of the future: The deforming continent

- EQs Mw 7.7, Mw 8.4, Mw 8.1
- Survey of 900+ volcanoes finds magma movement at 4 "dormant" sites

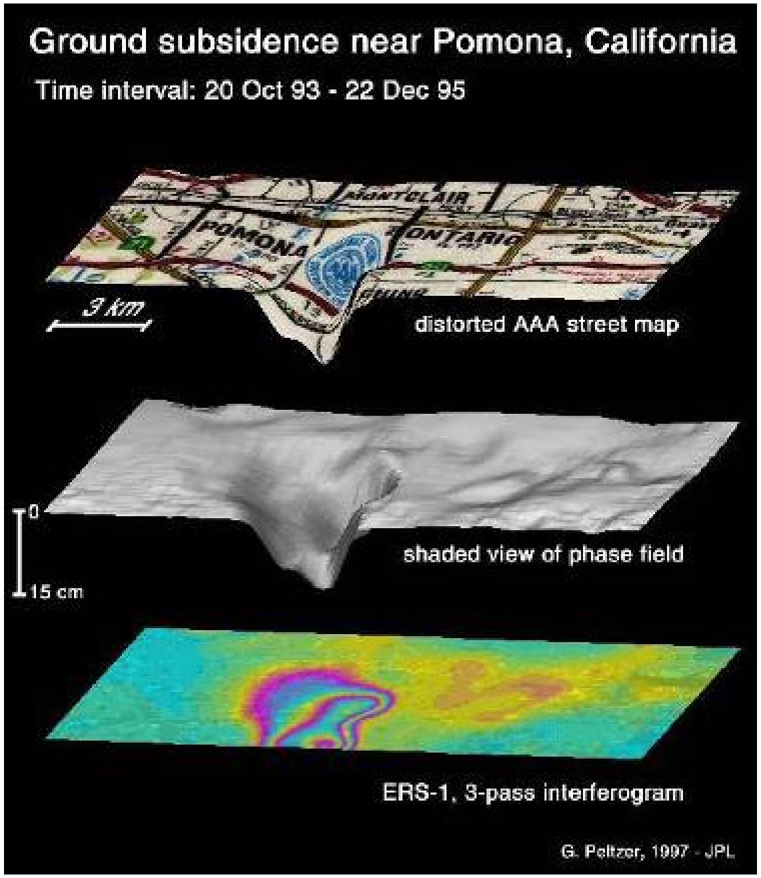


Pritchard et al., 2002
Pritchard and Simons, 2002
Pritchard and Simons, 2004a
Pritchard and Simons, 2004b

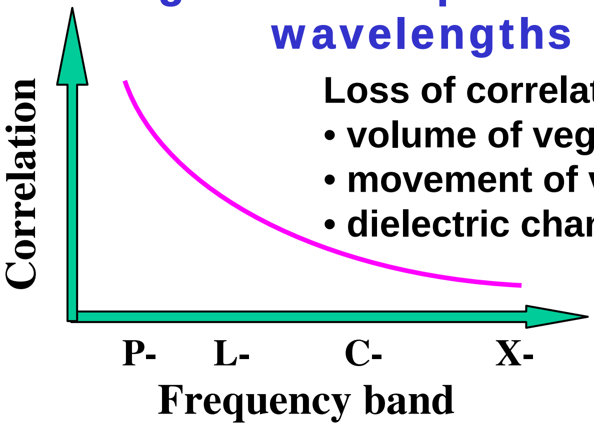
Repeat-pass Interferometry and Coherent Change Detection

L-Band low frequency improves correlation in vegetated areas

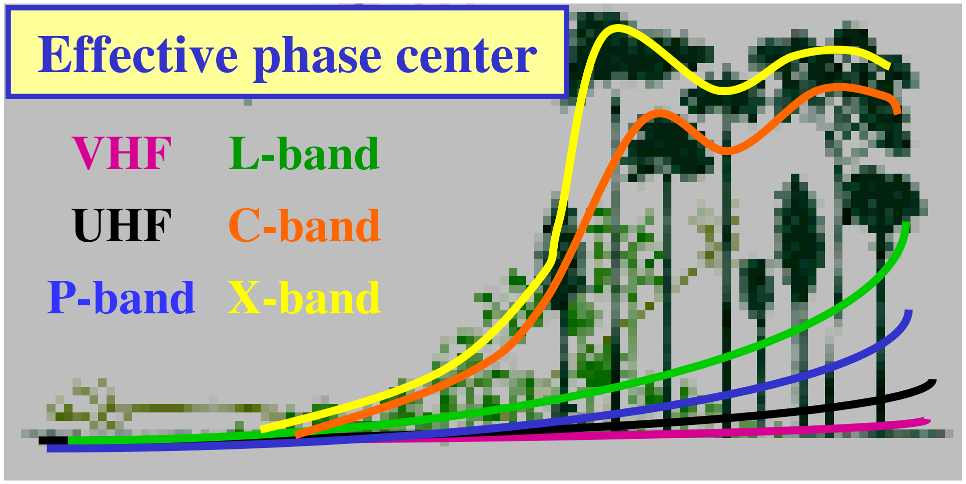
Most radars do well in areas of sparse vegetation



But maintaining correlation in dense vegetation requires longer wavelengths

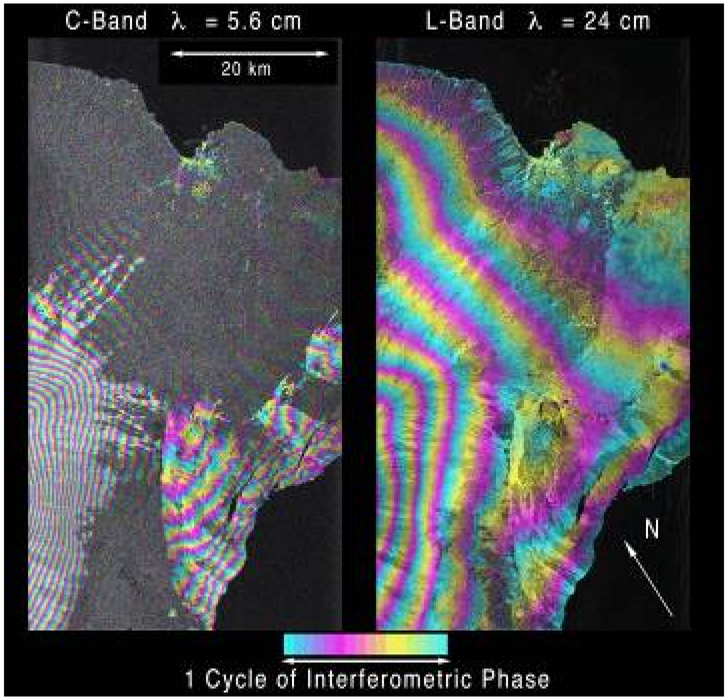


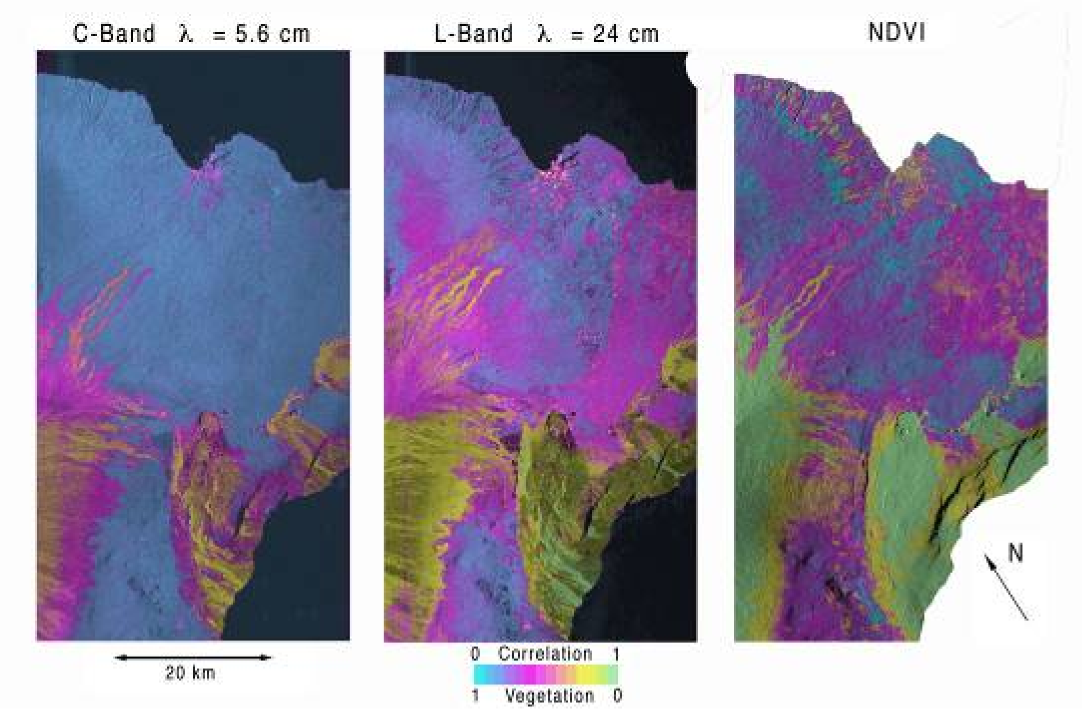
Loss of correlation is due to:
- **volume of vegetation**
- **movement of vegetation**
- **dielectric change (moisture)**



