High-resolution temporal imaging of crustal deformation using InSAR

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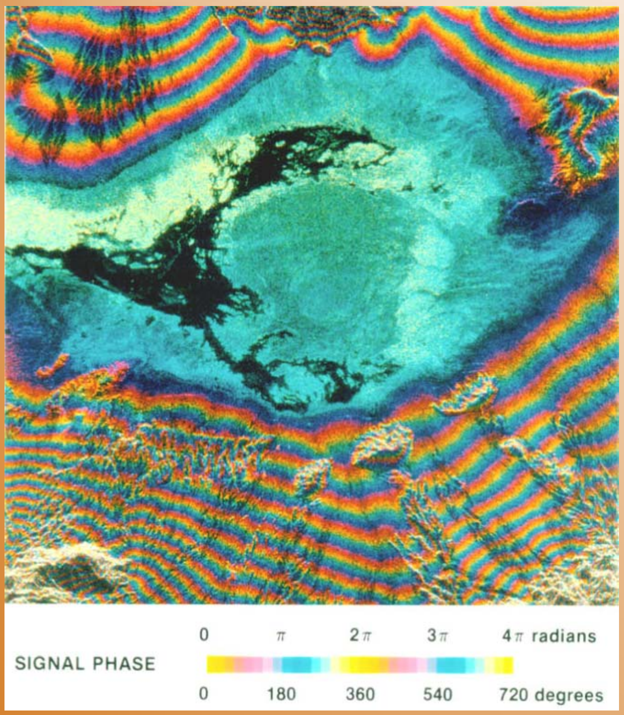
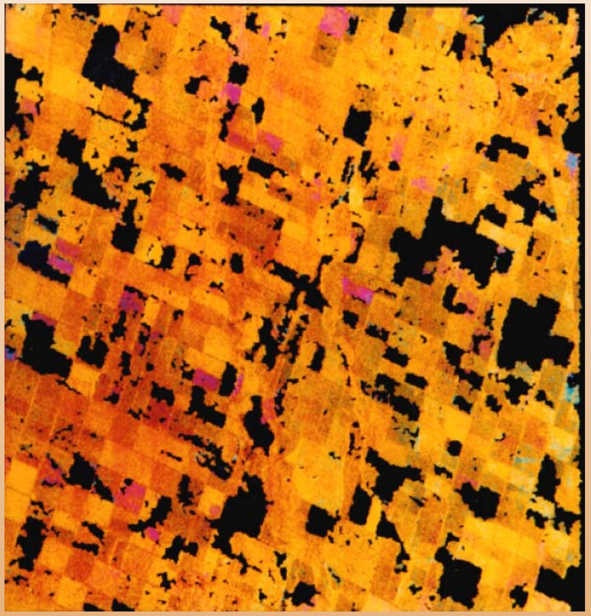
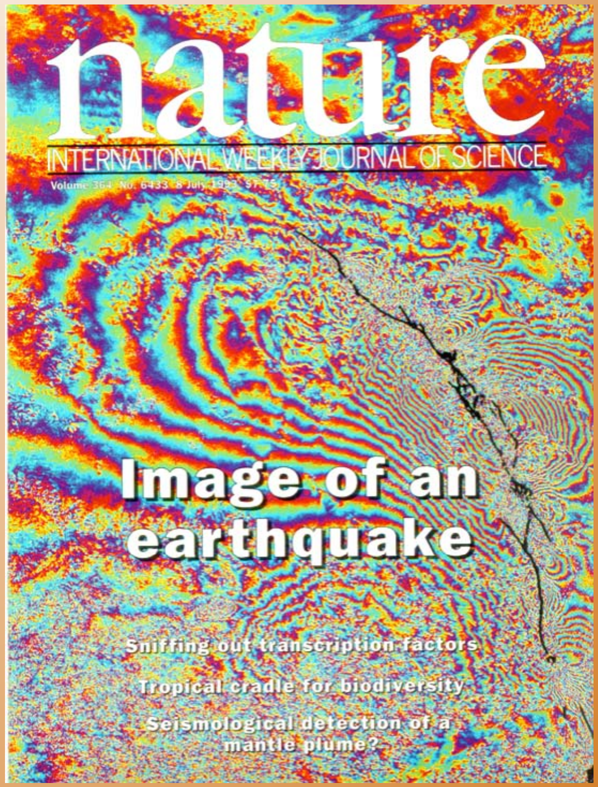
InSAR Prehistory



