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The Future of Scientific Computing for InSAR Geodetic Imaging

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Outline

- Background – geodetic imaging measurements
- Geodetic imaging science, present and future
- Anticipated missions and data sets
- Implications for computational infrastructure and capabilities

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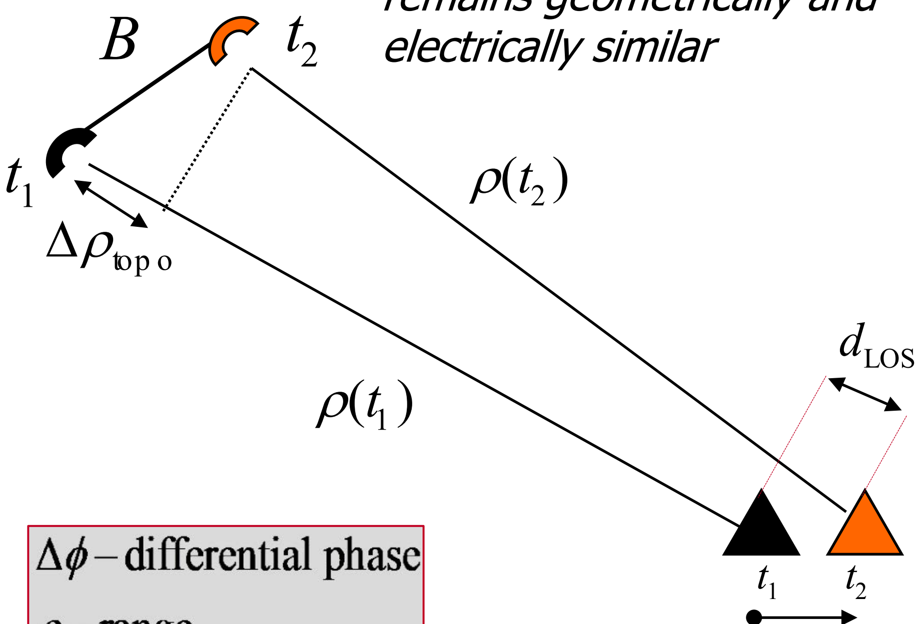
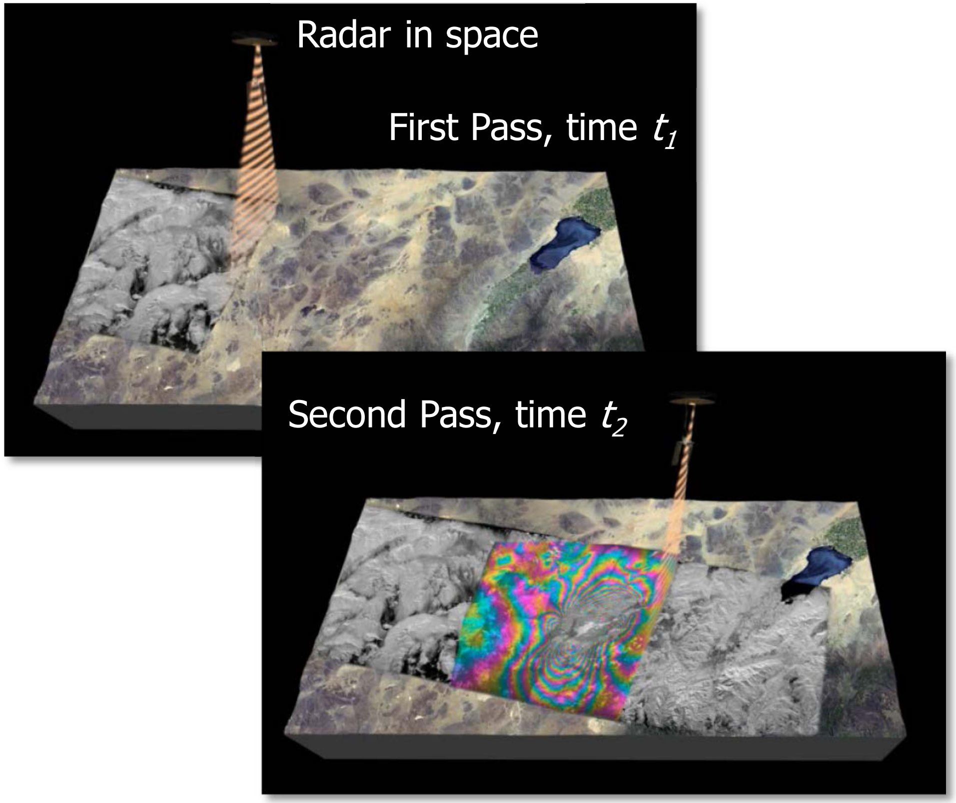
Differential Interferometry for Change

Two observations are made from different locations in space and at different times, so the interfero-metric phase is proportional to topography and topographic change.

Assumes surface element remains geometrically and electrically similar





$\Delta\phi$ – differential phase
ρ – range
λ – wavelength
B – baseline
t – time

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}(d_{LOS} - \Delta\rho_{topo}) + \text{noise}$$

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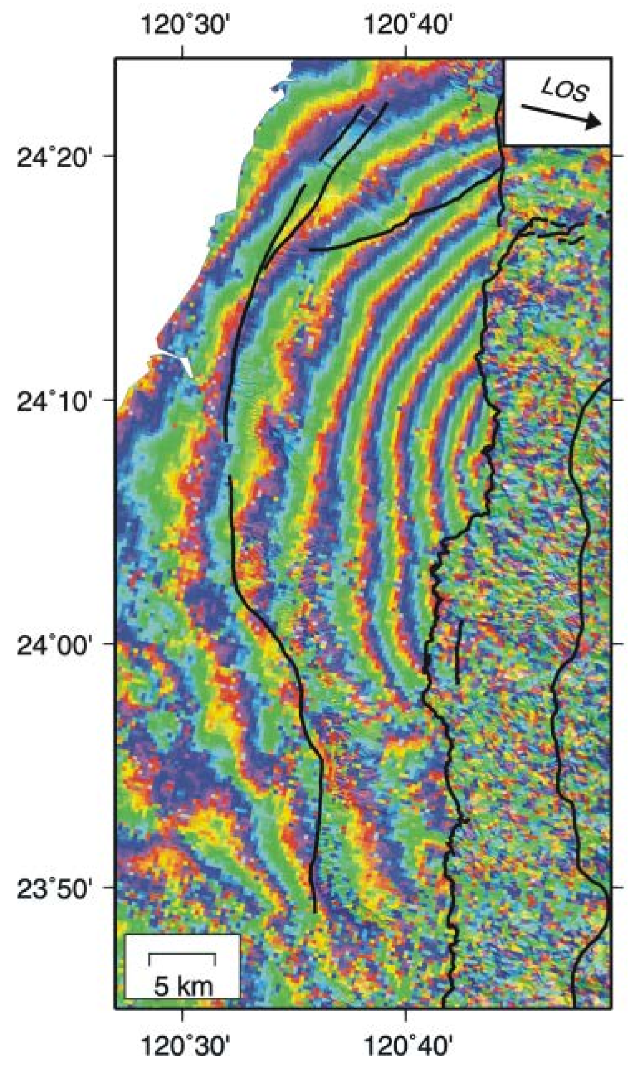
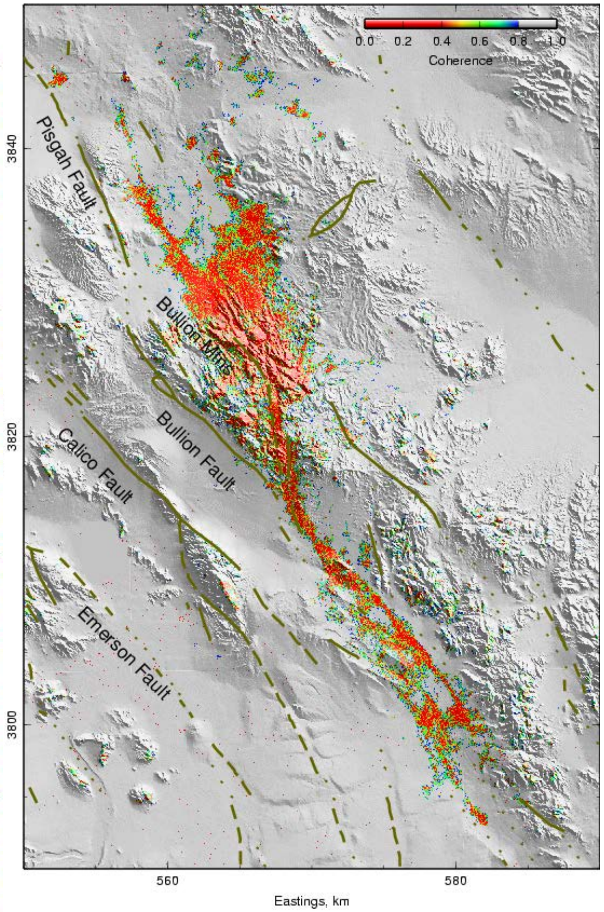
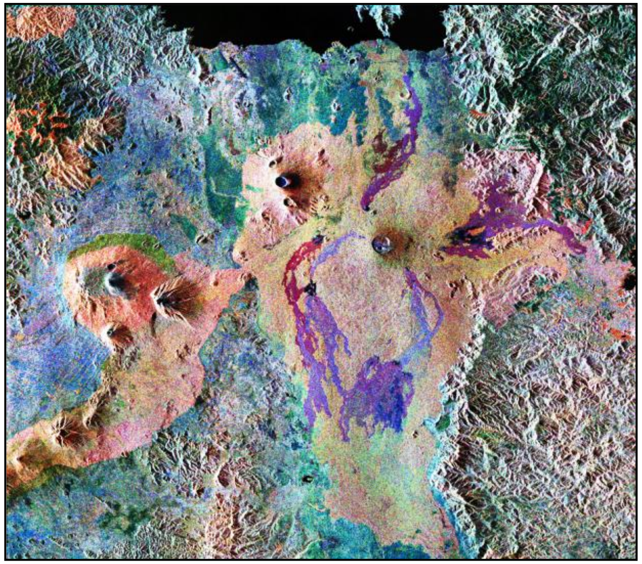
Basic Geodetic & Imaging Products



Interferogram (Taiwan)



Correlation (California)
Simons & Rosen (2007)



Polarimetry (Africa)

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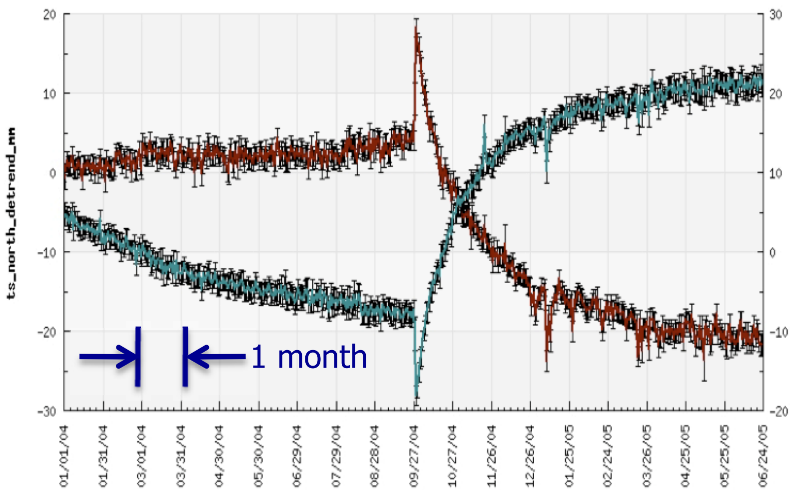
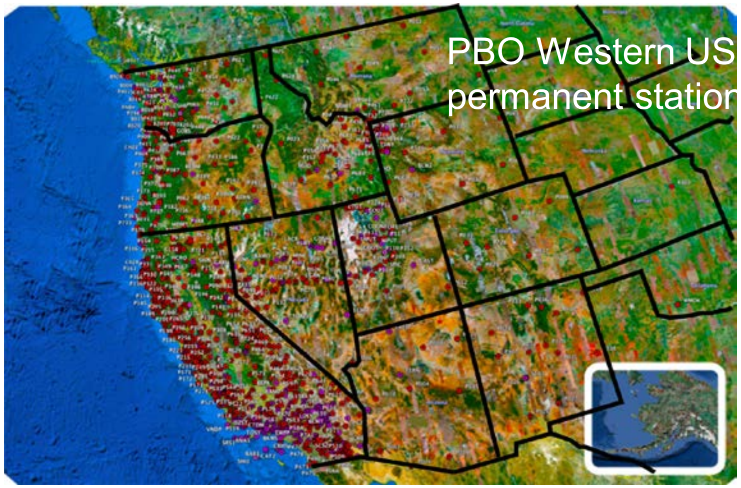
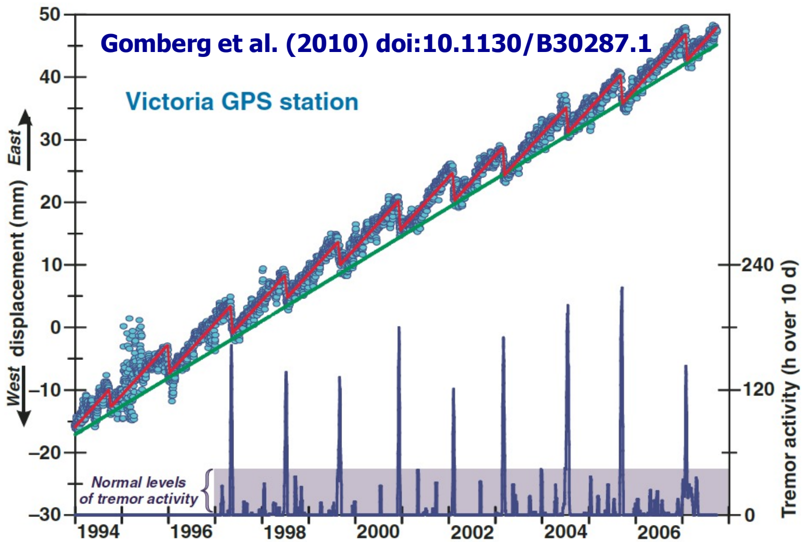
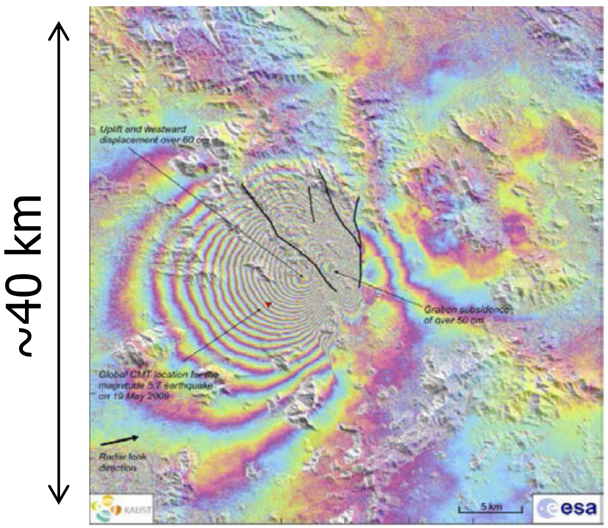
Dense Sampling in Space and Time to Understand Earthquake Mechanisms

Parkfield CARH GPS Station









Millions of "GPS-like" points in each image frame.