Repeat Pass InSAR Experience
SIR-C L and C-band Interferometry

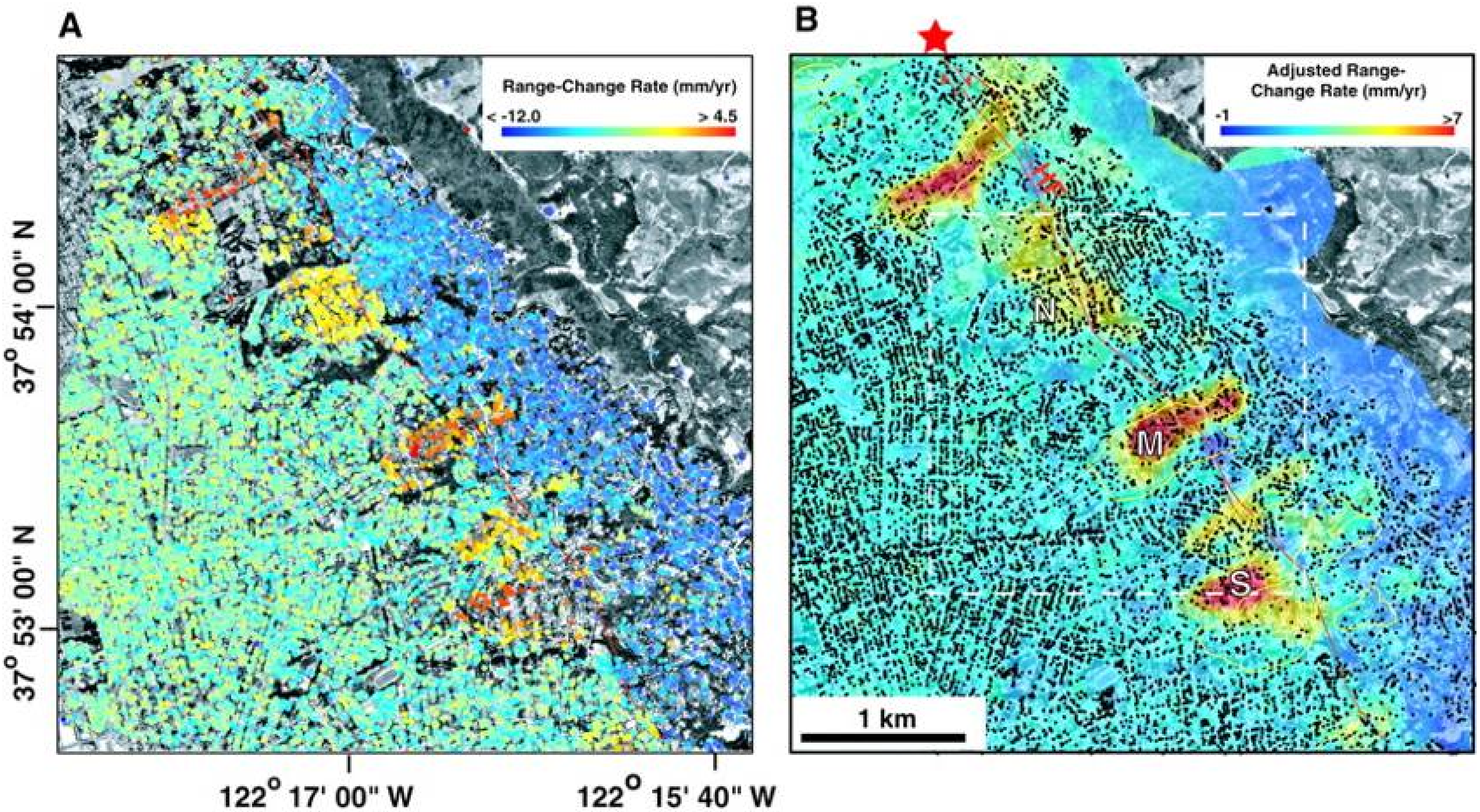
6 month time-separated observations to form interferograms
Simultaneous C and L band





Improved correlation at L-band reveals significantly more of the changing earth

Landslides in Berkeley using Interferometric Permanent Scatterers



Raw data shows creep on Hayward Fault

Removing creep signal yields measure of landslide slip

Hilley et al., 2004

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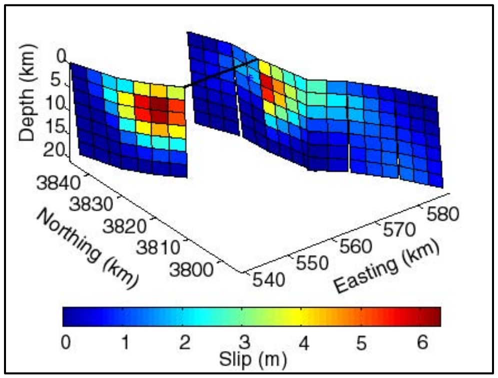
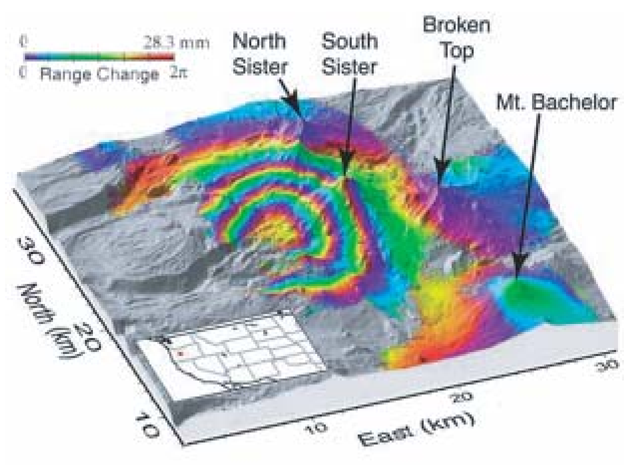
InSAR provides scientific insight that will save lives and property

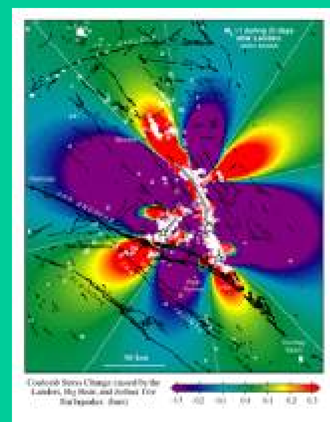
InSAR Data and Analysis



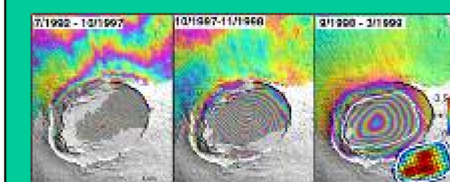
Fundamental Physics and Discovery of Earth Surface Change



Modeling and Application



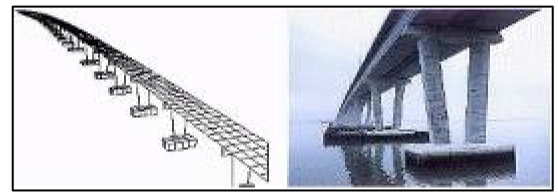
High Resolution Earthquake Hazard Information (Stress Map)