SEASAT Topographic Fringes



SEASAT Deformation

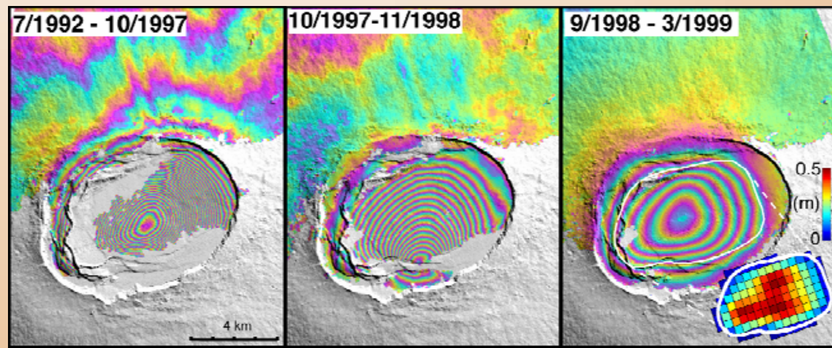


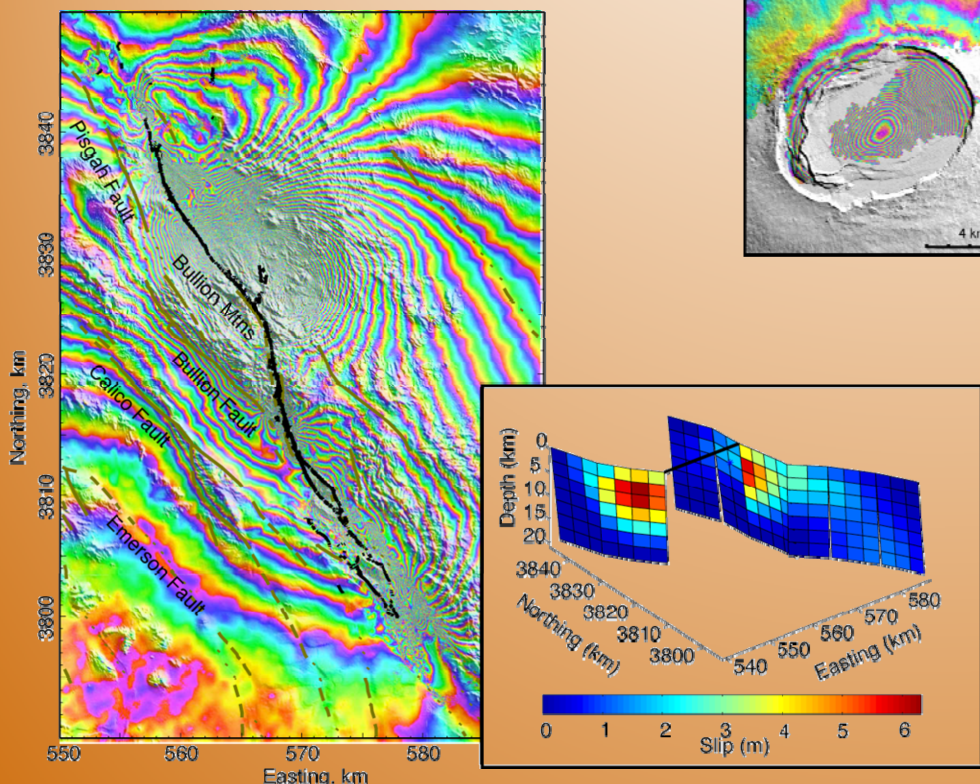
ERS Earthquake Image

- Accurate imaging of cumulative deformation and surface topography

InSAR Classical Period

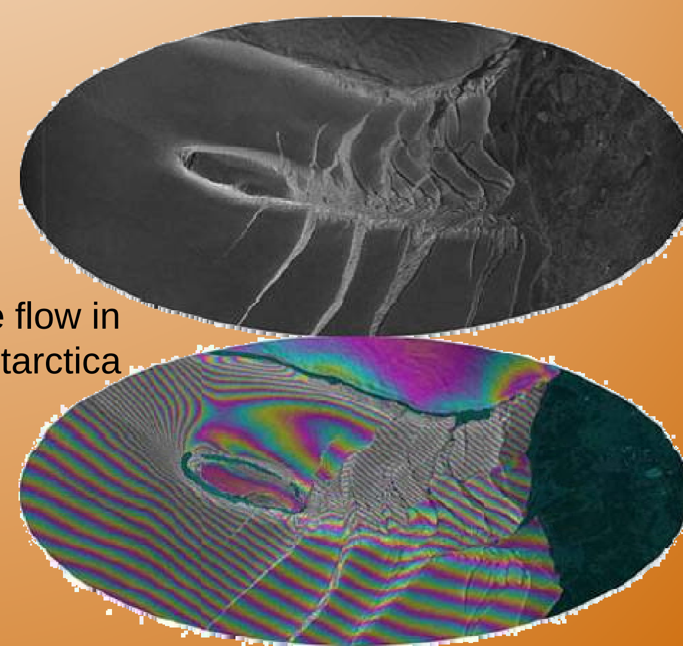
Volcano deformation, Galapagos





Earthquake displacement and slip, Hector Mine 1999 event

Ice flow in Antarctica



Classical InSAR Characteristics

- Exploit dense spatial sampling of cumulative deformation fields
- Measure static displacements of major events
  - Visualize displacements and average velocities
  - Solve for slip distributions along faults
  - Compute moment magnitudes of earthquakes
  - Constrain magma chamber geometries
  - Cryospheric, hydrologic, landslide, other uses
- Limitations