Frequent temporal snapshots will reveal new processes and improve models

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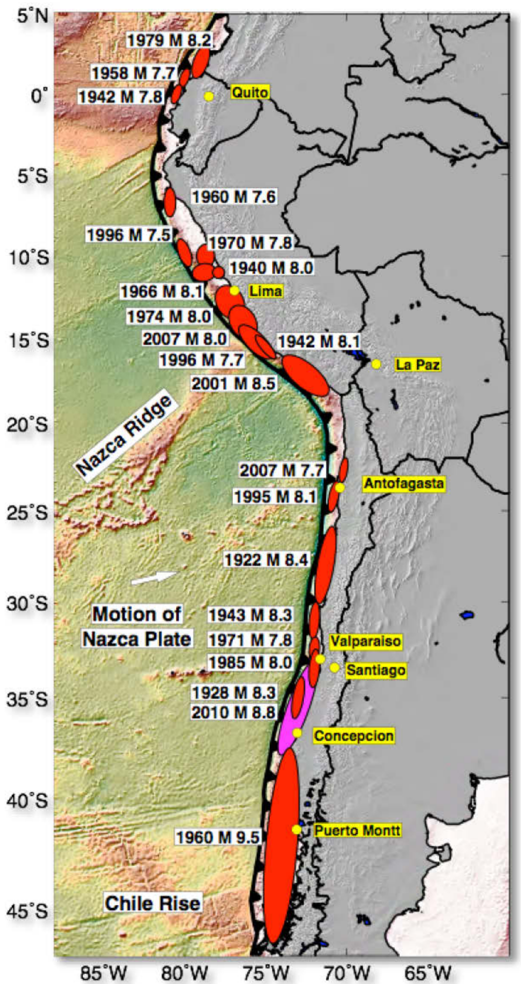
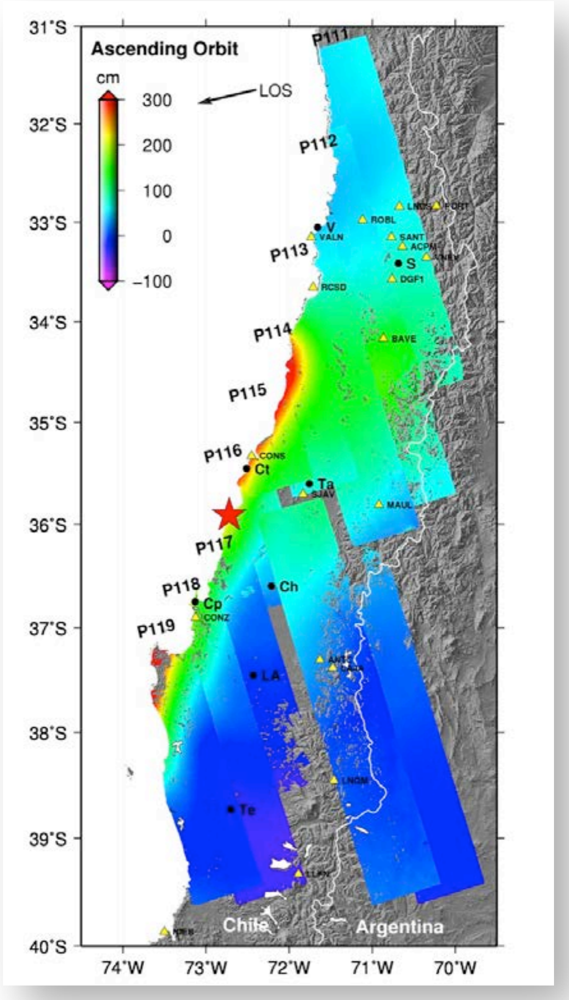
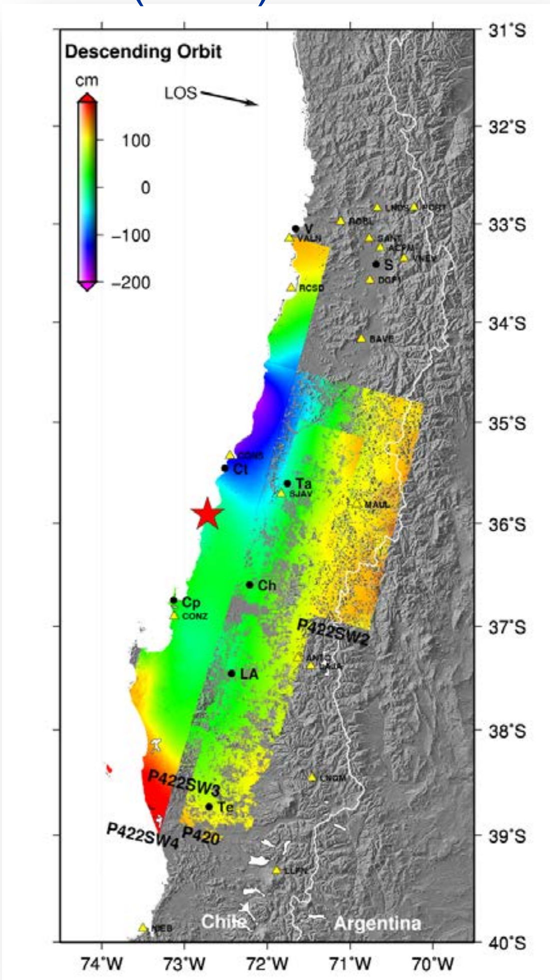
Spatial Synoptic coverage



2010 Mw 8.8 Maule (Chile)





Lin et al. (2012) Submitted to JGR

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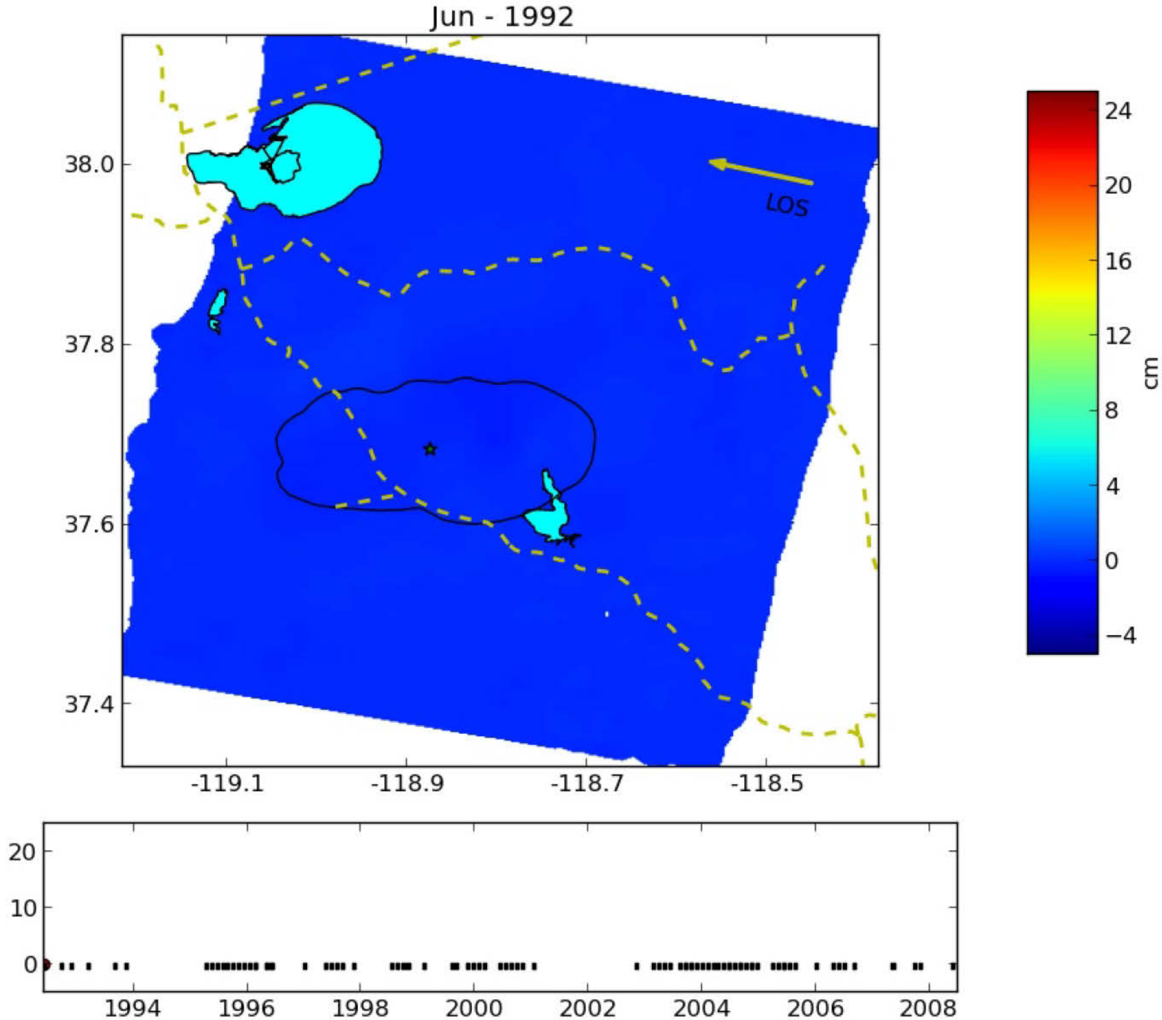
Long Valley Deformation Time Series

MInTS analysis, ECMWF-corrected



Agram, Jolivet, Simons et al (2012 in prep)

New methods for InSAR time series analysis give a new geophysical of Earth processes

Methods are becoming mature, sufficient to understand dynamics, provided:

1. Data are available
2. Data have suitable quality

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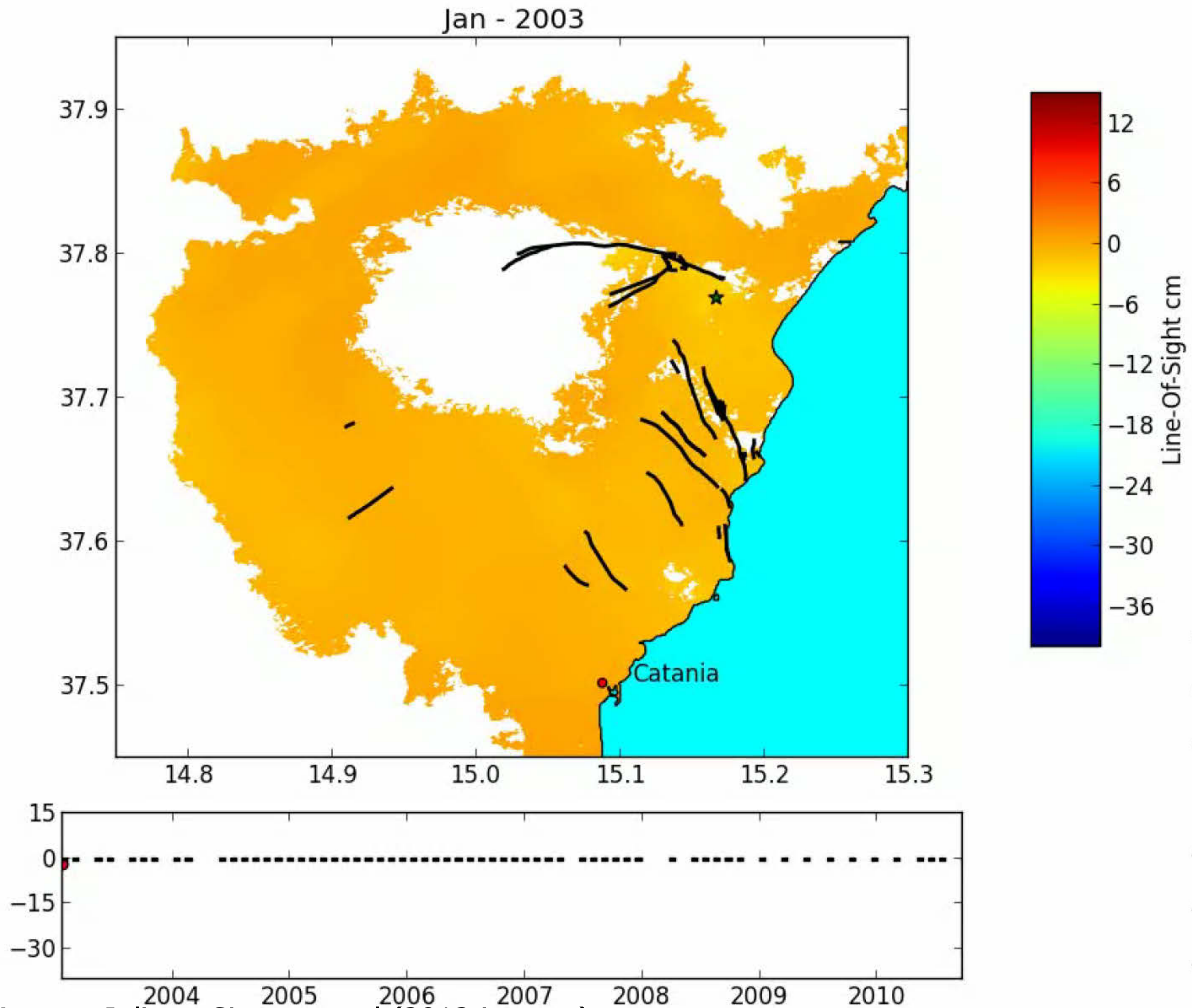
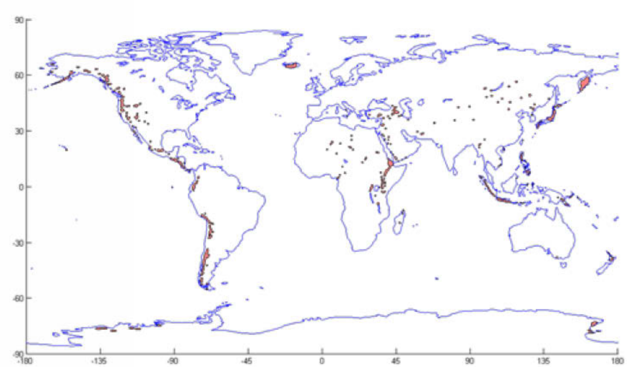
Etna Deformation Time Series

NSBAS analysis, ECMWF-corrected



Agram, Jolivet, Simons et al (2012 in prep)

With appropriate data, methods can be applied to under-standing eruption dynamics on global scale



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Hydrology with InSAR Time Series

Credits: InSAR analysis – Zhen Liu, Tom Farr (JPL); Visualization – Vince Realmuto (JPL)

http://photojournal.jpl.nasa.gov/catalog/PIA16293

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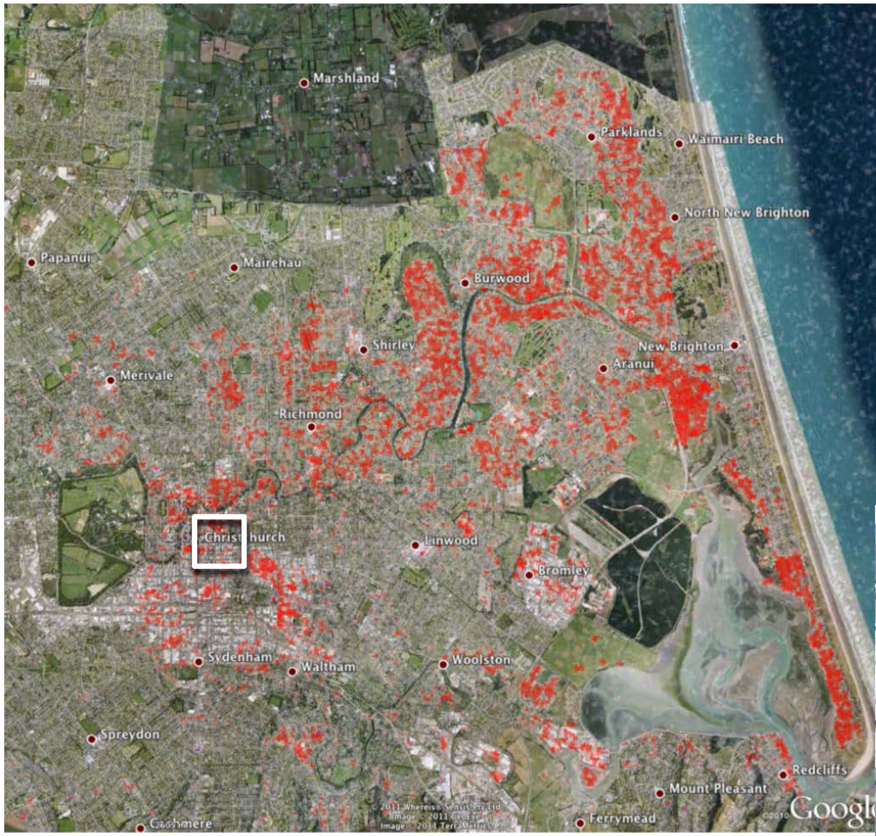
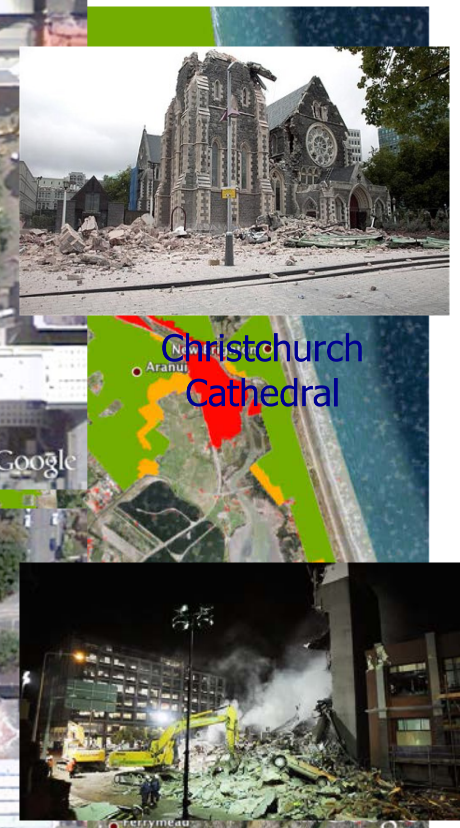
Assessing Devastation with Remote Sensing: Christchurch, NZ

In Hours to Days – Radar Remote Sensing



The Damage Proxy Map indicates significant centimeter scale change due to subsidence, inundation, or structure collapse allowing early assessment of the scale of damage. **[1]**

g Assessment

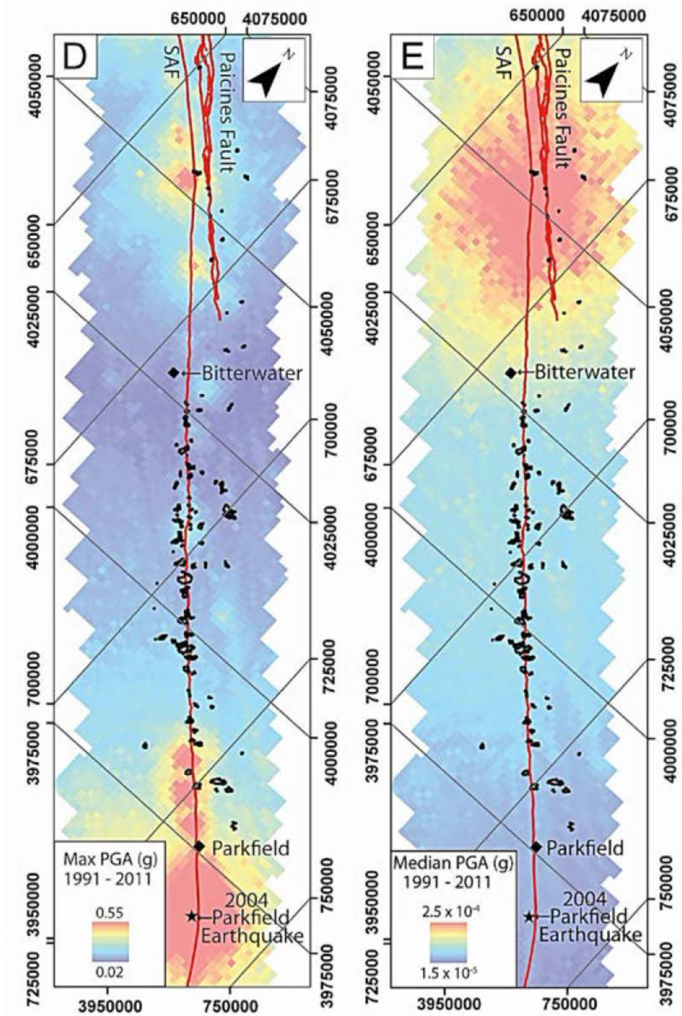


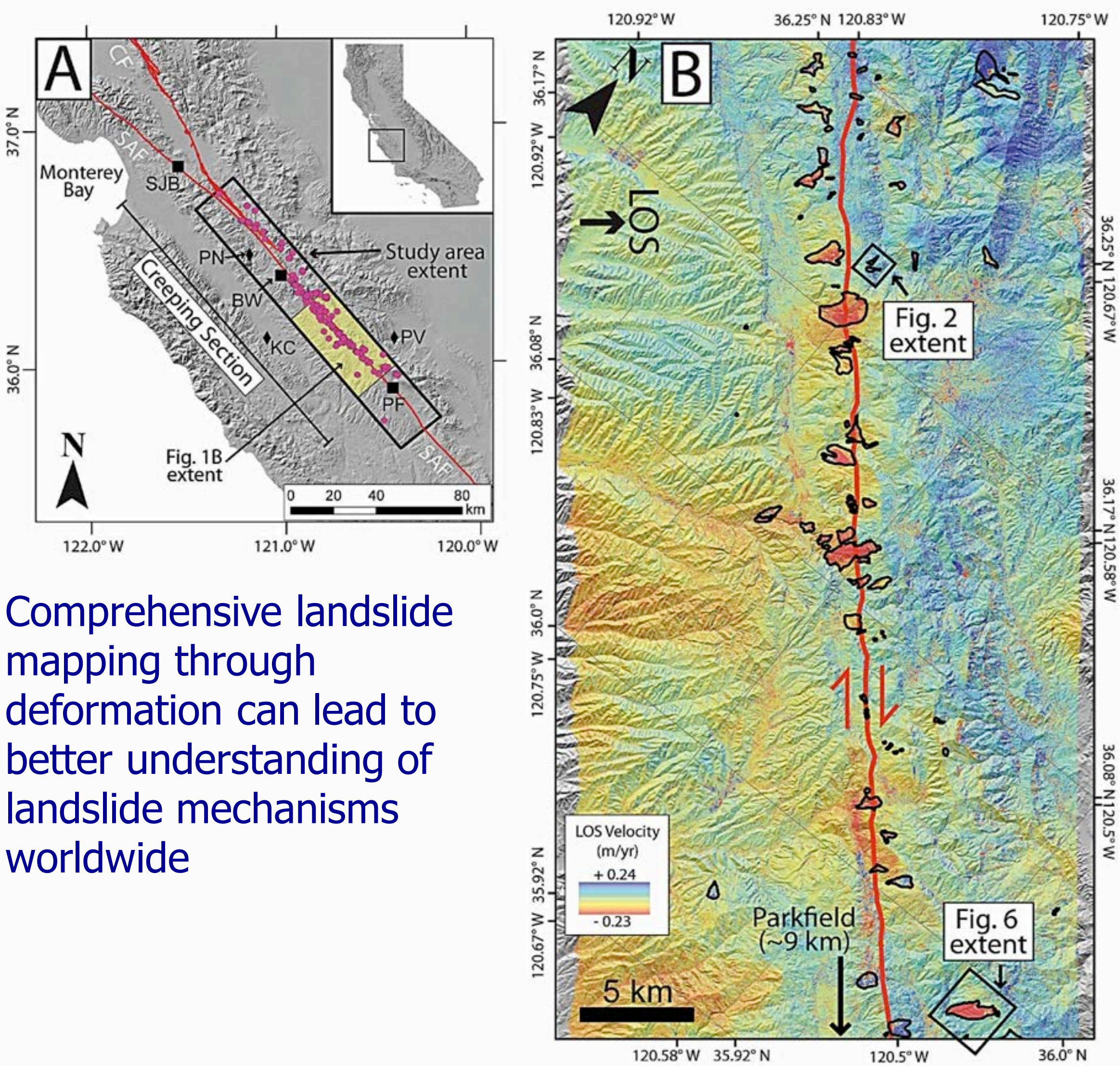
Christchurch Cathedral

Canterbury TV Building

and rebuilding will be
ny man-hours of effort
hey were built on. **[2]**

Landslide occurrences correlated to earthquake localities





Comprehensive landslide mapping through deformation can lead to better understanding of landslide mechanisms worldwide