Systematic Volcano Monitoring

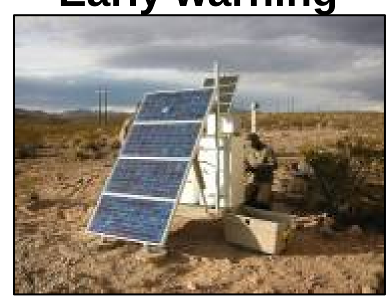
Planning and Preparation

Targeted retrofitting in high-risk areas

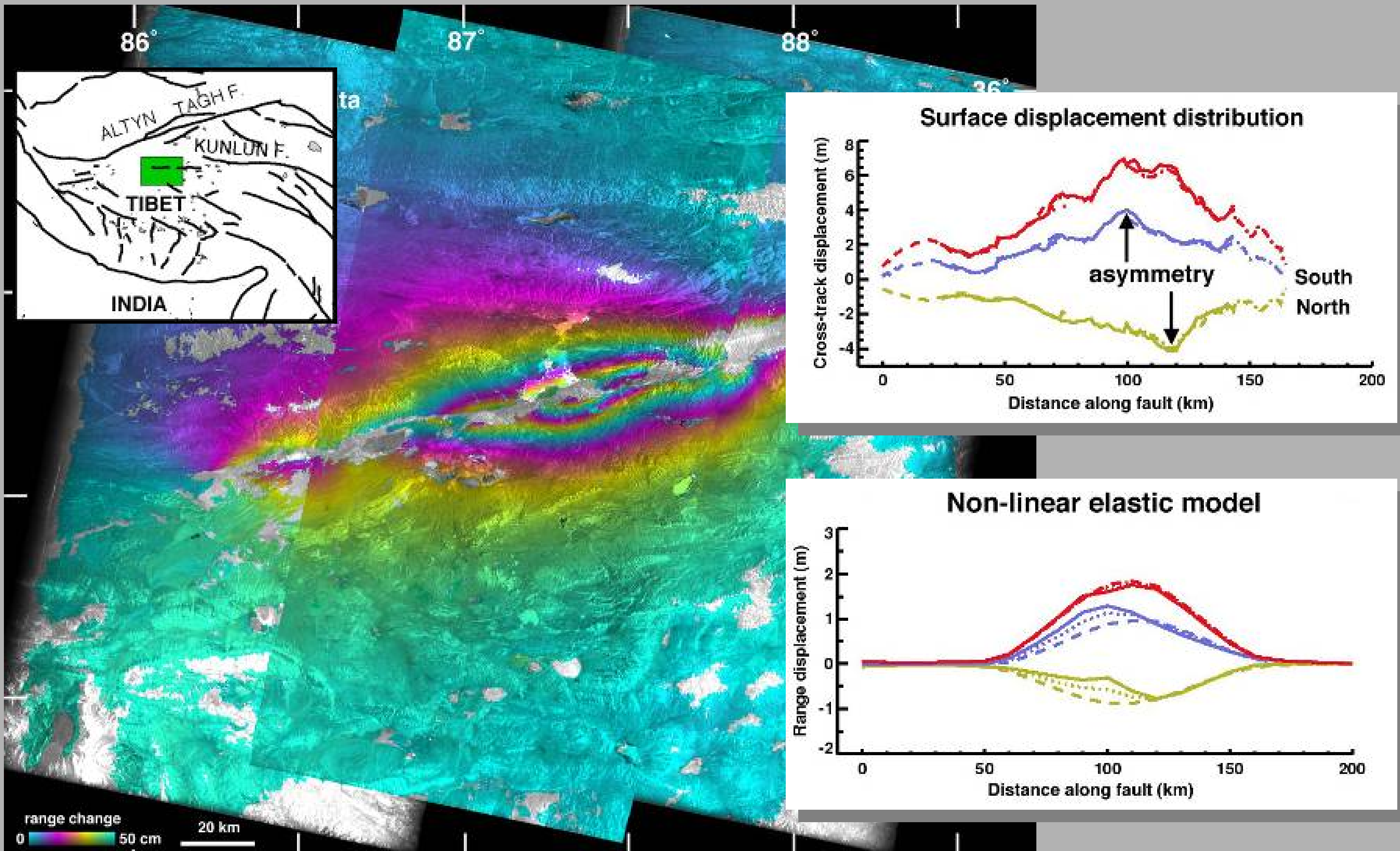


Rapid response and recovery

Early warning



Non-Linearity of the Crust Revealed by InSAR



Peltzer et al, JPL, 1999

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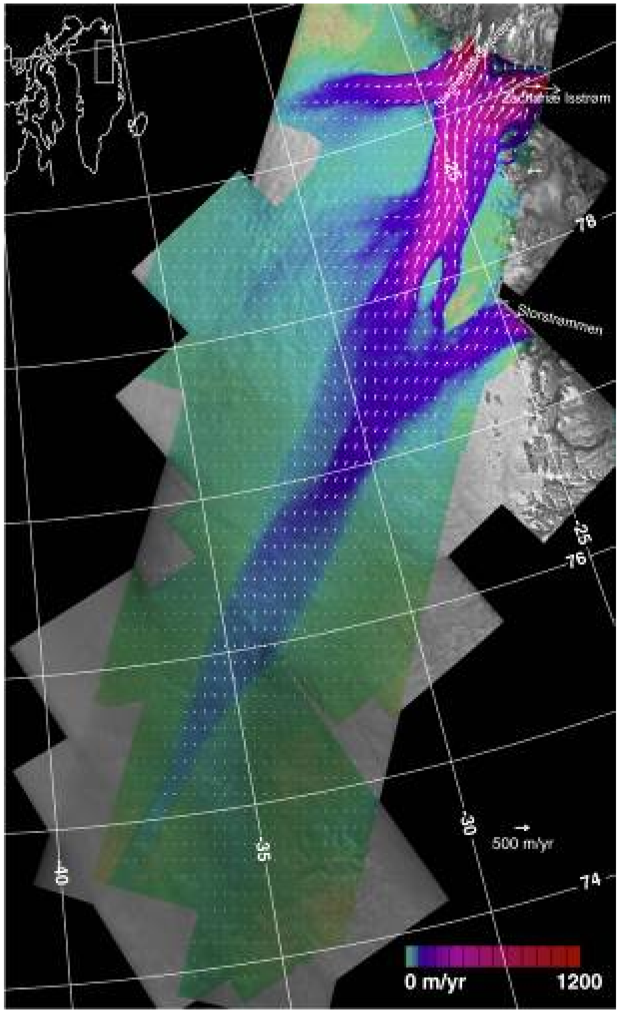
California Institute of Technology
Pasadena, California

L-Band Interferometry Over Ice Sheets

Once the interferogram is formed and the phase successfully unwrapped the problem is identical to that of determining flow rates as is done currently with C-band, as shown.

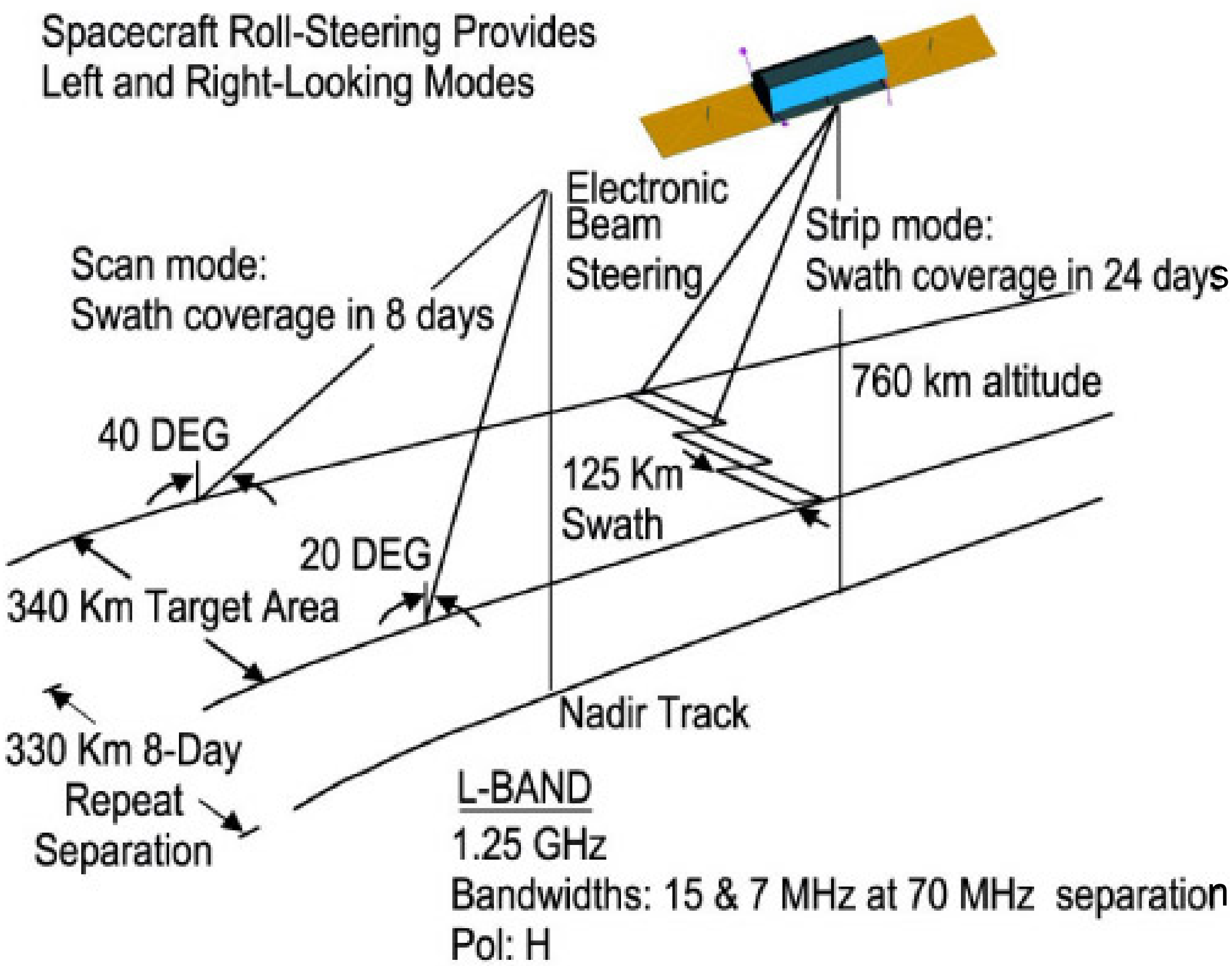
L-band rapid repeat data will complement numerous operating or planned C-band and X-band sensors