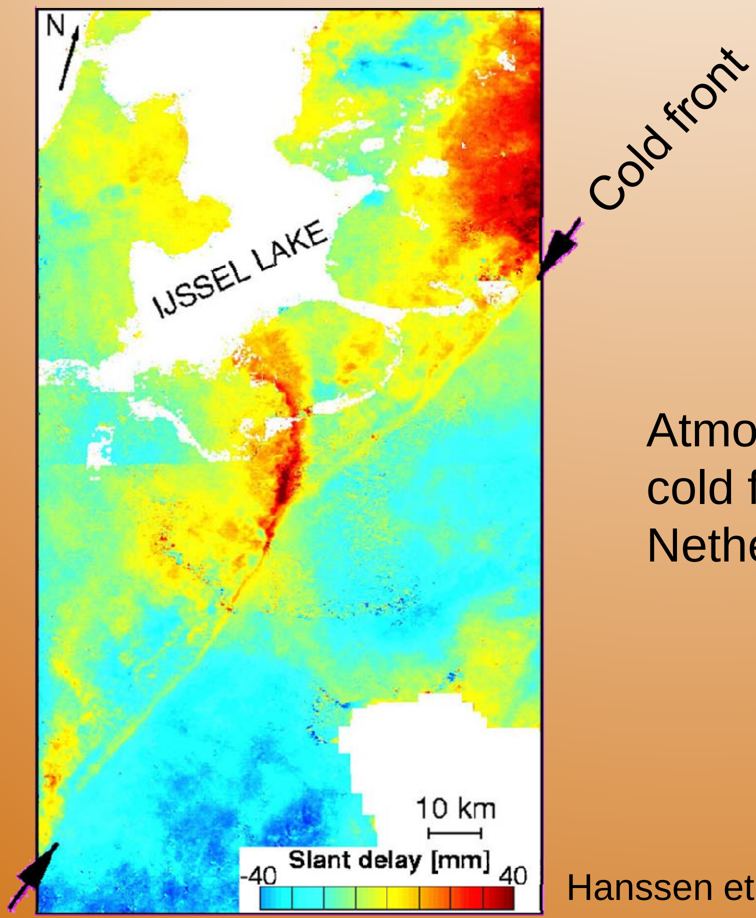
  - Large displacements (big earthquakes, volcano inflation) only as atmosphere contributes cm-level errors

  - Decorrelation, esp. in vegetated areas

  - Temporal data acquisition generally sparse, maybe only 2 or 3 SAR scenes for any area available