Scheingross et al. (2012) Accepted to JGR

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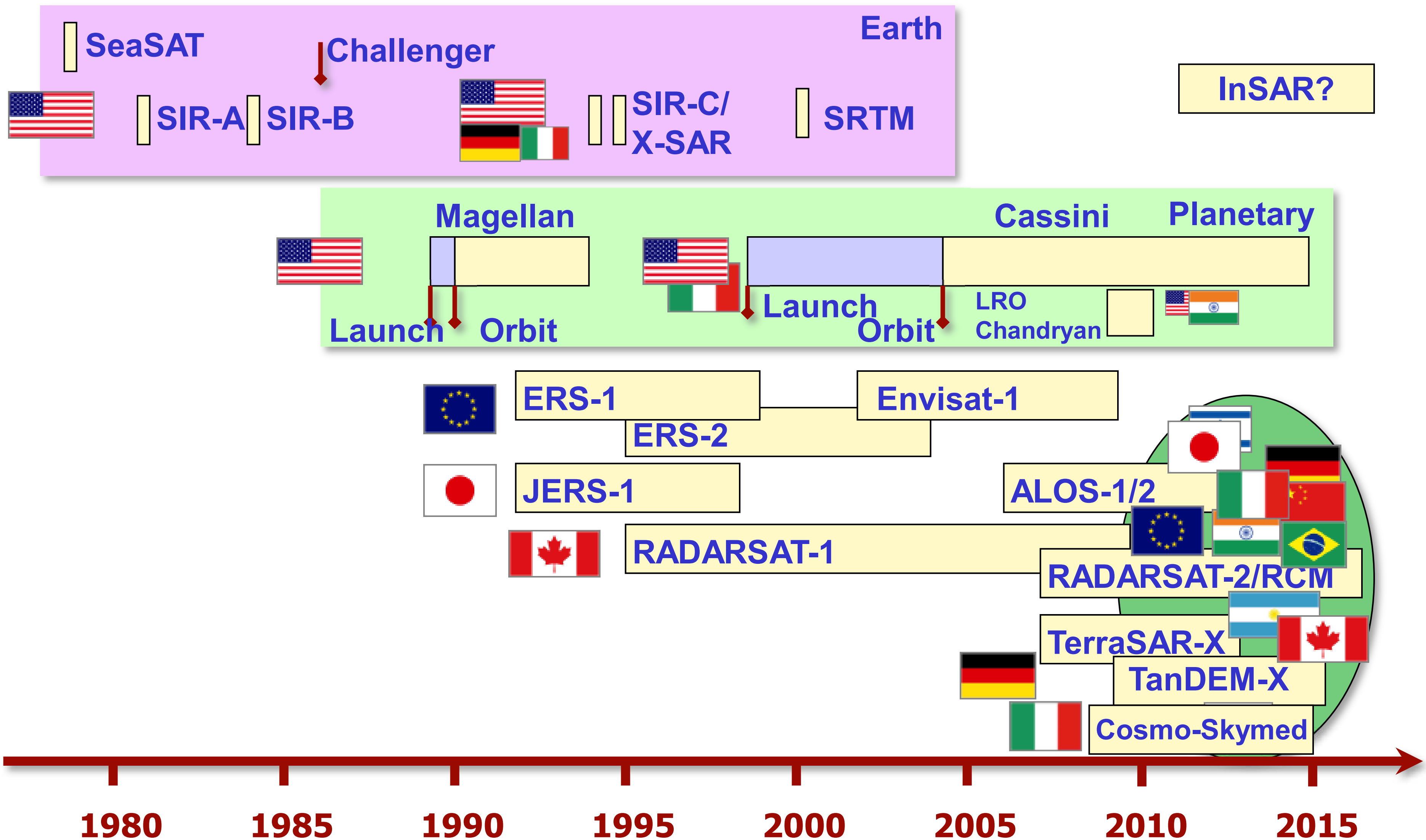
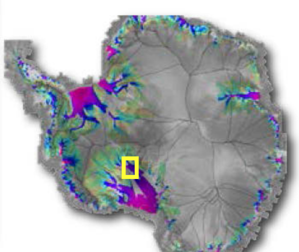
International SAR Missions "The Golden Age of SAR"



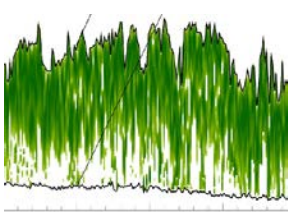
Decadal Survey: US L-band Mission Science

- Recommended by the NRC Decadal Survey for near-term launch to address important scientific questions of high societal impact:
  - *What drives the changes in ice masses and how does it relate to the climate?*
  - *How are Earth's carbon cycle and ecosystems changing, and what are the consequences?*
  - *How do we manage the changing landscape caused by the massive release of energy of earthquakes and volcanoes?*
- Planned by NASA as one of the following 4 Decadal Survey TIER 1 Missions
  - *SMAP*
  - *ICESat-II*
  - *DESDynI*
  - *CLARREO*

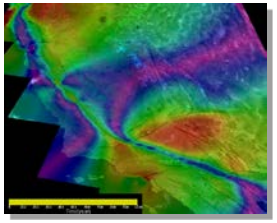
- **Ice sheets and sea level**
  - *Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctic and, if so, how rapidly will this occur?*
  - *What will be the time patterns of sea level rise as a result?*
- **Changes in ecosystem structure and biomass**
  - *How does climate change affect the carbon cycle?*
  - *How does land use affect the carbon cycle and biodiversity?*
  - *What are the effects of disturbance on productivity, carbon, and other ecosystem functions and services?*
  - *What are the management opportunities for minimizing disruption in the carbon cycle?*
- **Extreme events, including earthquakes and volcanic eruptions**
  - *Are major fault systems nearing release of stress via strong earthquakes?*
  - *Can we predict the future eruptions of volcanoes?*



Ice Dynamics



Biomass



Deformation

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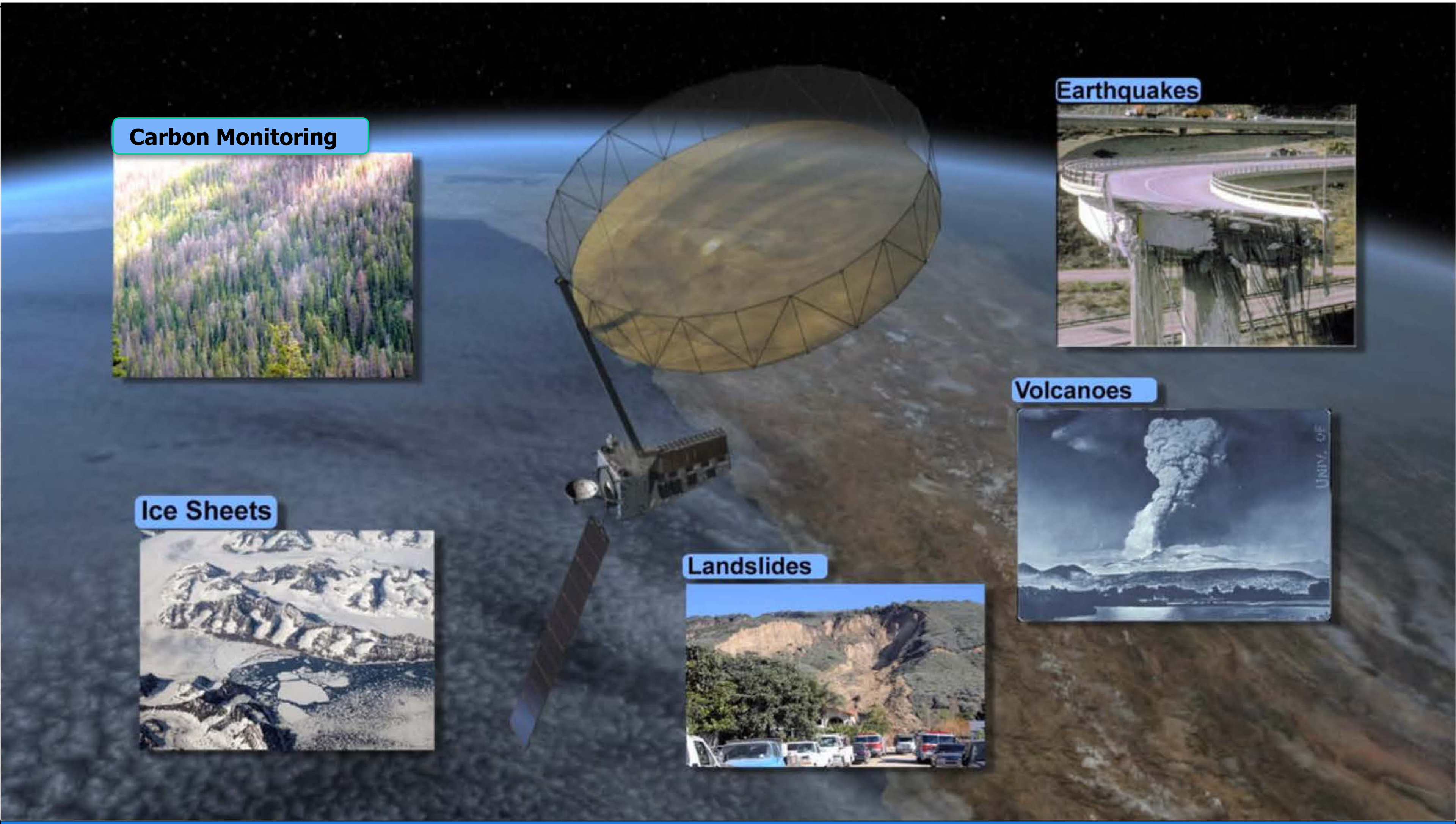
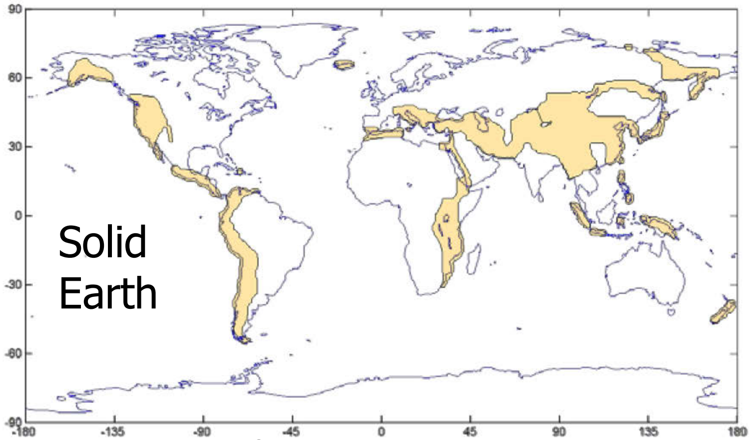
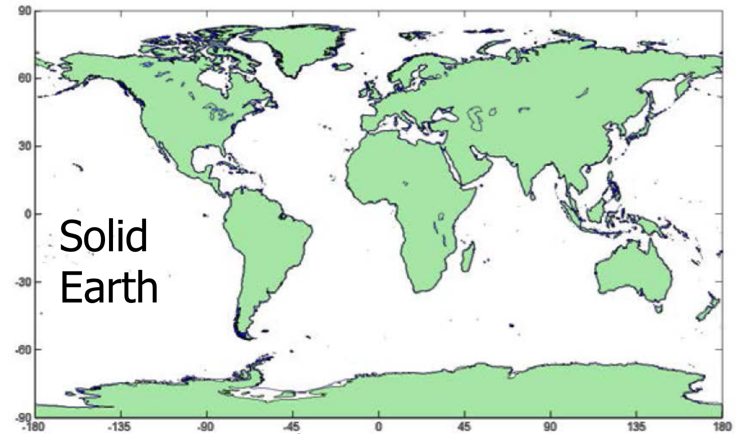
Science Requires Frequent Revisit, Global Coverage, Reliable Data



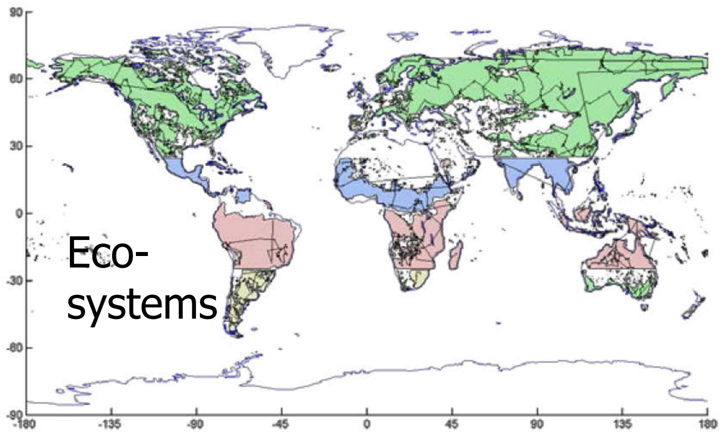
Coverage Area and Frequency



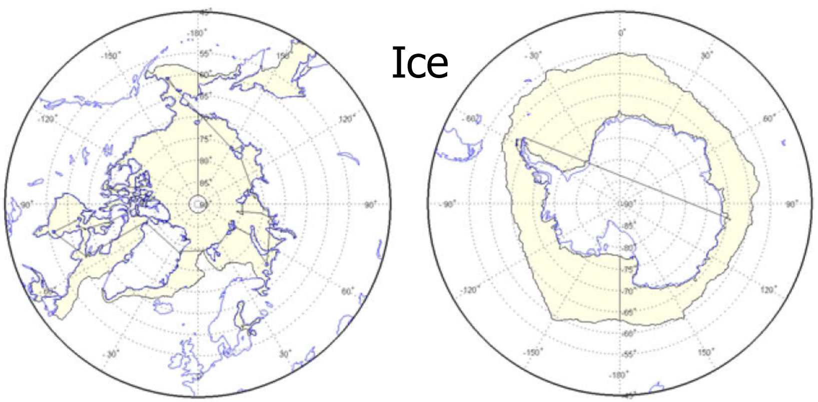
41,637,823 km^2; Every Cycle, A/D; Single-Pol