C: ENVISAT; Sentinel; Radarsat-2
X: Terrasar-X; Tandem-X, Cosmo-Skymed, Space Radar?



C-band; Joughin et al., 2001

InSAR Observation Strategy



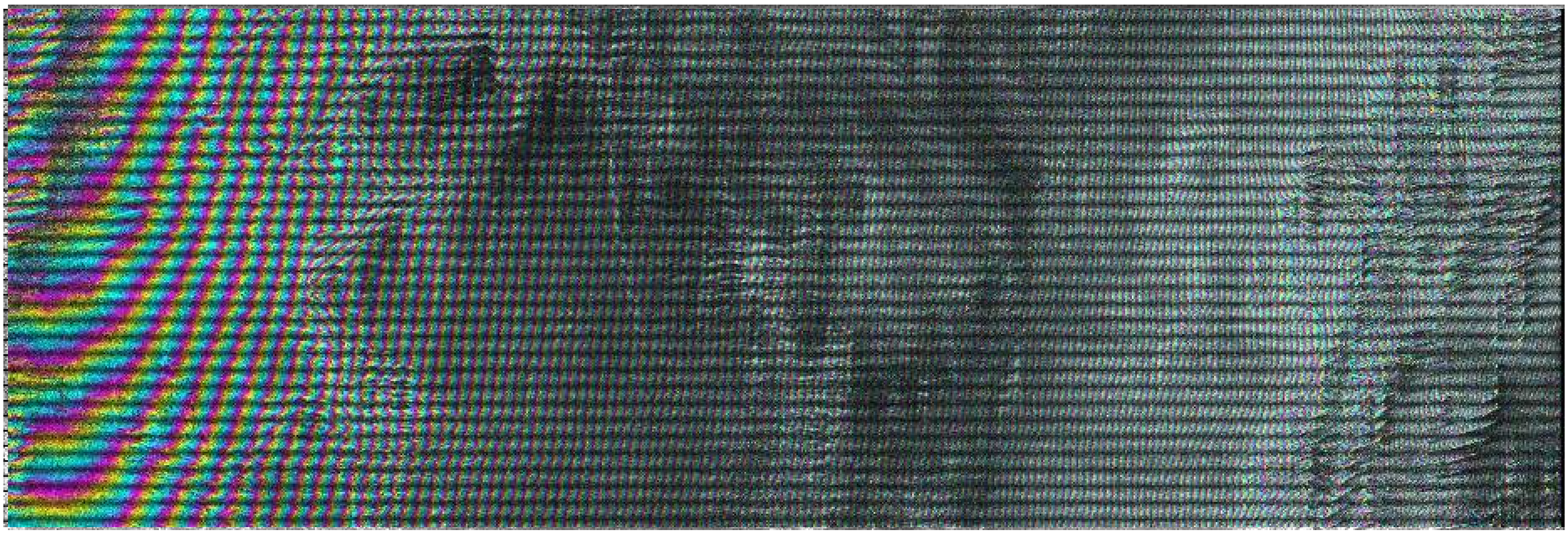
Repeat observations aimed at building *time-series* of deformation over the life of the mission

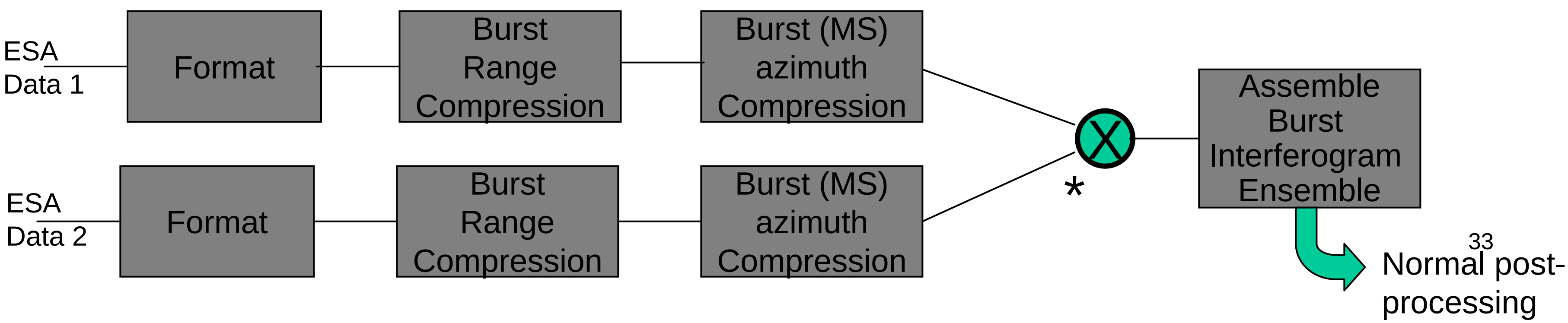
Modest resolution but extensive and rapid repeat

L-band to optimize coherence and sensitivity

ScanSAR Processing for Repeat Pass Interferometry

Sample of data from Envisat Beam 1 (of 5)





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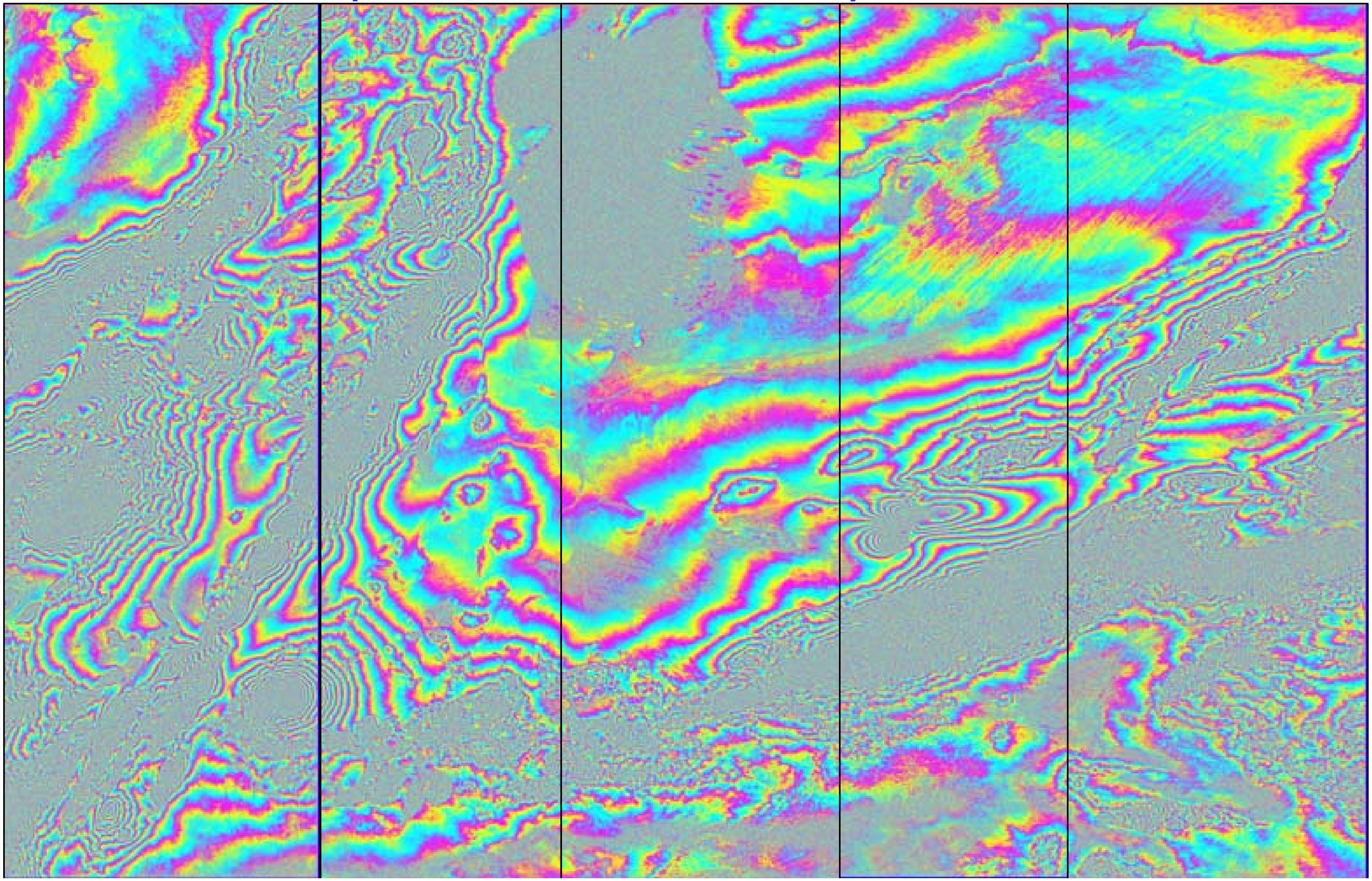
ScanSAR Processing for Repeat Pass Interferometry