Atmosphere limits

- Variation of water vapor in troposphere gives cm-level errors throughout image

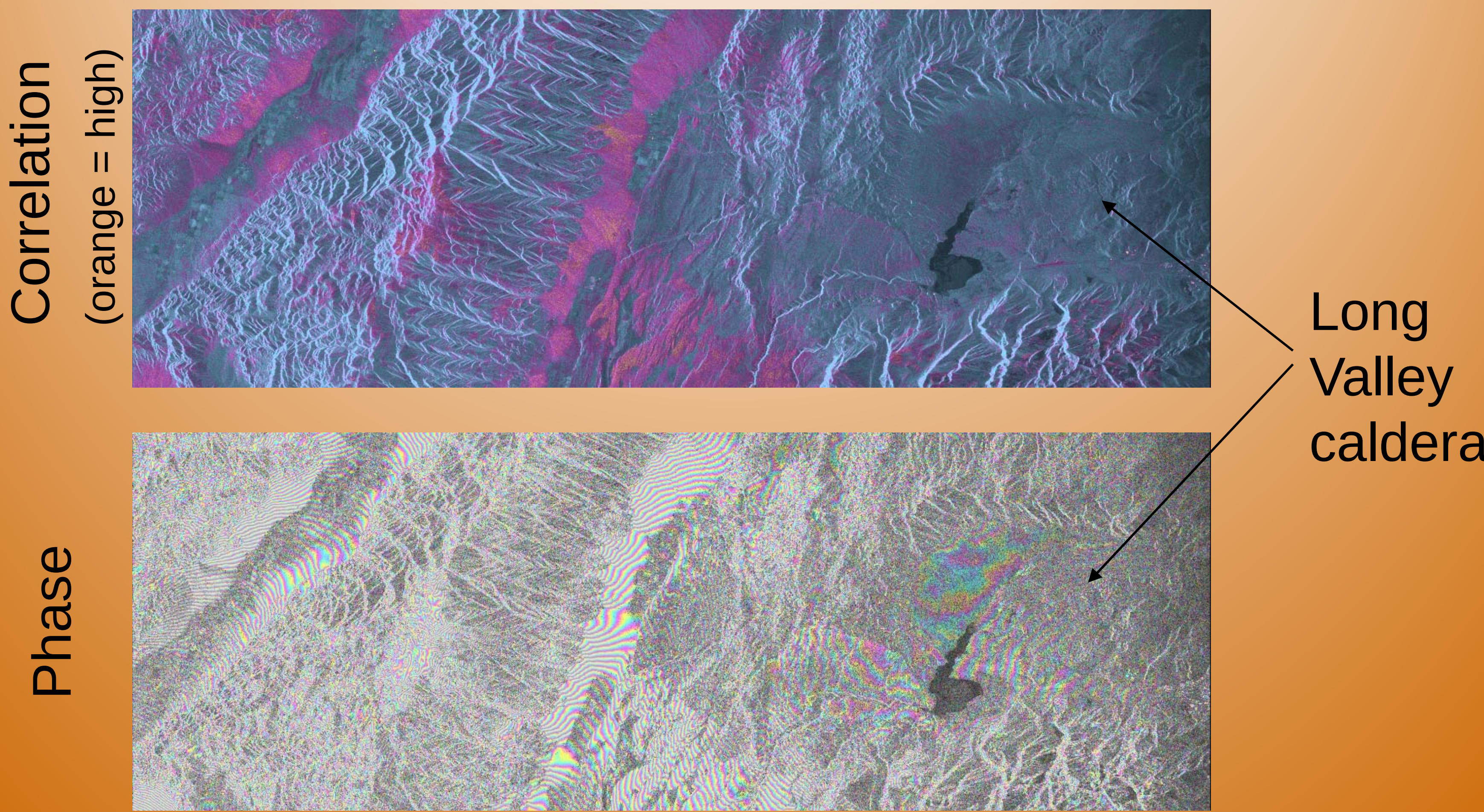


Atmospheric signature of cold front moving across Netherlands

Hanssen et al., Science, 1999

Decorrelation limits

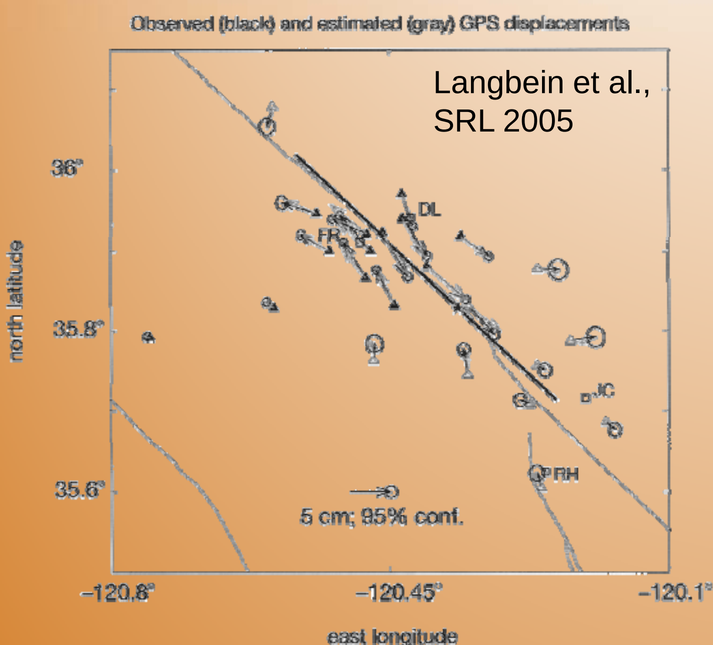
- Areal coverage limited to areas with high correlation, often fails in vegetated regions

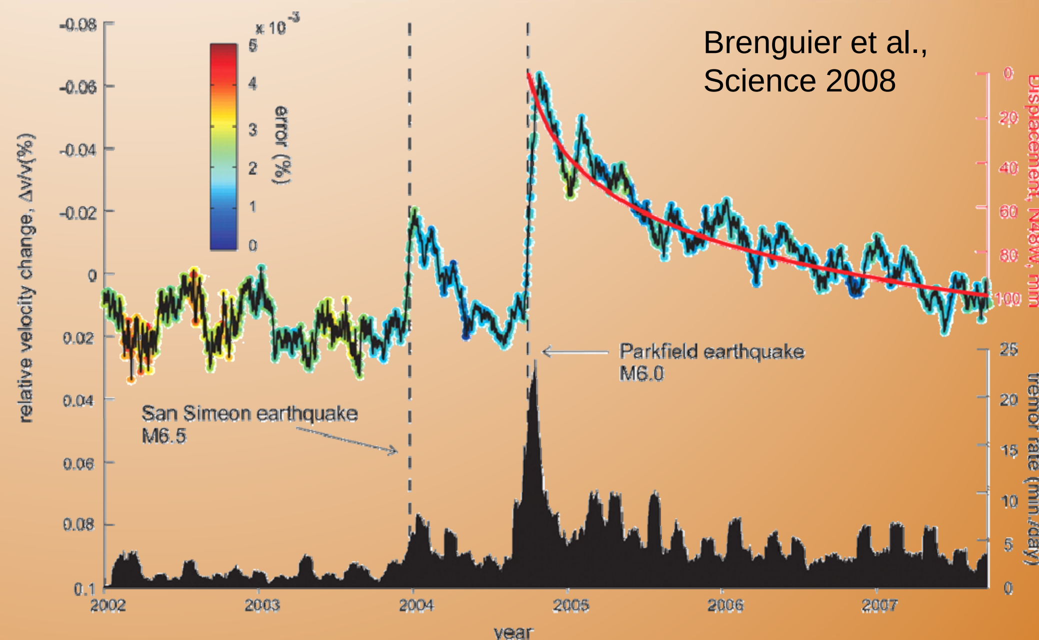


Modern era InSAR: We are heading toward time series analysis

- Current research and future is time series methods
  - Persistent scatterers
  - Small baseline subset analysis
  - Many yet to come
- Enables temporal analysis, observation of new phenomena, reveals previously unknown or poorly characterized processes
- Increases sensitivity by minimizing atmosphere and other phase contaminating terms
- Requires consistent data acquisition