87,061,332 km^2; 2 per yr, A/D; Single-Pol



87,776,900 km^2; 1 per seas., Quad-Pol



34,839,285 km^2 ;5 per cycle; Single-Pol

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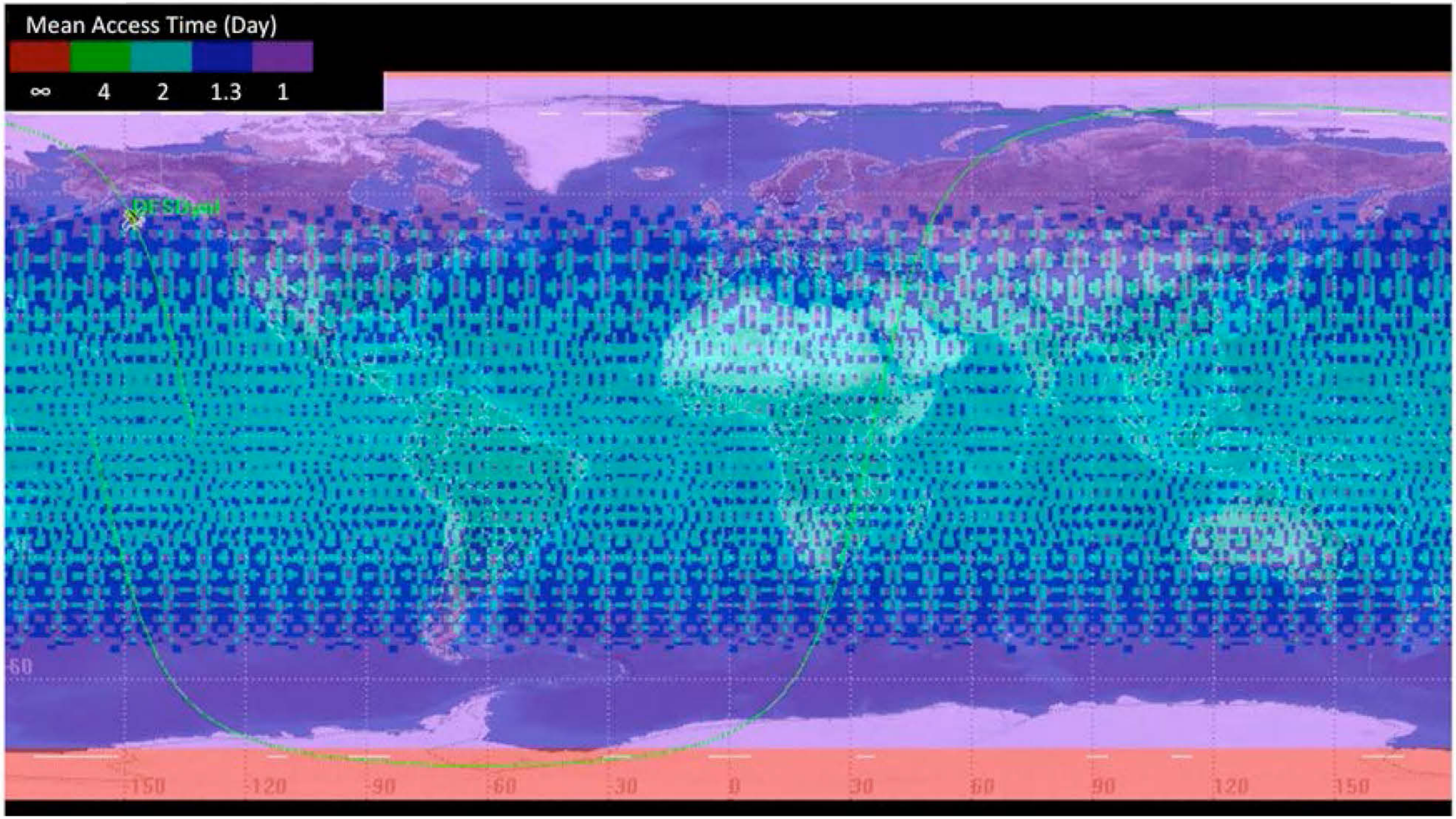
Average access latency to reimage any point on Earth with a single 8 day orbiting radar



The key is **free, open and low latency access** to raw data and the infrastructure to exploit it fully for societal and scientific benefit

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User Communities for SAR Data

Wide-range of needs and capabilities

- Individual Scientists and Modelers
  - Small areas, specific problems
- Science "Power Users"
  - Large scale problems (interseismic, global carbon, pan-icesheet)
- Operational Agencies
  - Ship tracking, water resource monitoring, frac-ing, oil-spills, levees
- Disaster/hazard response
  - Earthquakes, volcanoes, fires, floods, etc.

➢ Implies flexible and extensible algorithms and processing

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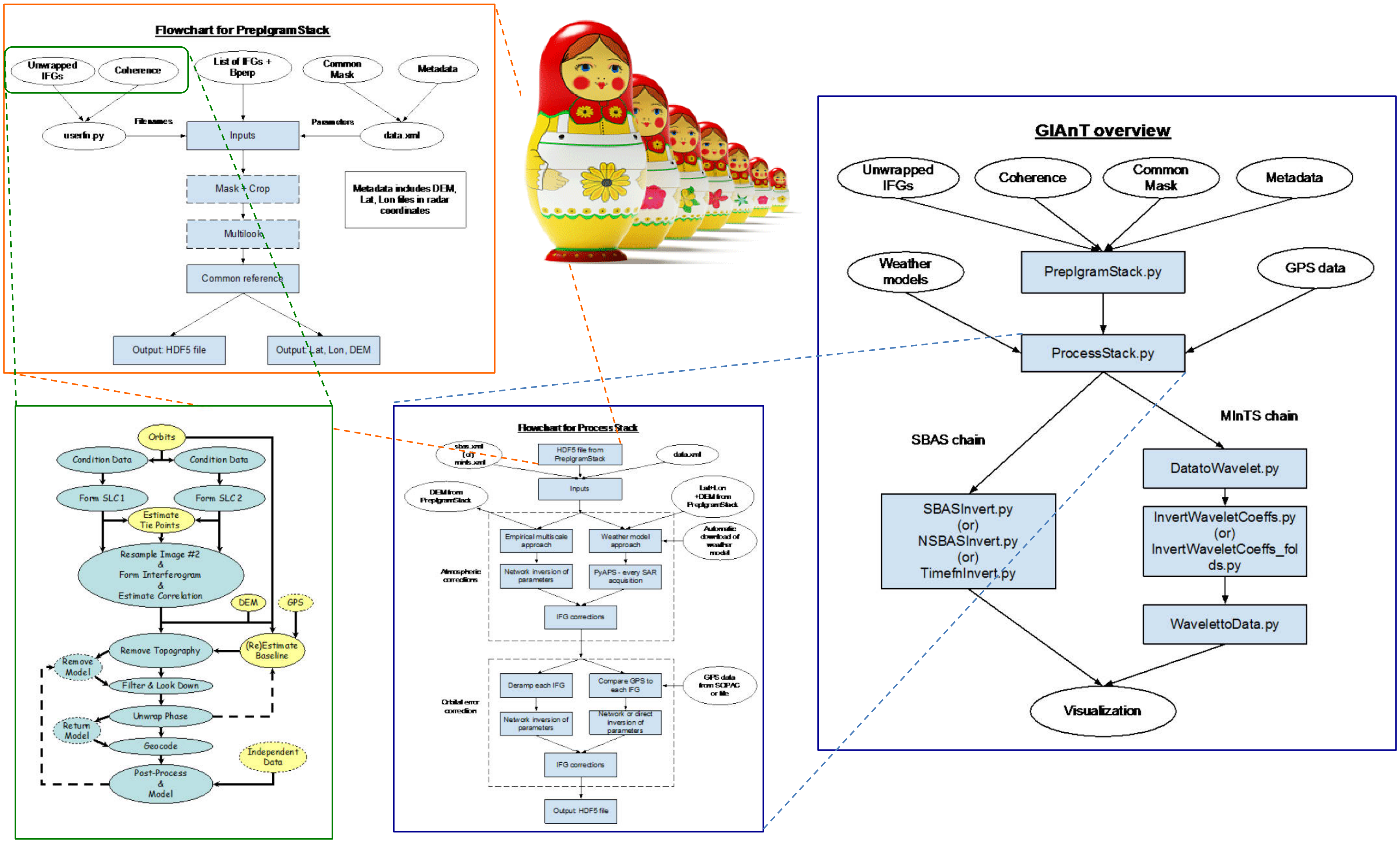
Computational Complexity



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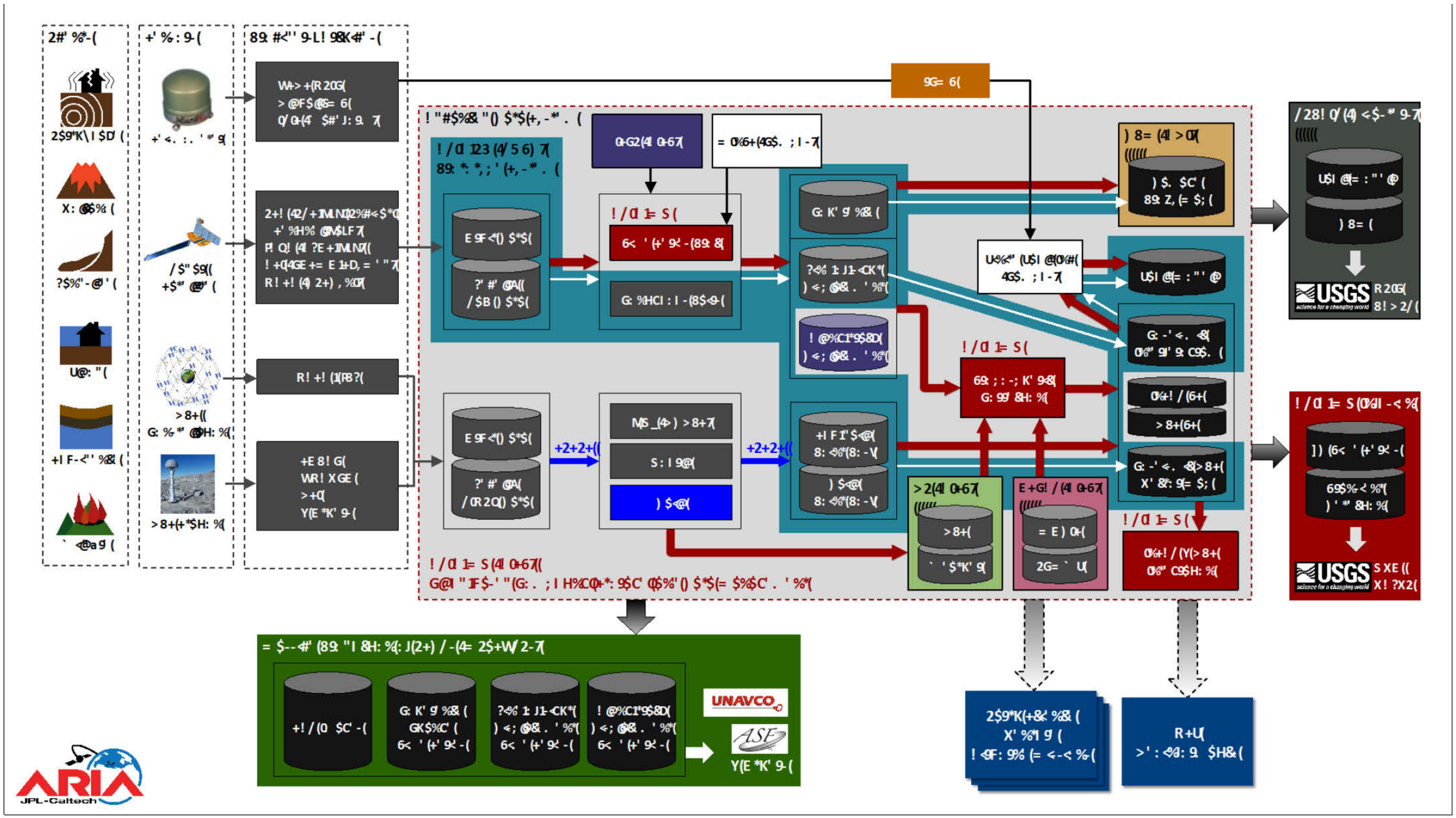
Automated Rapid Analysis Data System