Five Envisat Beams (350 km across x 200 km down)



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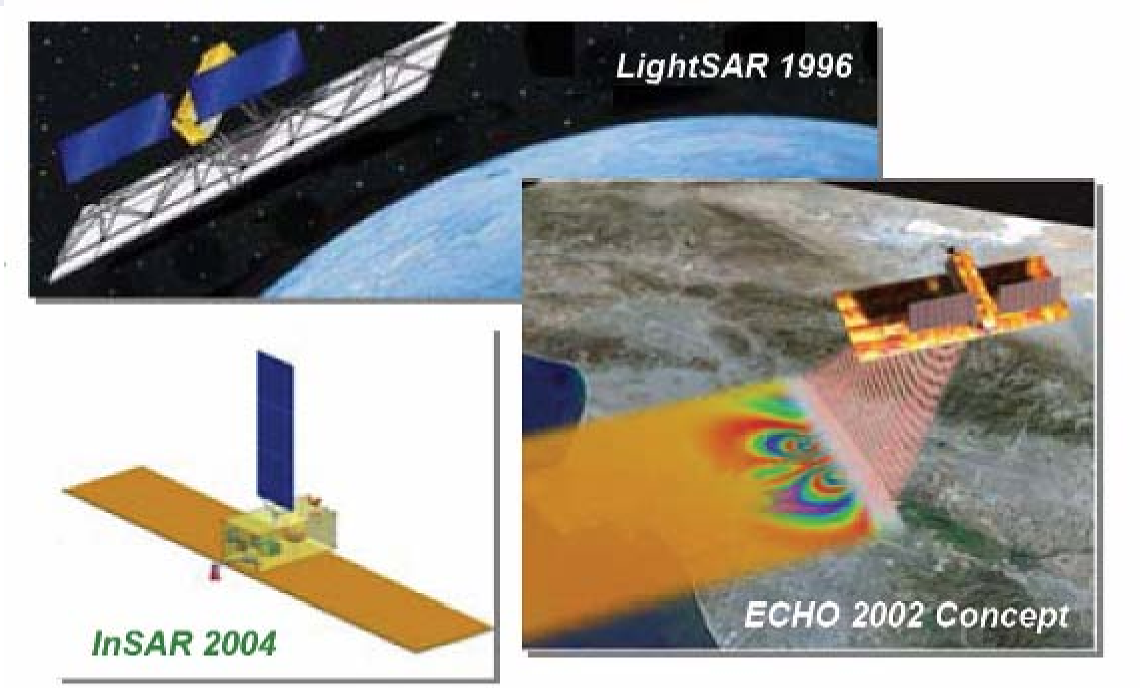
Status of InSAR as a Mission



Previous proposals to NASA failed

- **National priority**
- **Cost**
- **Cost credibility**
- **Competing SARs**

Future proposals to NASA must await an opportunity

- **NASA awaiting NRC Decadal Survey for Earth Science**
- **If InSAR is ranked high, NASA can make an opportunity**
  - **High-cap Announcement of Opportunity**
  - **Directed sustaining science mission**

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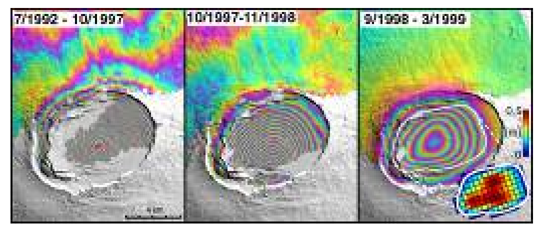
UAVSAR: NASA’s Future Airborne Radar Science and Technology Testbed