GPS crustal deformation – time dependence insights



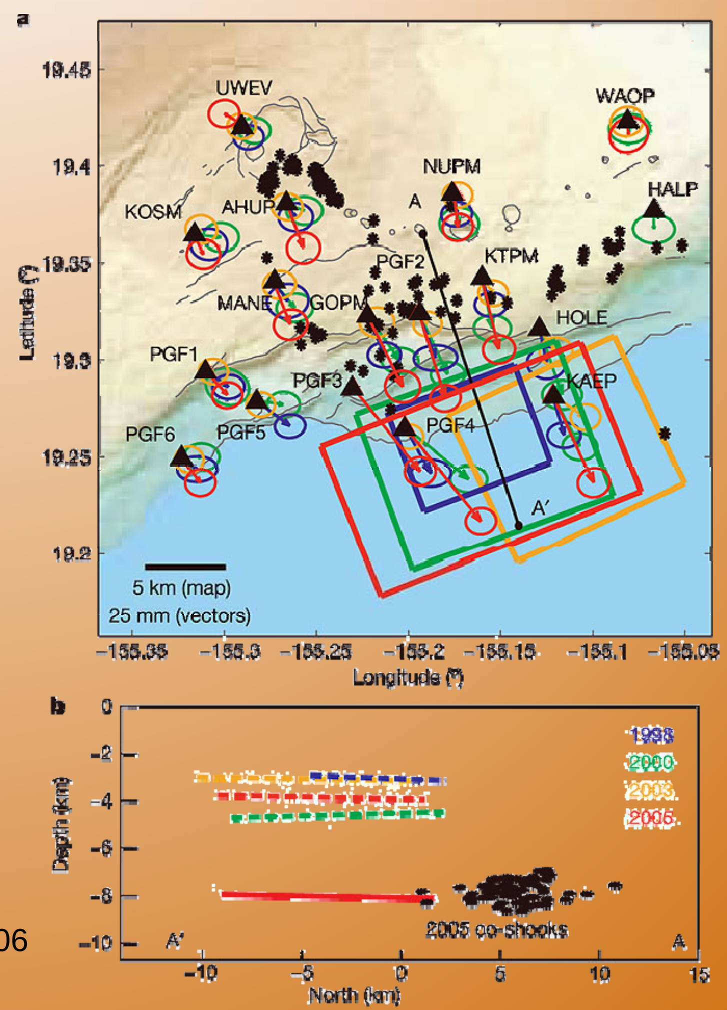


Static deformation map
Parkfield, CA

GPS temporal displacements (red) plus
other data sources, Parkfield, CA

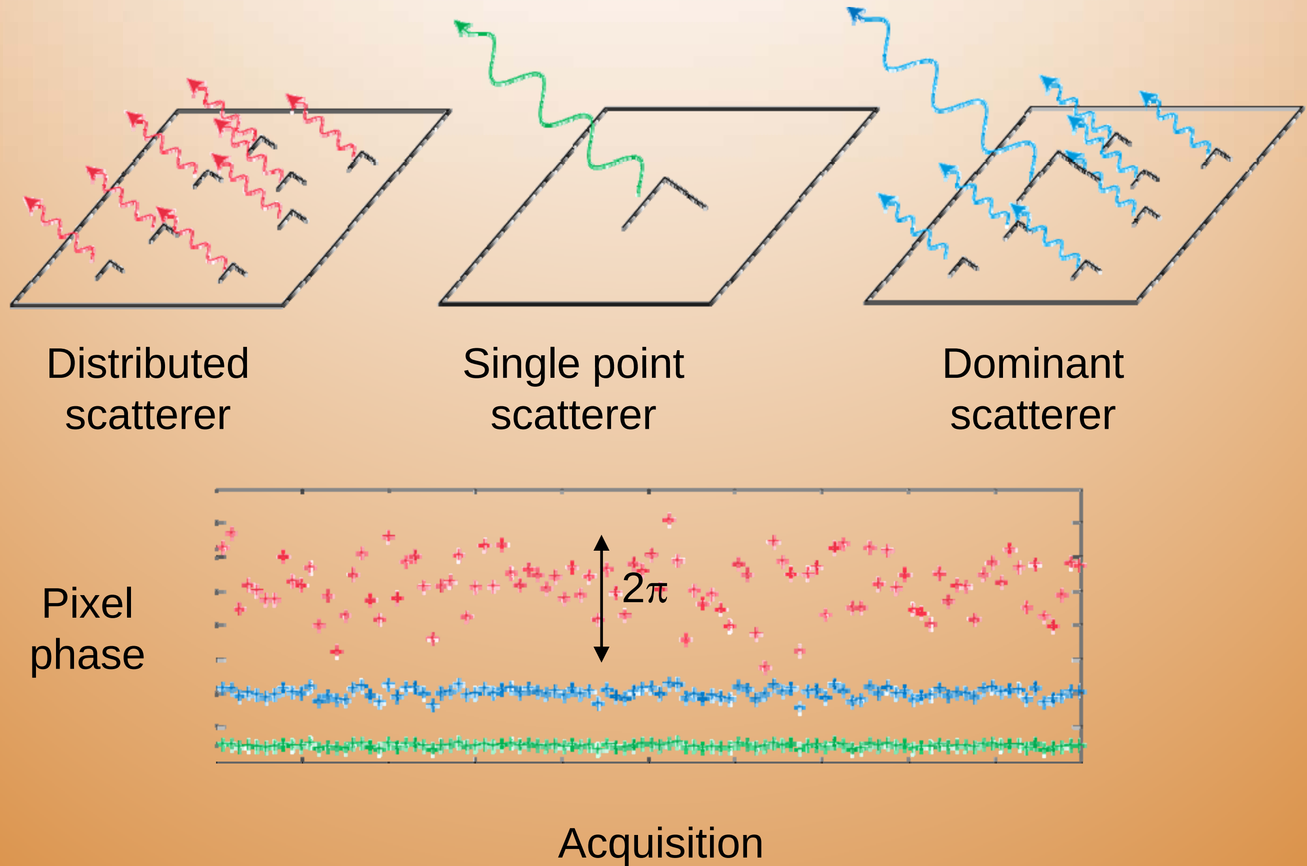
Aseismic activity – important unappreciated stress transfer