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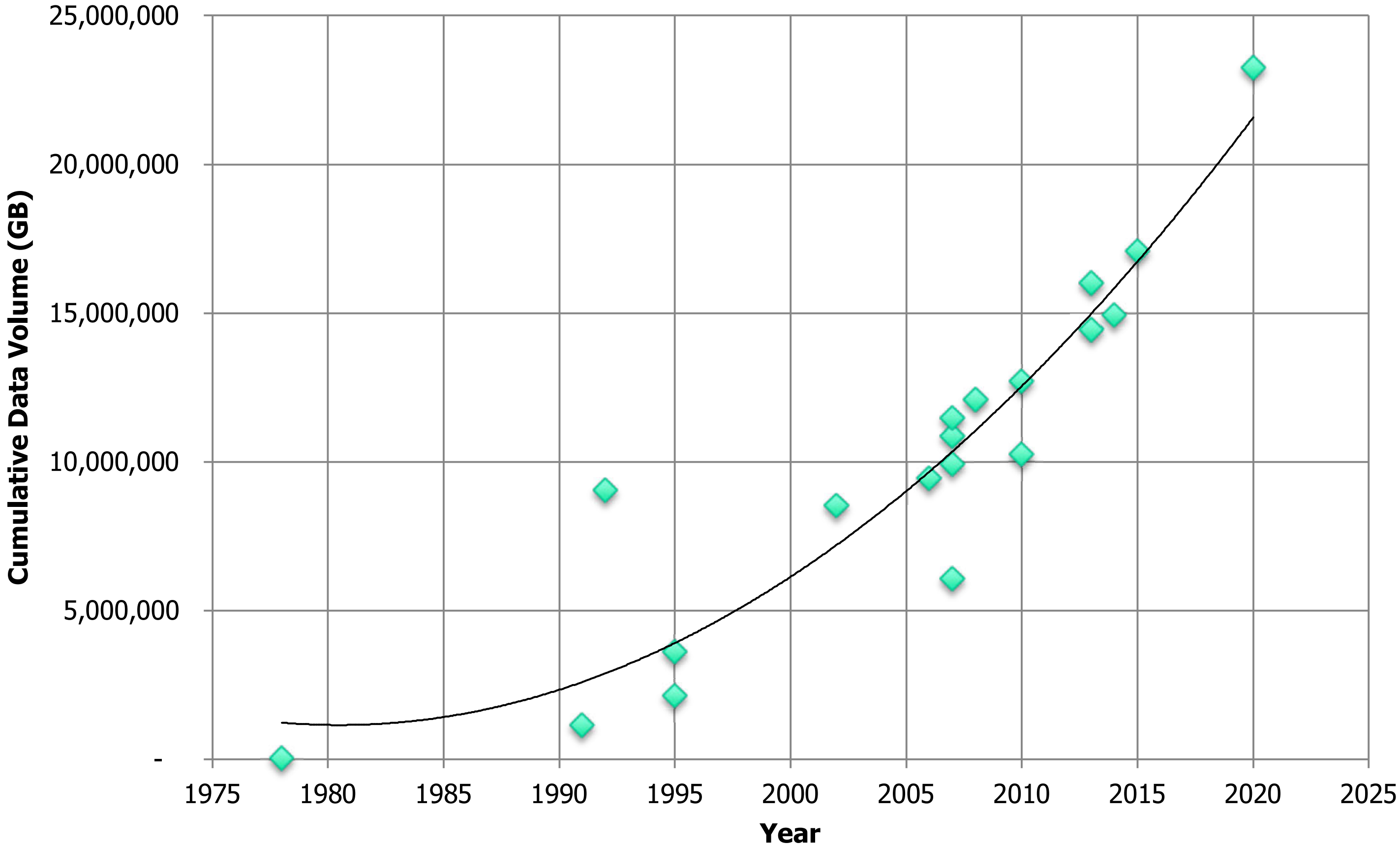
The Data Explosion

Gigabytes of International Civil SAR Data (cumulative)



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Sample Sizing for 350,000 ALOS scenes

Processing Steps	Processing hours per scene	Processing hours for 350K scenes	Number of Nodes[1]
Common Processing Steps	0.20	70,000	9
LOS Surface Displacement Maps[2]	1.33	466,667	62
AT Surface Displacement Map[3]	1.50	131,250	17
Atmospheric Correction	0.08	29,167	4
Surface Change Map[2]	0.08	17,500	2
LOS Surface Deformation Time Series	0.25	87,500	12
AT Surface Deformation Time series[2]	0.25	21,875	3
Surface Change Time Series	0.02	5,833	1
Total	3.68	829,792	110

Product	Temp Storage (per product)	Archived Volume
LOS Surface Deformation Maps	20 Gb	735 Tb
AT Surface Deformation Maps	20 Gb	735 Tb
Surface Change Maps	20 Gb	735 Tb
LOS Deformation Time Series	~35 – 480 Gb	110 Gb
AT Deformation Time Series	~35 – 480 Gb	110 Gb
Surface Change Time Series	~35 – 480 Gb	110 Gb

350,000 scenes =250 Tb

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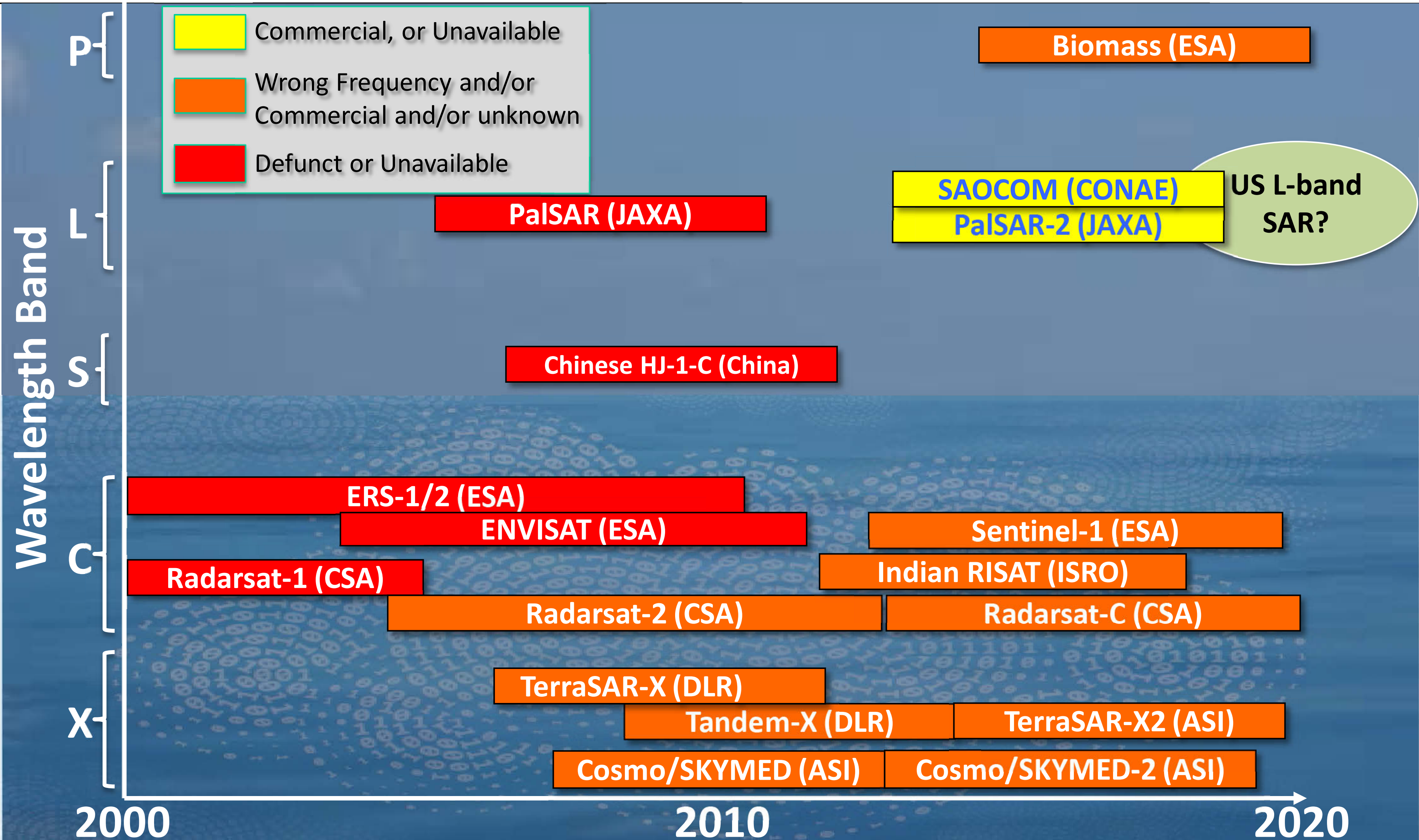
Added computational complexity: data isn't always optimal for our purposes



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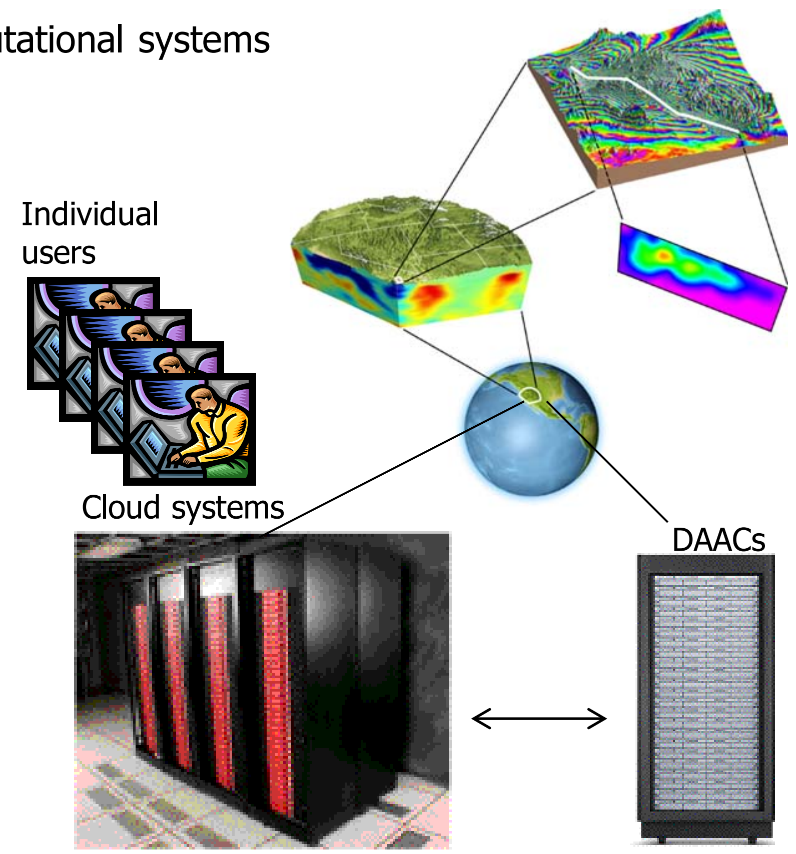
Software and Methods for Diverse Users

- Processing this sea of data will require modern methods
  - Computational architecture that can address complex data analysis/processing and interoperability of products, processing and models in a heterogeneous web-based environment
  - Seamless communication between users, data, and models in the field and elsewhere
  - Software scalable from single users to large computational systems

- The next generation tools being built have the following attributes:
  - Python-based, with consequent rich ready-made tool set
  - Object-oriented
  - Interoperable
  - Recipes for incorporating legacy code, even in FORTRAN

- Likely basis of US SAR mission production processor
- Being tested by other large scale projects



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The future

- A lot of data – many petabytes New homogeneous data sets suitable for global time series
  - Historical and new heterogenous datasets from legacy systems, small-sats, and other international sensors.
- Mature Algorithms for time-varying geodetic imaging and geophysical exploitation thereof
- Desireable future architecture features:
  - Loosely-coupled architecture to enable rapid assimilation of new technology advancements in different components as they develop
  - Elastic compute resources for processing on demand
  - Distributed data storage to facilitate low-latency data access across geographically dispersed compute nodes.
  - Interoperable metadata models and encoding formats that are infused into tools, data systems, and used across different communities.

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The future – cont'd

- More architectural features
  - Federated data discovery and access enabling scalable handling of "big data". InSAR data alone cannot be effectively handled by one data center.
  - Data product preservation and stewardship enabling product provenance, transparency, and reproducibility.
  - Visualization environments with sufficient network and processing bandwidth to enable innovation and discoveries not otherwise possible.