<u>Salient Features</u>

- ***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



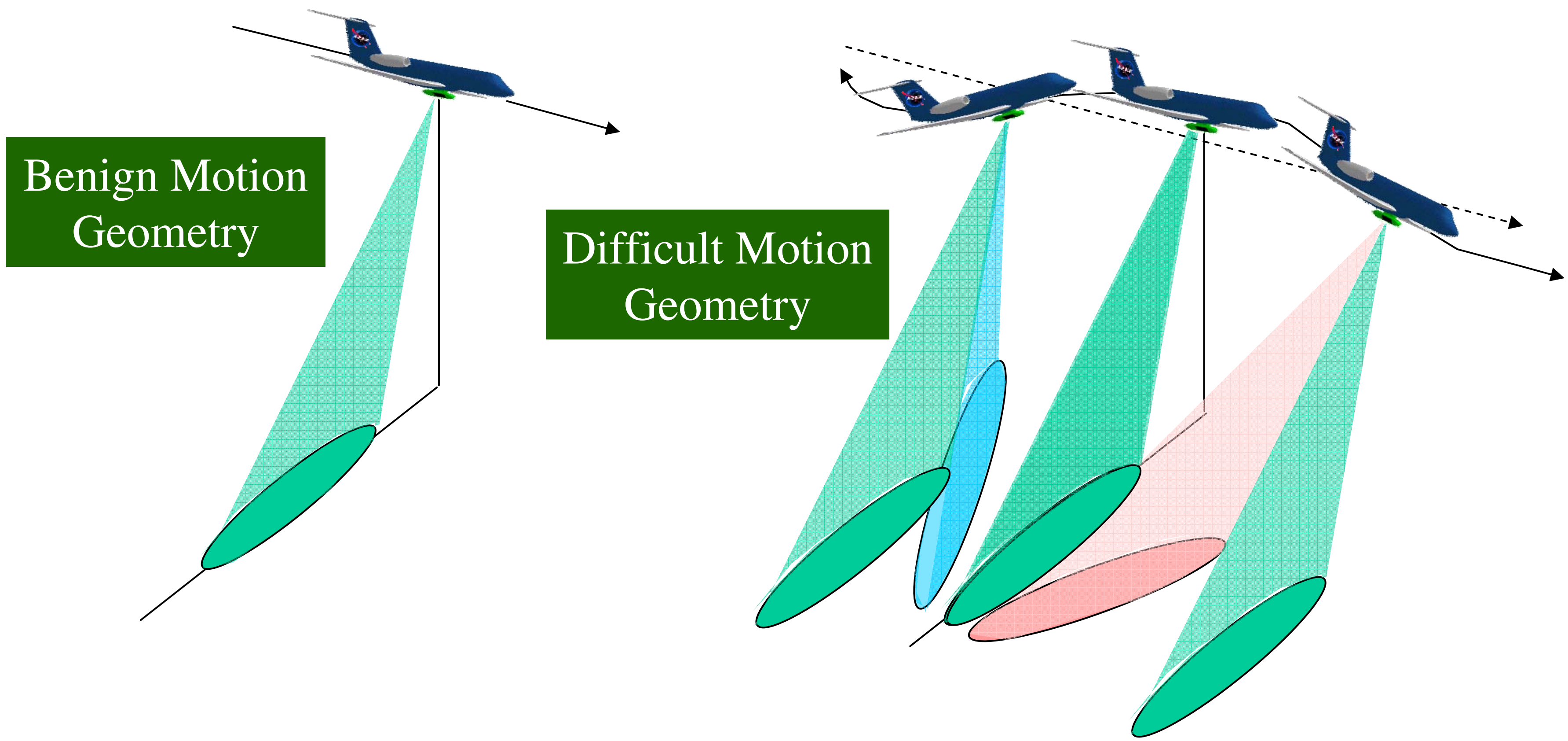
Volcanic Surface Deformation

<u>Science</u>

- ***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.***

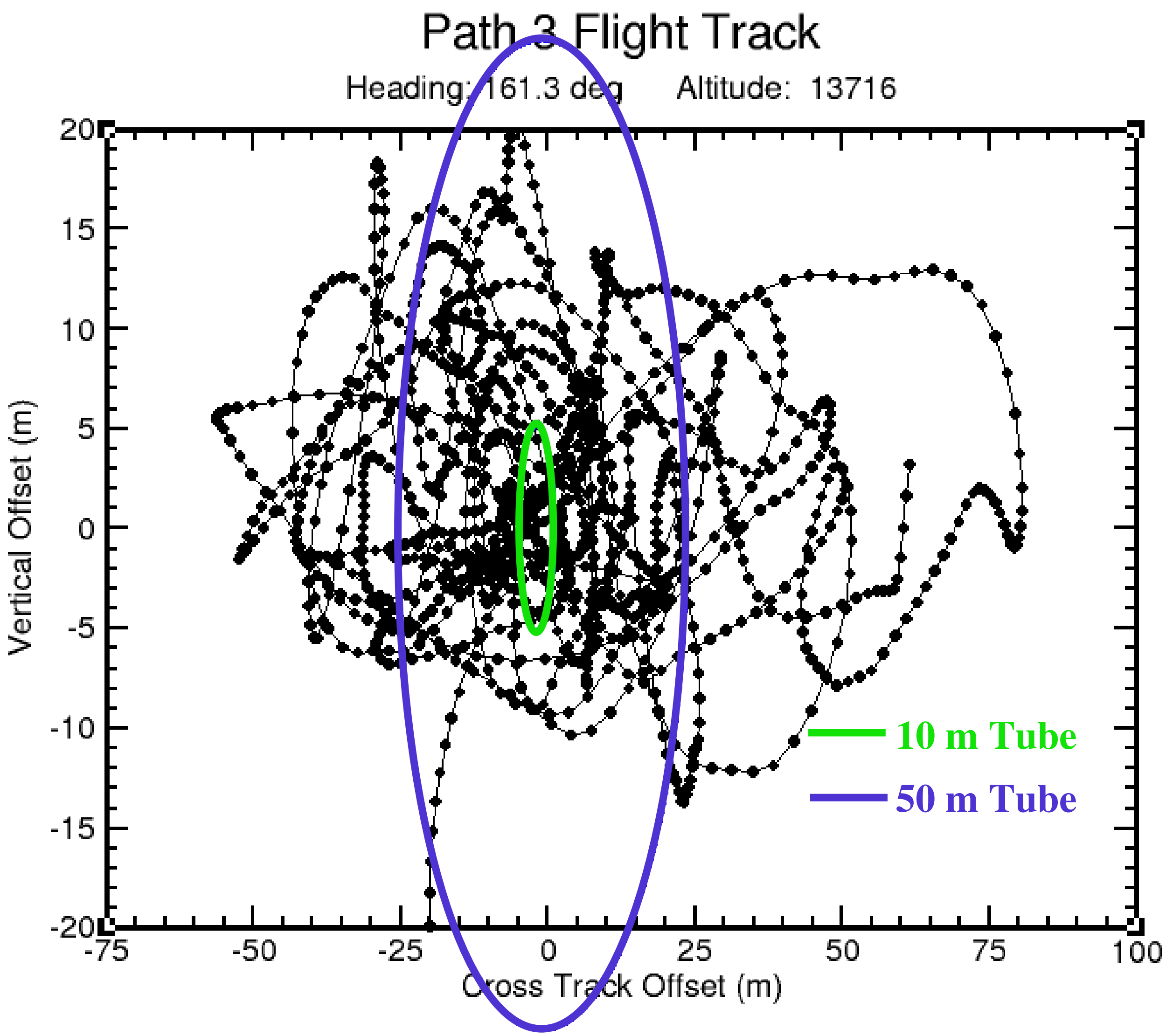
Electronic Steering of the Antenna

- **Efficient batch processing assumes that the Doppler Centroid (direction the antenna is pointing) is not changing by more than a fraction of a beamwidth (7.5° for UAVSAR) over a processing interval**



- **When the aircraft attitude changes too quickly data quality suffers. UAVSAR effectively attitude stabilizes the antenna through electronic steering.**

Cross Track and Vertical Offsets with Desired Flight Tube Overlaid



- The third pass was by far the best pass and was indicative of the pilots learning to fly the aircraft more effectively using the GPS navigation display.

- The pilots were much better able to maintain position within the 50 m tube, however most of the time the aircraft was outside the required 10 m tube.

UAVSAR System Parameters

Parameter	Value
Frequency	**L-Band 1217.5 to 1297.5 MHz**
Bandwidth	**80/100 MHz Chirp/Noise**
Resolution	**2 m range, 0.8 m Azimuth**
Polarization	**Full Quad-Polarization**
Bits in ADC	**1 to 12 bit selectable BFPQ, Selectable**
Waveform	**Nominal Chirp/Arbitrary Waveform**
Antenna Dimensions	**0.5 m range/1.5 azimuth**
Azimuth Steering	**>±20°**
Power	**> 2.4 kW**
Polarization Isolation	**-20 dB (-30 dB goal)**

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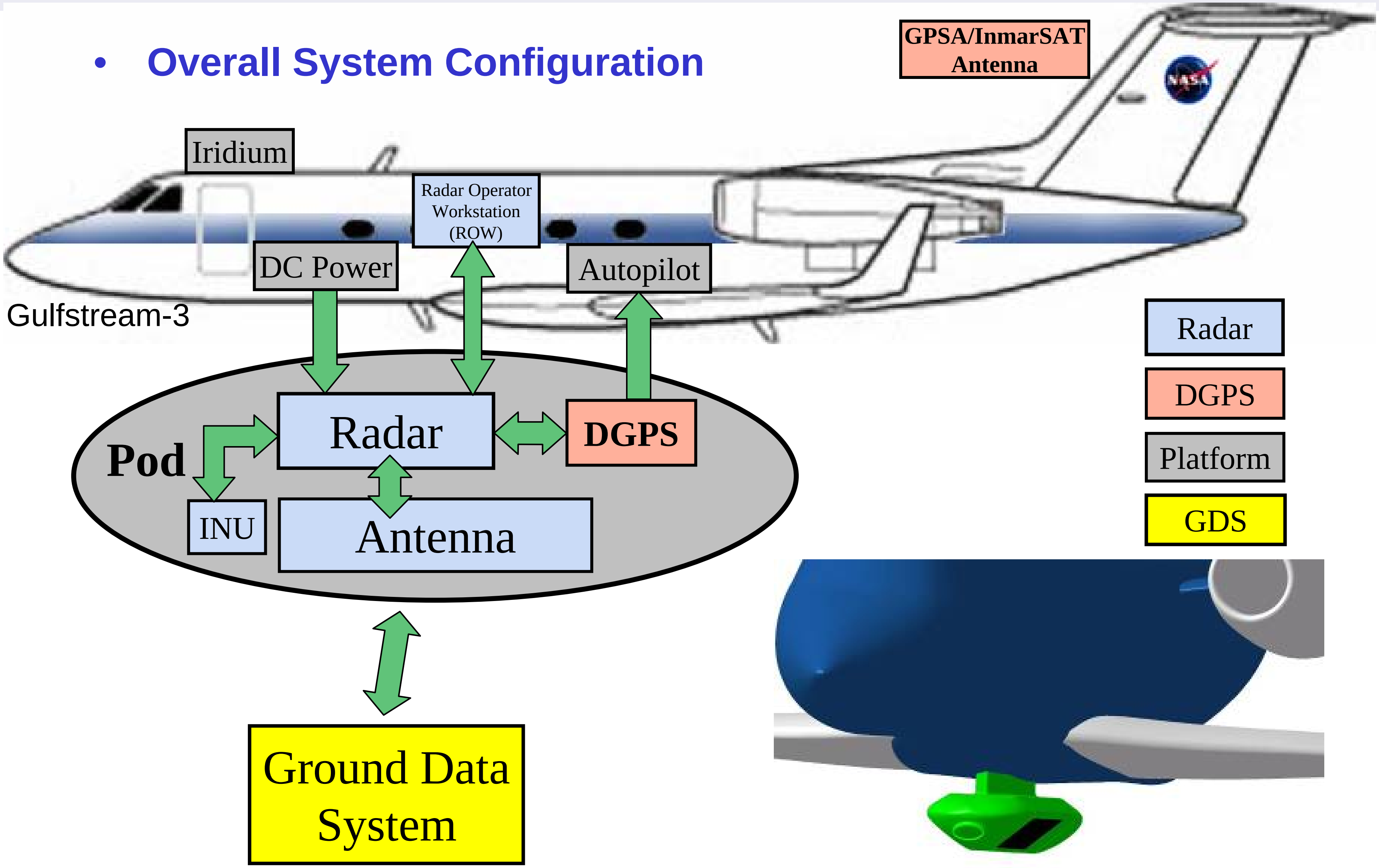
High Level Architecture