- Time scales days to months
- Too slow for seismic signals, too local for tectonic observations
- Maybe ubiquitous around Earth



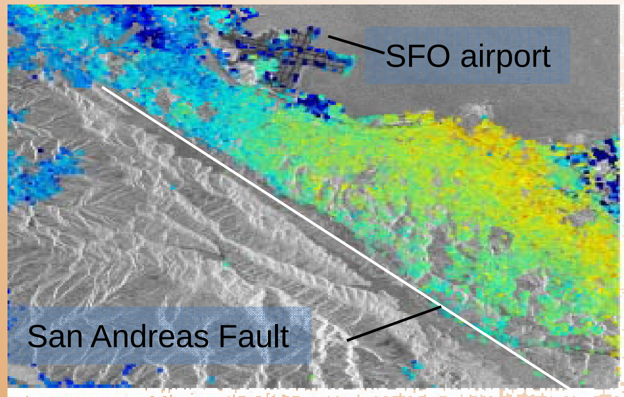
Segall et al., Nature 2006

InSAR time series: persistent scatterers

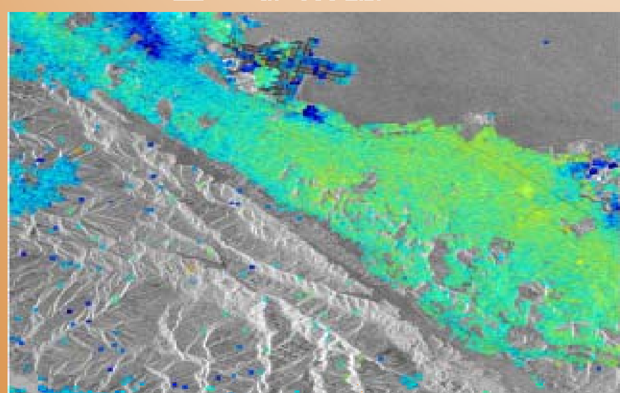


- Find the pixels with stable phase over many observations

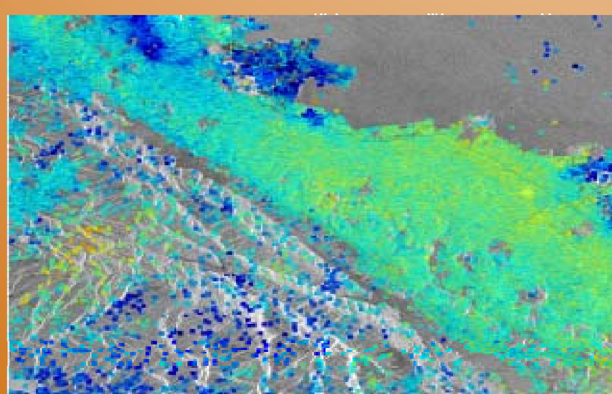
PS selection methods



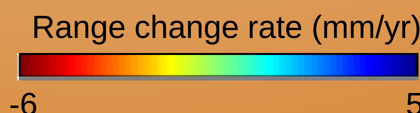
Permanent scatterers amplitude dispersion
Ferretti et al., 2000