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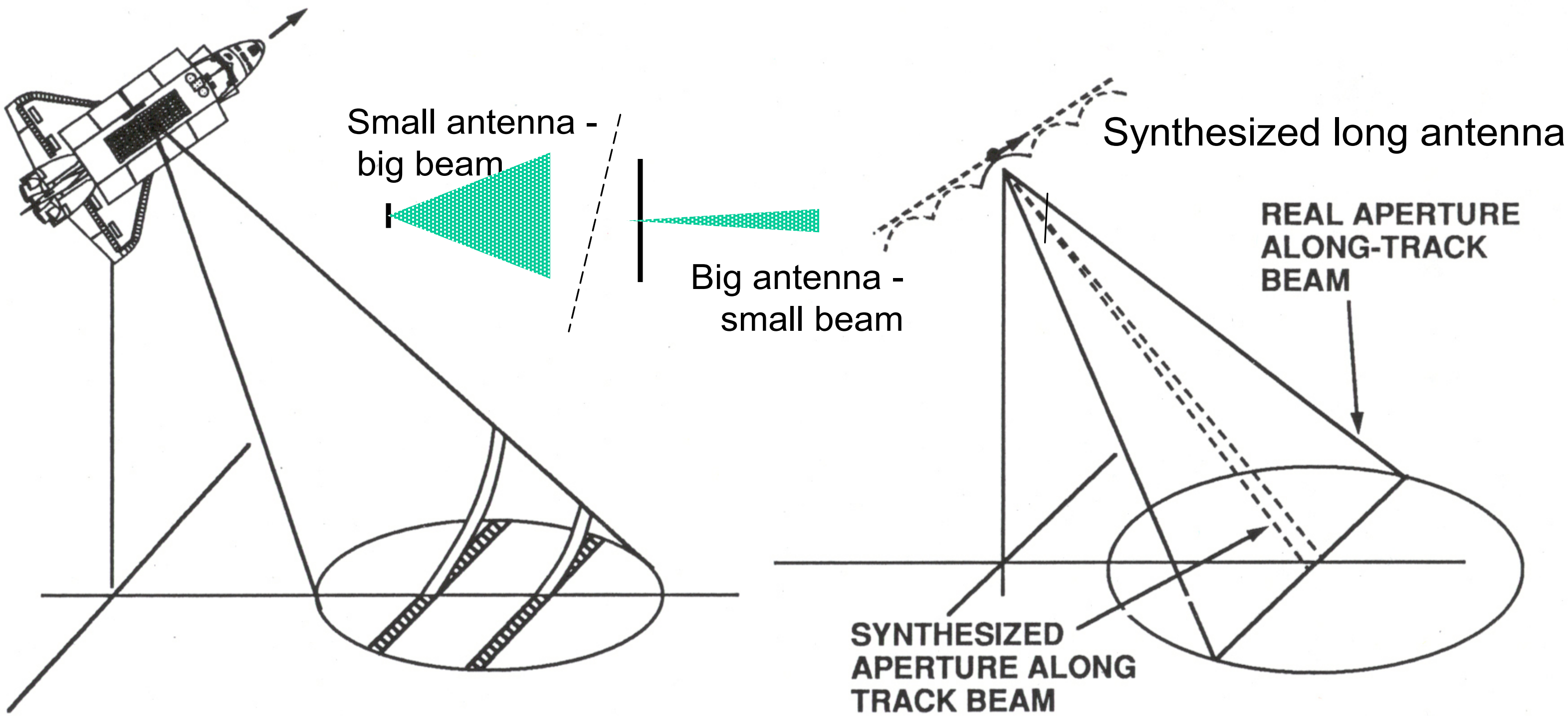
Synthetic Aperture Radar



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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Some Examples of Data Access Issues for US Investigators

- ALOS-2
  - L-band, 14-day repeat: good for US science objectives
  - Multi-mode, campaign mapping like ALOS-1 (as far as we know)
  - Some commercial pressure
- Radarsat-2
  - C-band, 24-day repeat: Limited science potential
  - Fully commercial - $3K per image – 1M images = $3B
  - Multi-mode
  - Pre-existing orders limit data-taking flexibility
- Cosmo-Skymed
  - X-band, 1- to 11-day repeat: often good for US science objectives
  - Multi-mode, dual-use limits data-taking flexibility
  - Undersized downlink capacity and distribution system (to date)

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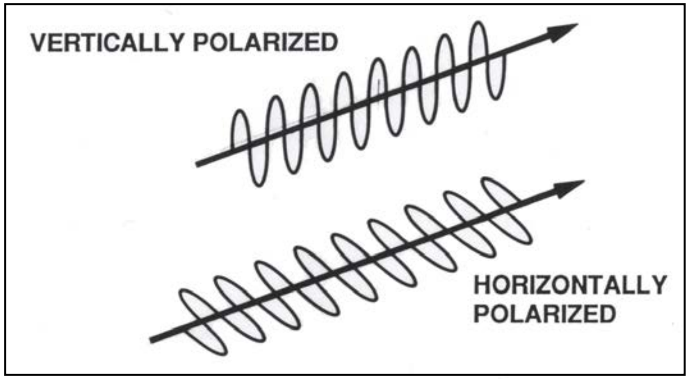
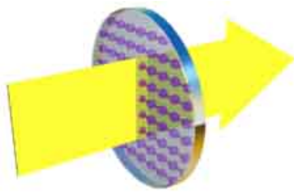
Polarization - A Measure of Surface Orientations and Properties

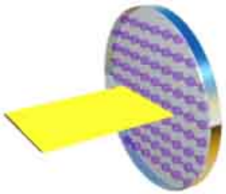
Wave Polarization



Polarization Filters

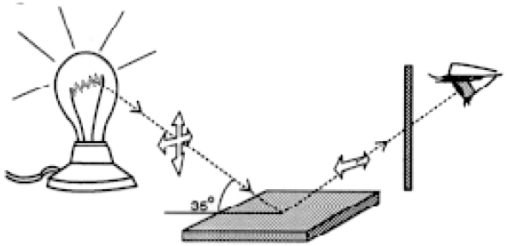


Vertical polarization passes through horizontally arranged absorbers.

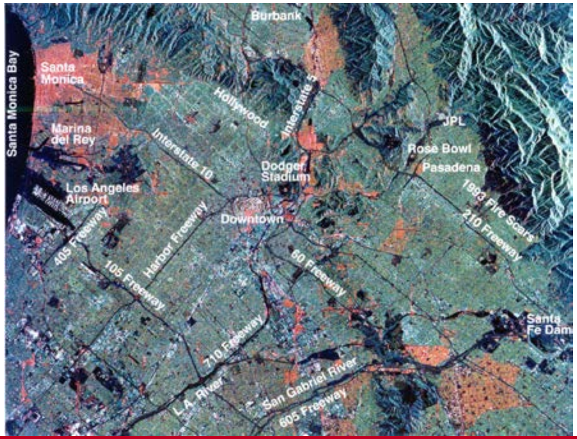


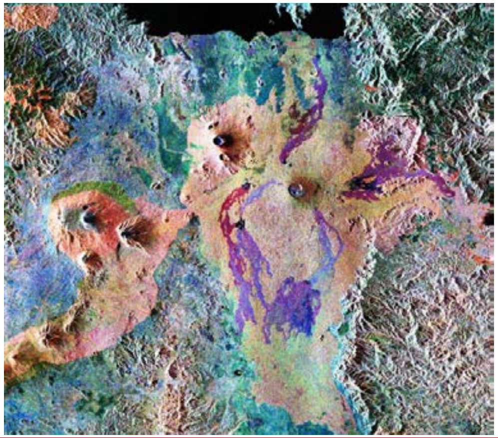
Horizontal polarization does not pass through horizontally arranged absorbers.

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



Mostly horizontal polarization is reflected from a flat surface.





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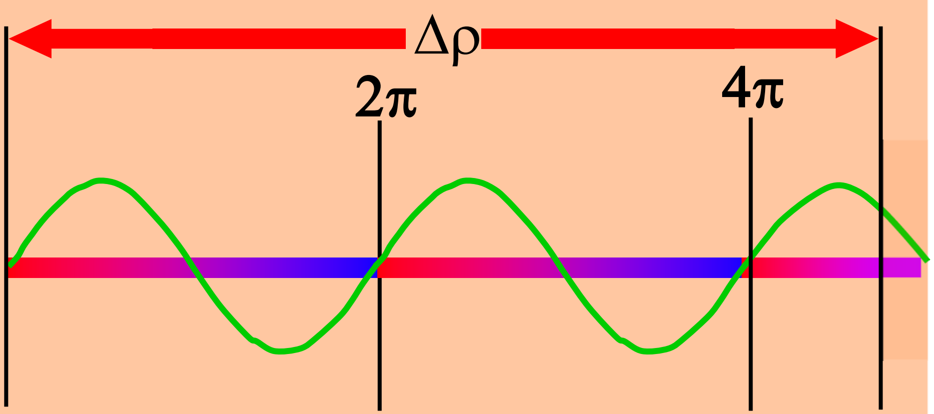
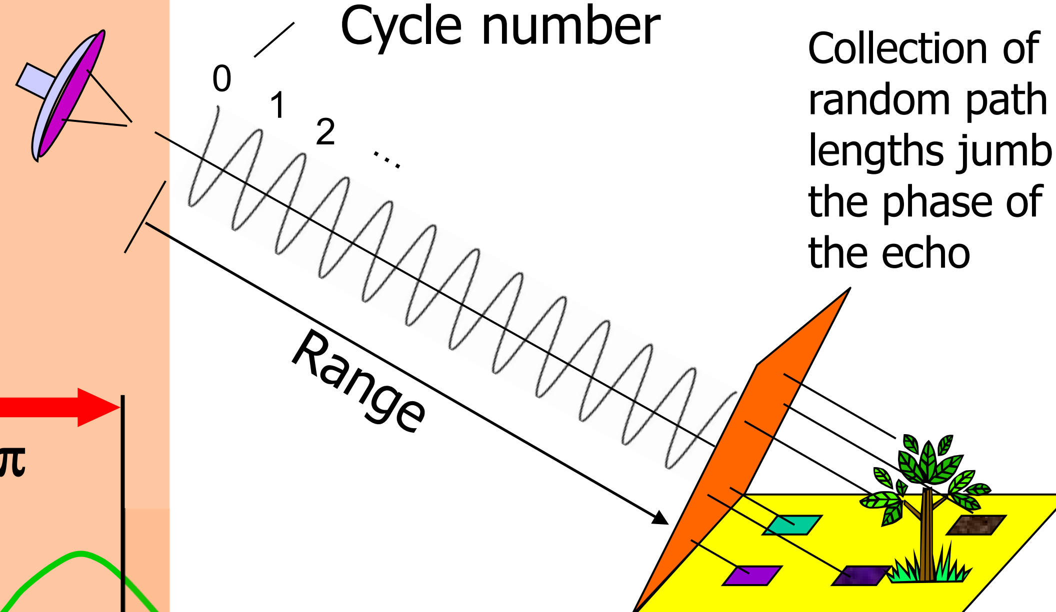
Phase and Radar Interferometry

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.



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



Collection of random path lengths jumbles the phase of the echo

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

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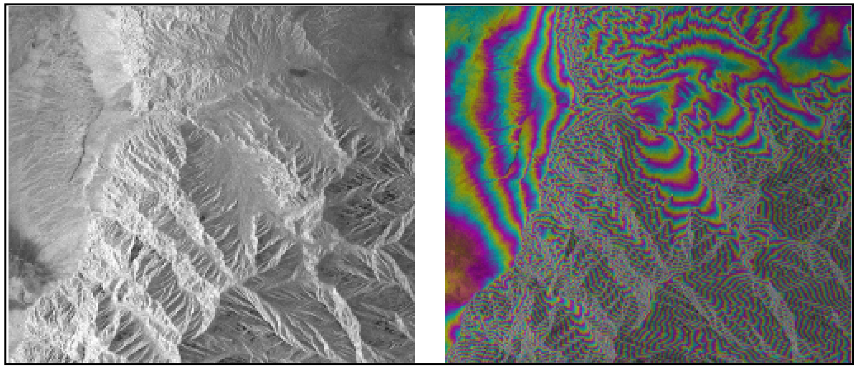
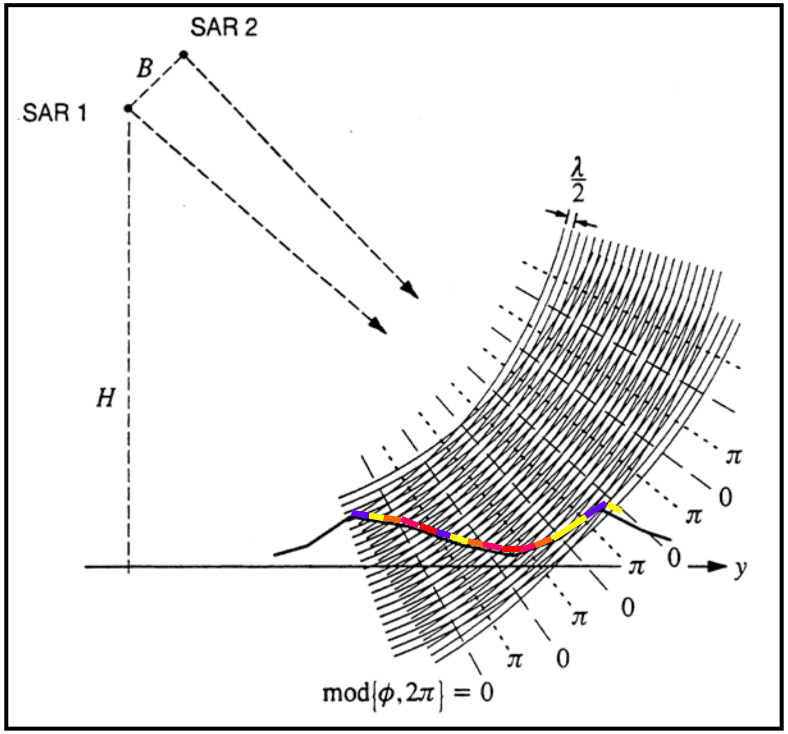
Radar Interferometry for Topography

- The two radar (SAR) antennas act as coherent 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

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(s_1) - \rho(s_2)) = \frac{4\pi}{\lambda}\Delta\rho_{\text{topo}} + \text{noise}$$





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Radar Design to Meet Critical Requirements

Repeat Period requirement for Deformation science drives the Radar Swath

12M-day Repeat Period => 240/M-km Swath Width

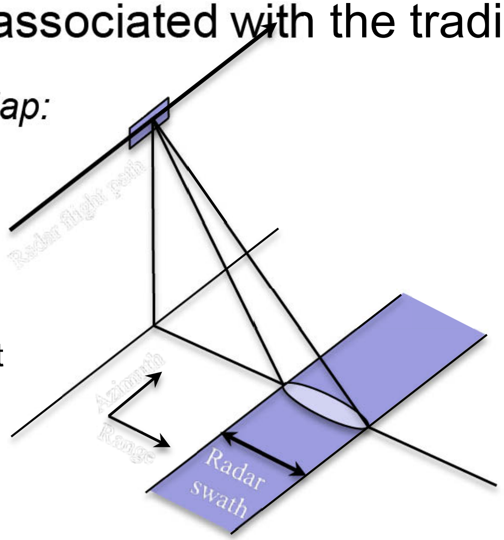
Sensitivity requirement for Biomass (cross-pol) measurement drives Antenna Size and Radar Power