- **Overall System Configuration**



Deformation Performance Estimates

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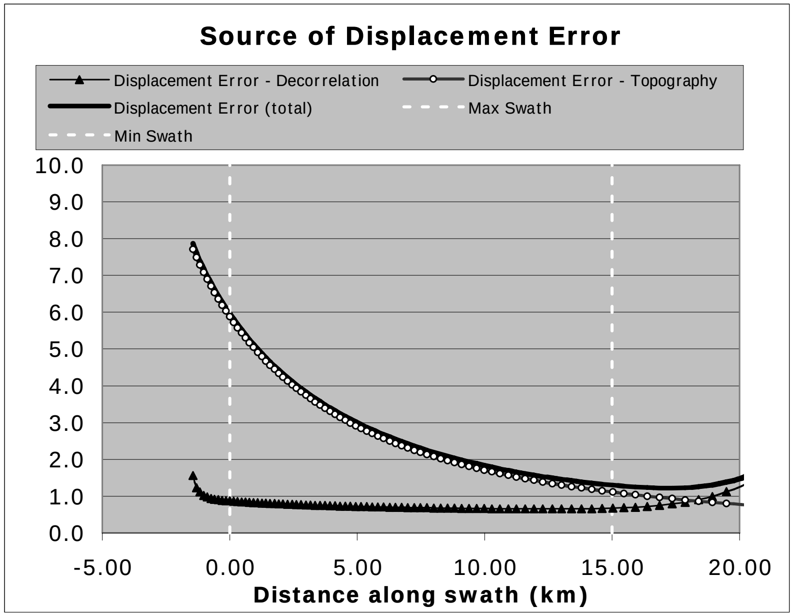
- **At 20 m x 20 m resolution cells, deformation measurement accuracy is dominated by uncertainty of the terrain knowledge (assuming SRTM level accuracy) coupled with the flight path repeat error.**
- **Improving knowledge in terrain height through improved topography maps or 3 pass techniques will improve this error.**



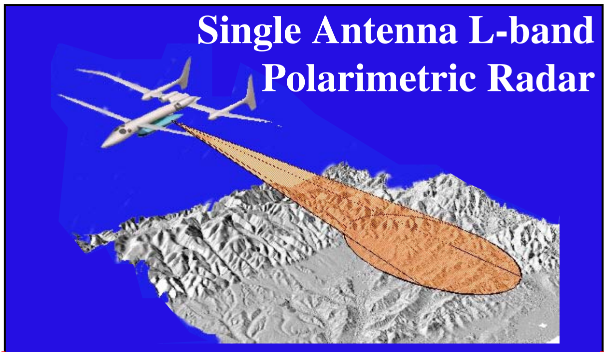
Deformation Error Budget

Error Contributor	Displacement Error (mm)
SNR Decorrelation	0.2
Instrument Phase	0.6
Geometric/Temporal Decorrelation	1.0
Flight Path Uncertainty*	1.0
Topo Uncertainty	5.5

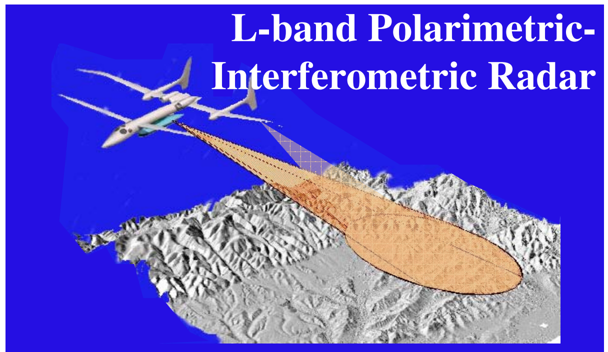
* Relative repeat pass flight path knowledge derived from fit of the image displacements. Results will be scene dependent

UAVSAR Science Upgrade Plans

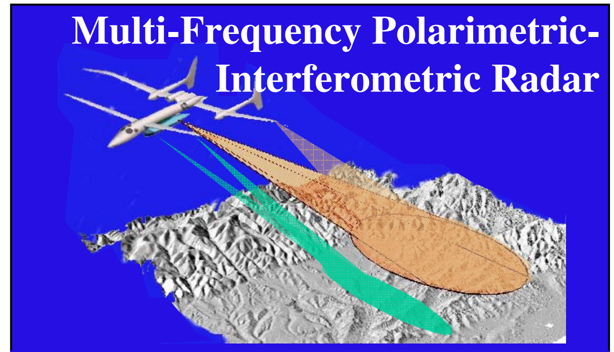
Increased Capability



Repeat Pass Deformation
Land Cover Classification
Soil Moisture Studies
Geology



Repeat Pass Deformation
Land Cover Classification
Soil Moisture Studies
Geology
Vegetation Structure
Hydrology

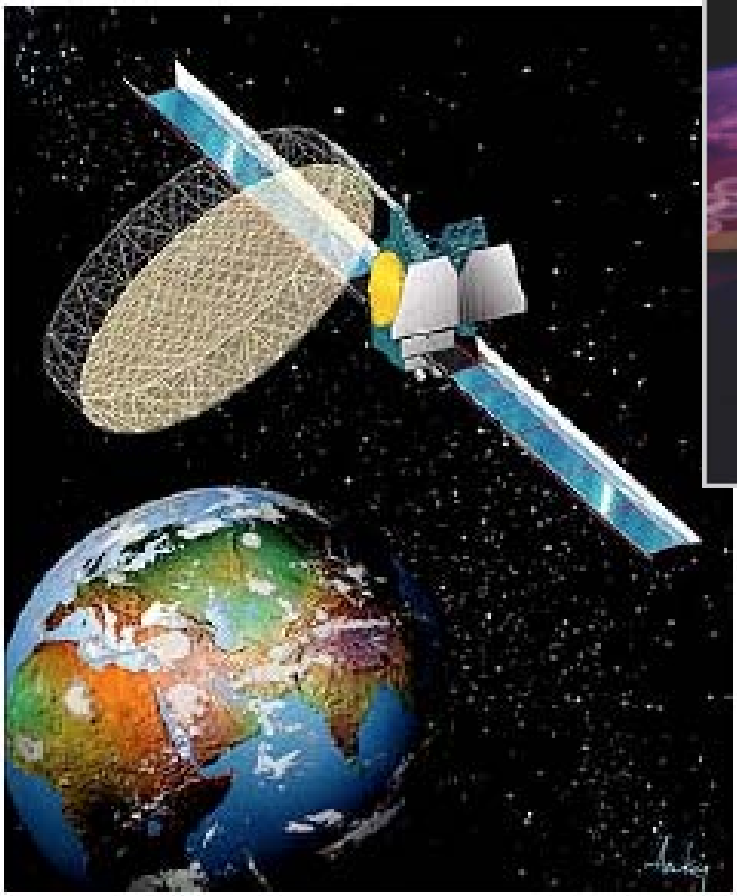


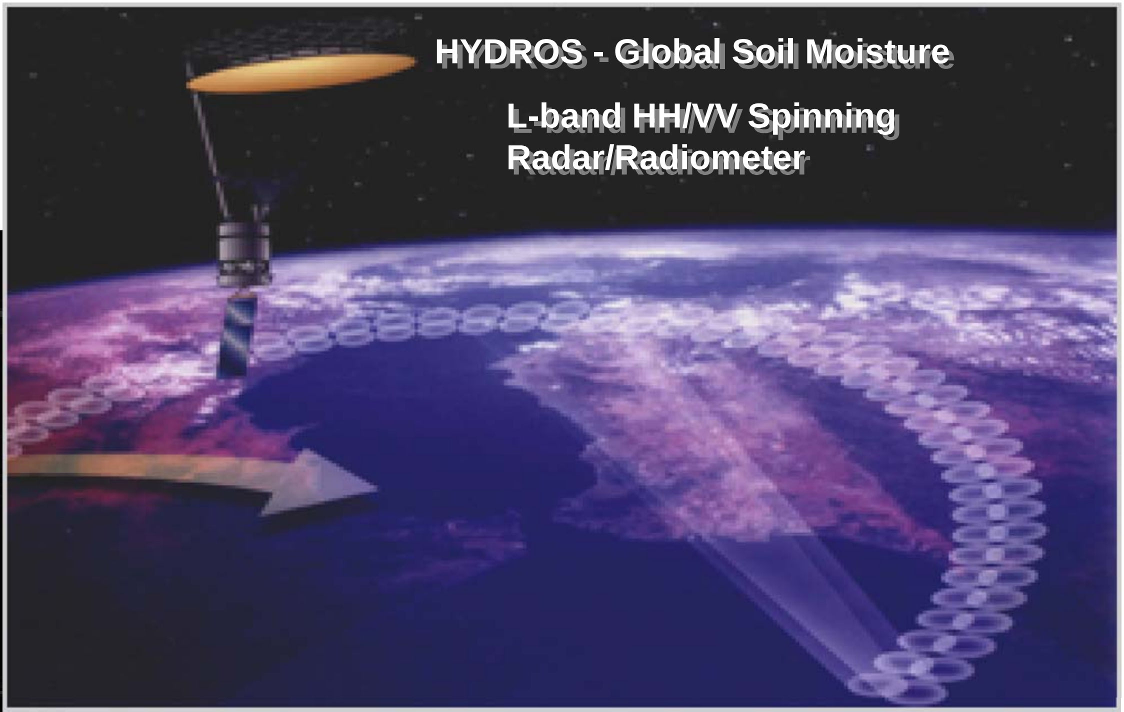
Repeat Pass Deformation
Land Cover Classification
Soil Moisture Studies
Geology
Vegetation Structure
Hydrology
Cold Land Processes
Ocean Studies