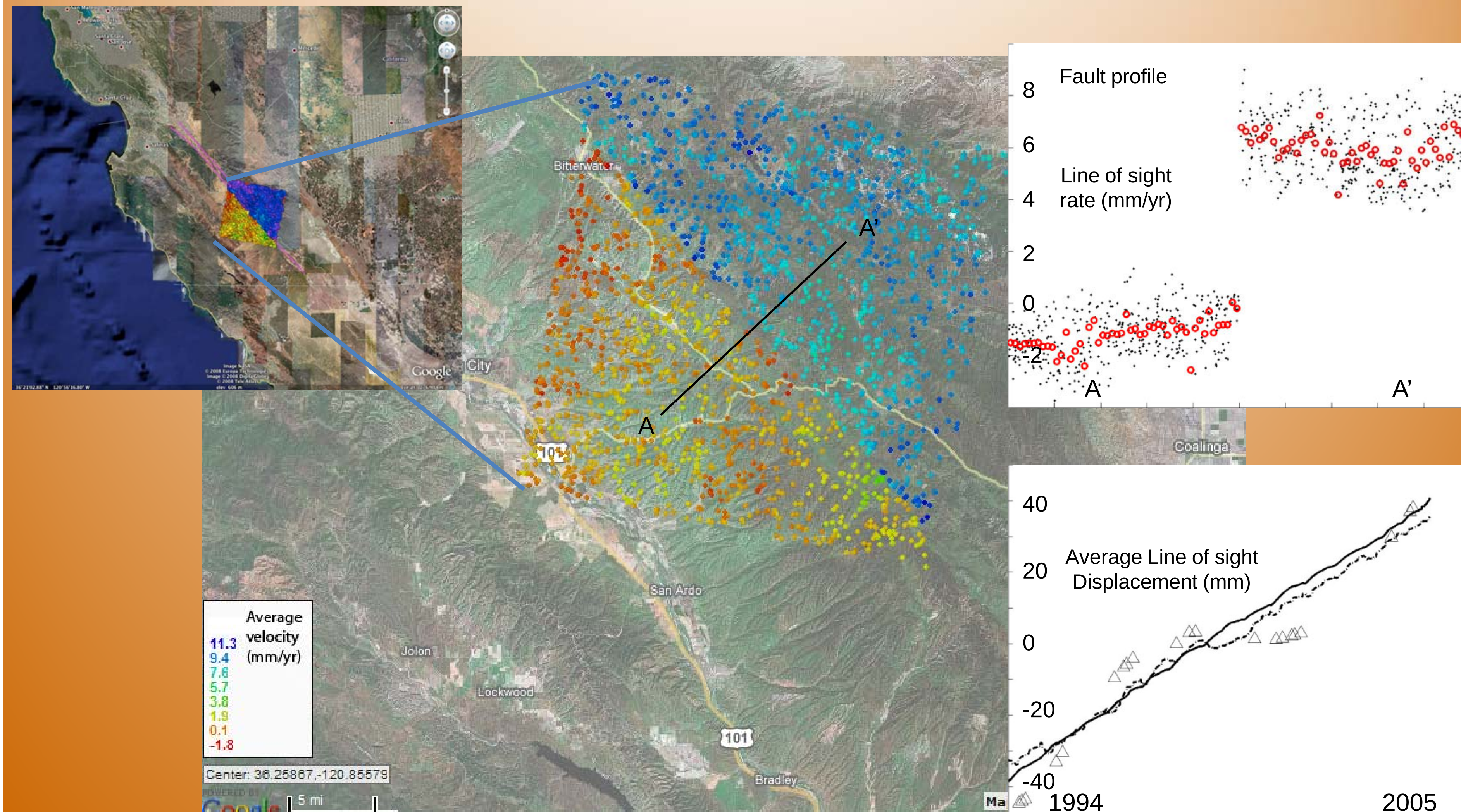
Pixel phase and filtering
Hooper, 2004



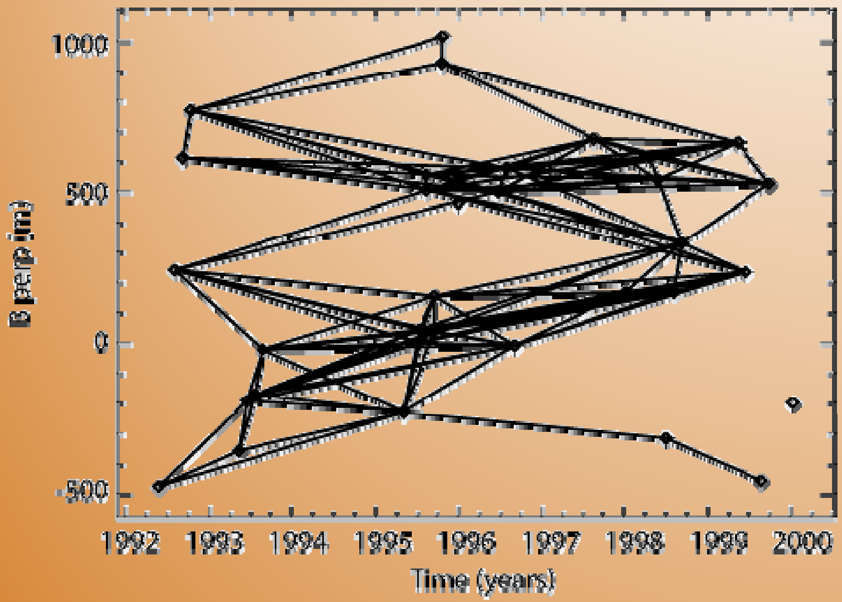
Maximum likelihood
Shanker and Zebker, 2007