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

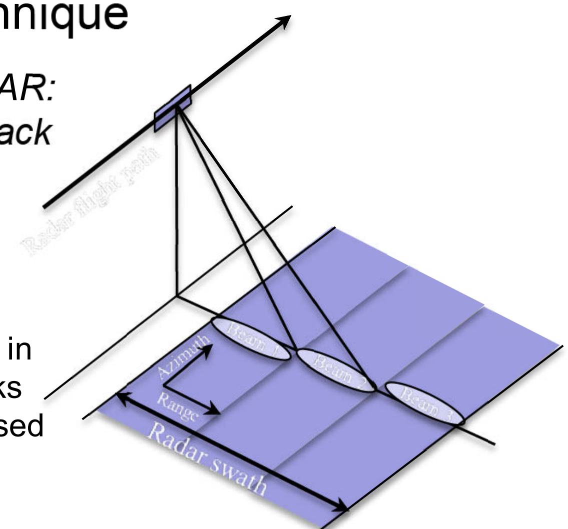
Conventional StripMap:
<~70km Swath

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

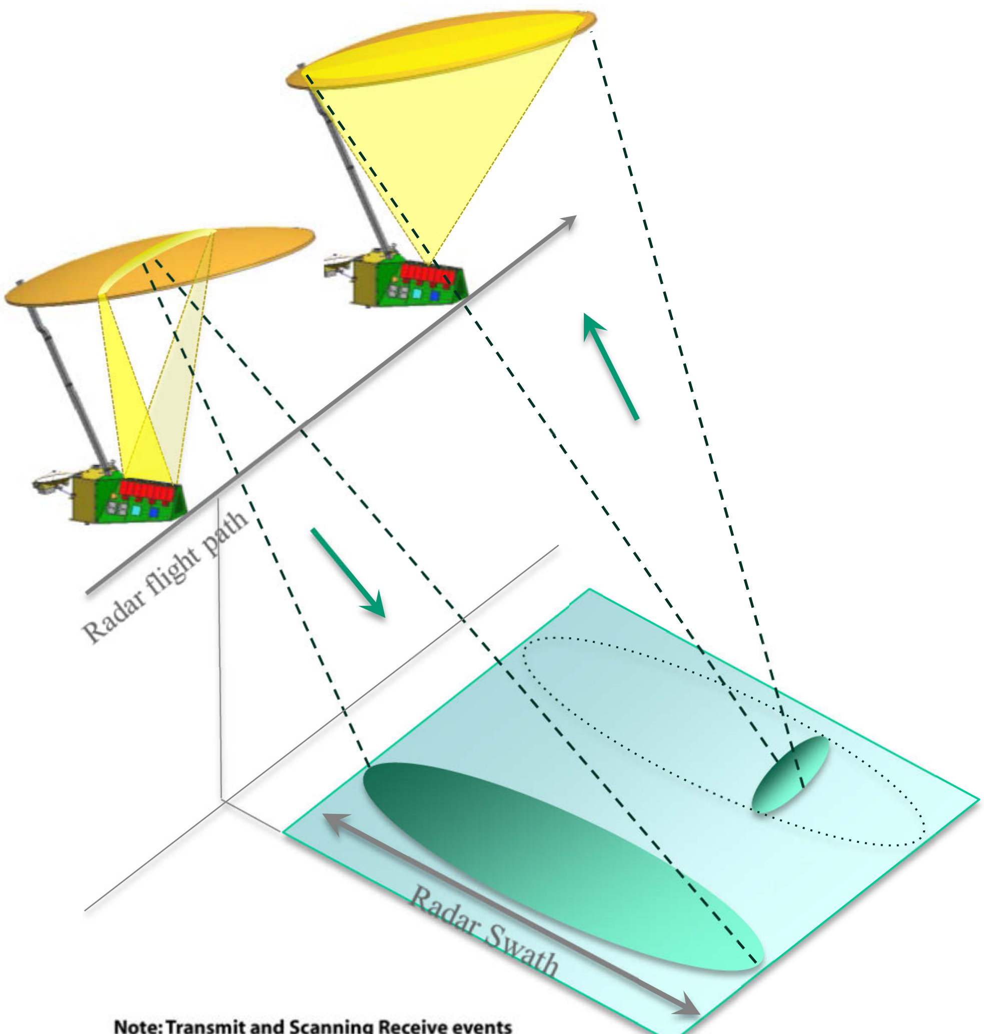
Uses large reflector to provide high aperture gain

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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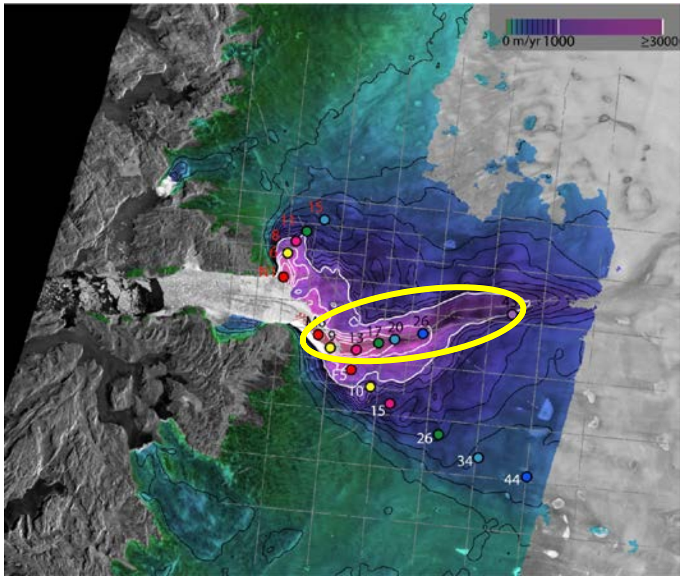
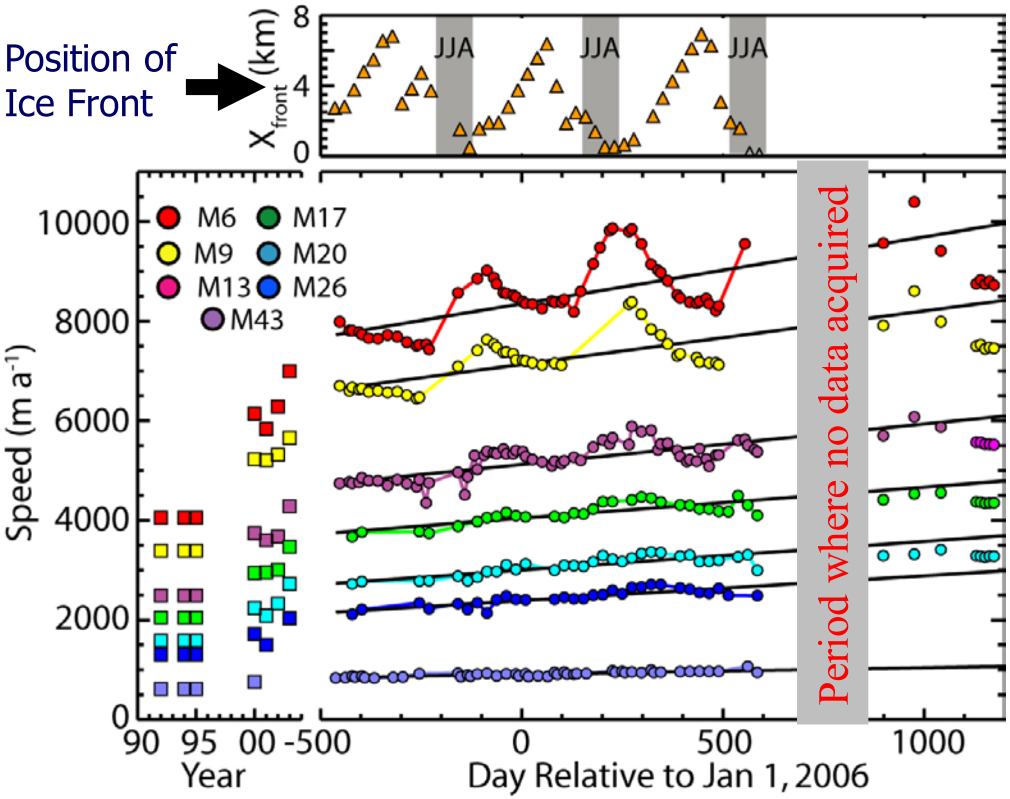
Jakobshavn Isbrae
Highly Variable in Time and Space



Jakobshavn Isbrae is one of the few glaciers where frequent InSAR observations are available.

Position of Ice Front



Despite spare spatial and sporadic temporal sampling, existing SAR data reveal large variations in glacier flow.

Science requires fine temporal sampling of all rapidly evolving outlet glaciers and ice streams.

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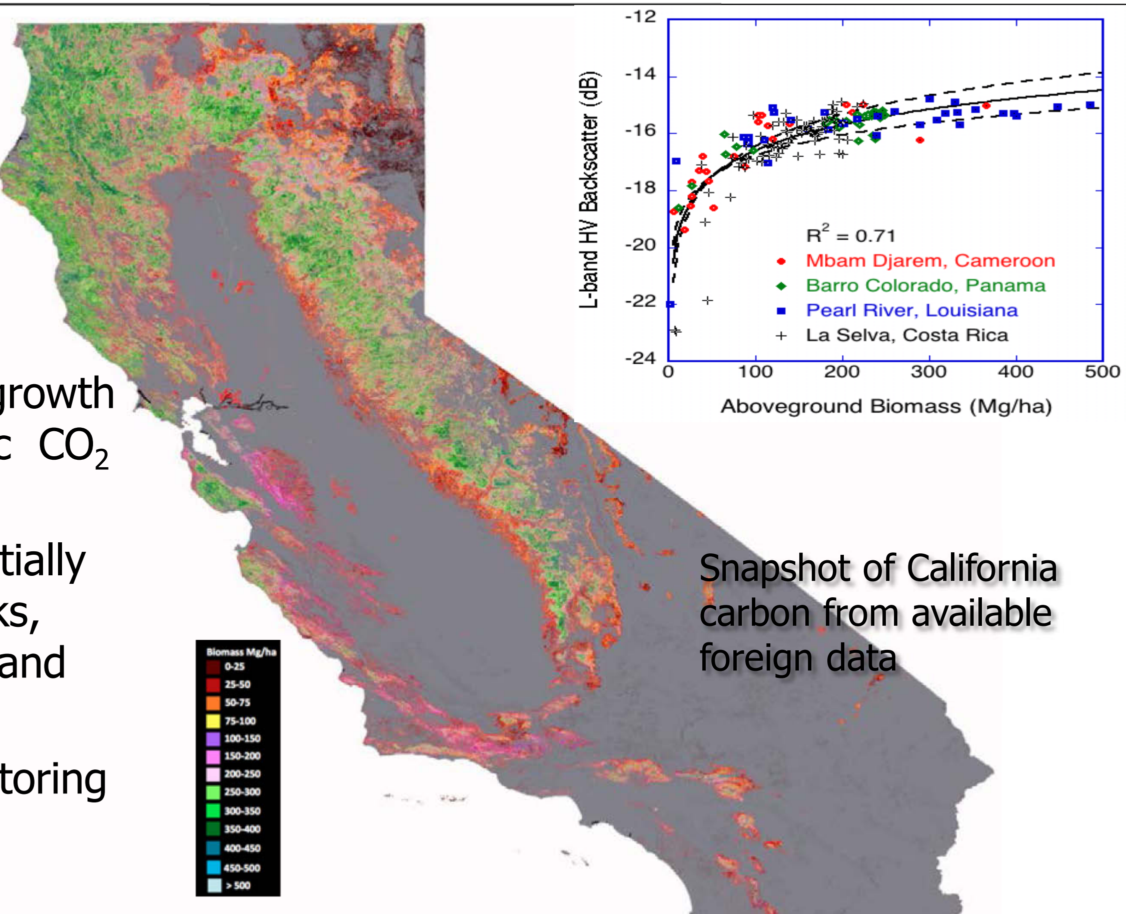
Global Carbon Monitoring

- Global mapping of carbon and biomass dynamics at high spatial resolution and high accuracy
  - Determines carbon stored in vegetation and the net effect of changes from fires and other disturbances and subsequent regrowth on concentrations of atmospheric CO_2
  - *Supports climate treaty implementation* by providing spatially explicit estimates of carbon stocks, accumulation in growing forests and losses to existing stocks
  - Essential to reliable Carbon Monitoring System



Snapshot of California carbon from available foreign data

- A US mission would then enable global carbon modeling at spatial scales commensurate with disturbances and environmental gradients
  - Critical for initializing models that evaluate policy actions by predicting future land/atmosphere carbon dynamics

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How Much Data is Enough Data?

It depends on perspective:

- Science
  - Problem of interest (Time and spatial scales, required accuracy, etc.)
  - Region of Interest (Vegetation, Access, Cloud cover, etc.)
  - Resources (available grants, computers, students)
- Policy/Program
  - National priorities (science or society?)
  - Science priorities (e.g. climate or hazards?, continuity or discovery?)
  - Cost (of buying data vs. building a mission)