Increased Science Application

A Bright Future for SAR in the US?

UHF SAR - Carbon Stock and variability
6 MHz bandwidth
P-band Quad Pol

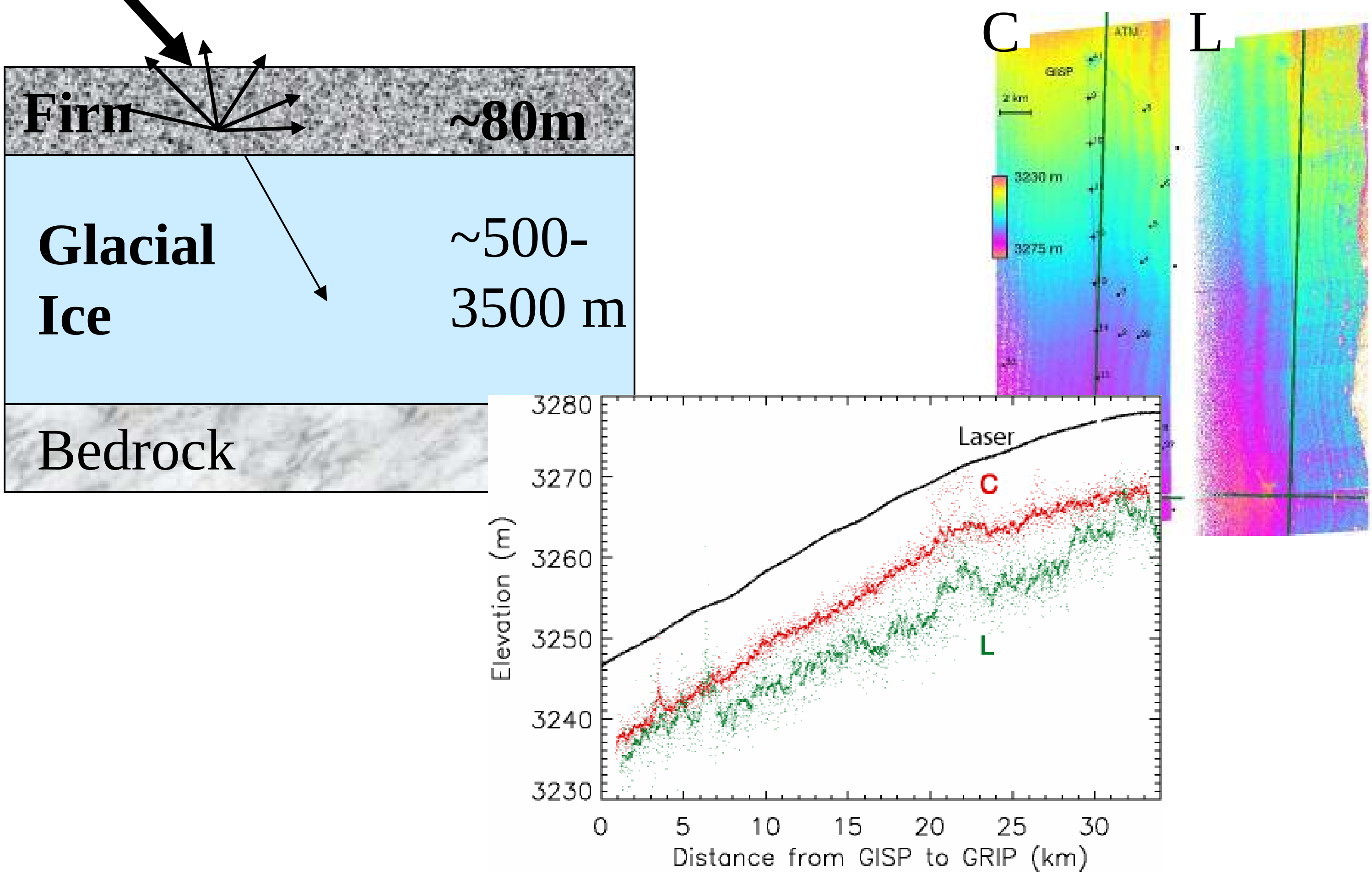




With or without InSAR, earth scientists require radar observations from space

It's only a matter of time…

L vs. C-band Penetration



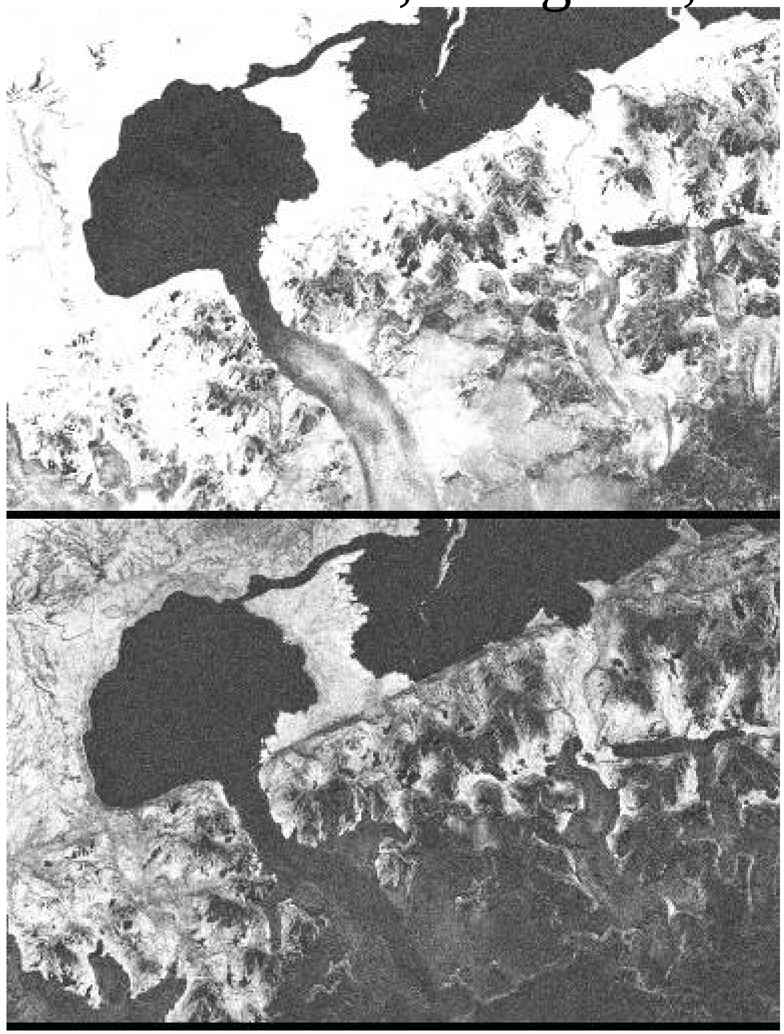
- ➢Slightly increased penetration at L-band not a significant factor in performance

SIR-C L- vs. C-Band Correlation

San Rafael Glacier, Patagonia, Chile

L-Band

C-Band



Rignot, et al., 1996

Issues Related to Phase Unwrapping

- The fringe rate determines whether phase can be unwrapped.
- The fringe rate for ECHO 8-day data will be equivalent to 2-day C-band data.
- Speckle tracking can be used in place of phase data where needed.

Nominal 8-day repeat

Fringe Rate

C-band	0	5	10	15	20	25
L-band	0	20	40	60	80	100