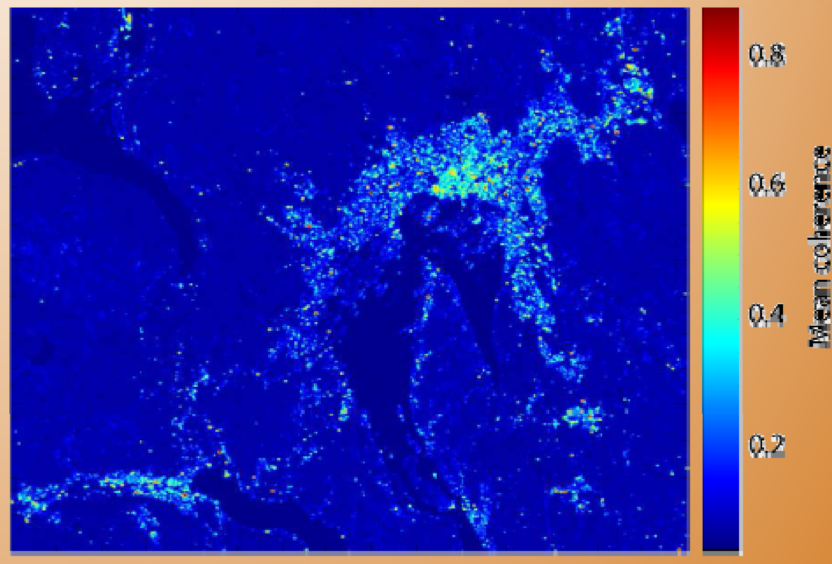
PS observations of central San Andreas fault



InSAR time series: small baseline subset (SBAS)



Time-baseline relations

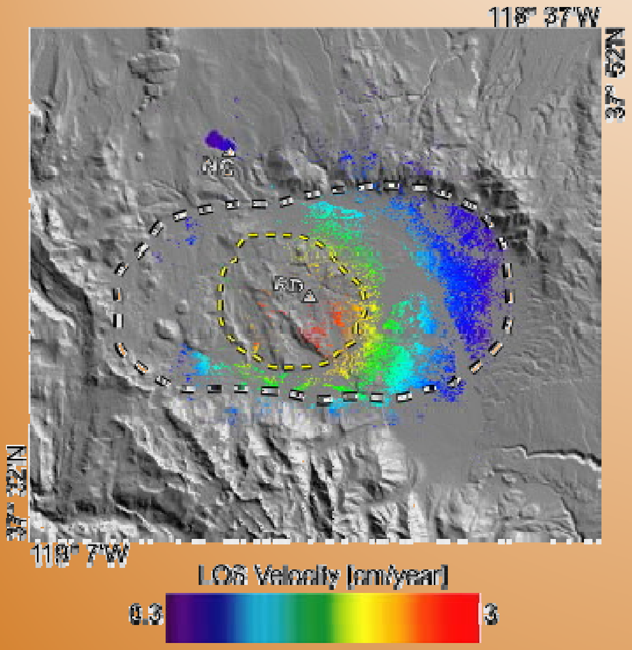


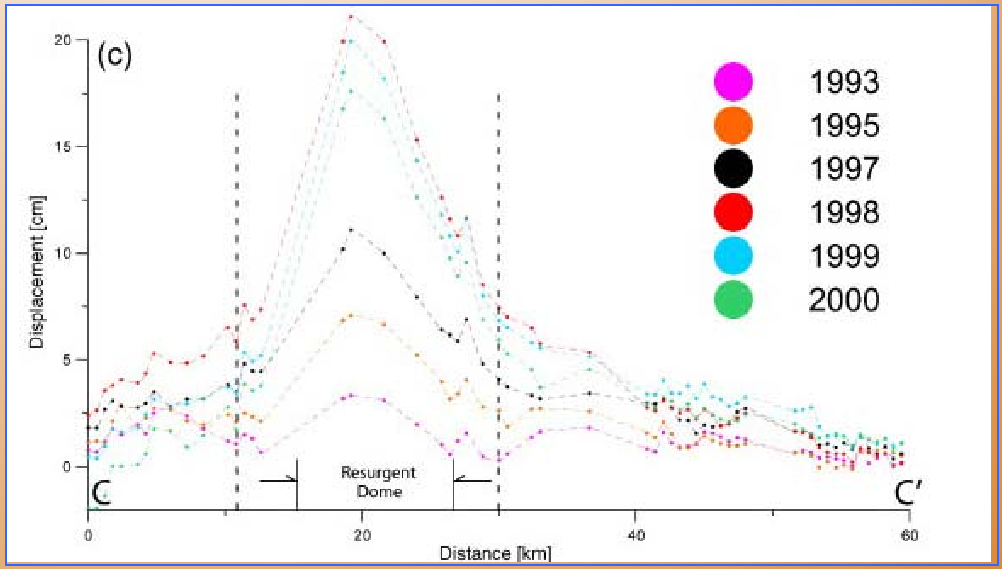
Mean coherence image

- Find regions with high correlation over many observations

SBAS analysis of Long Valley, CA

Temporal evolution of resurgent dome



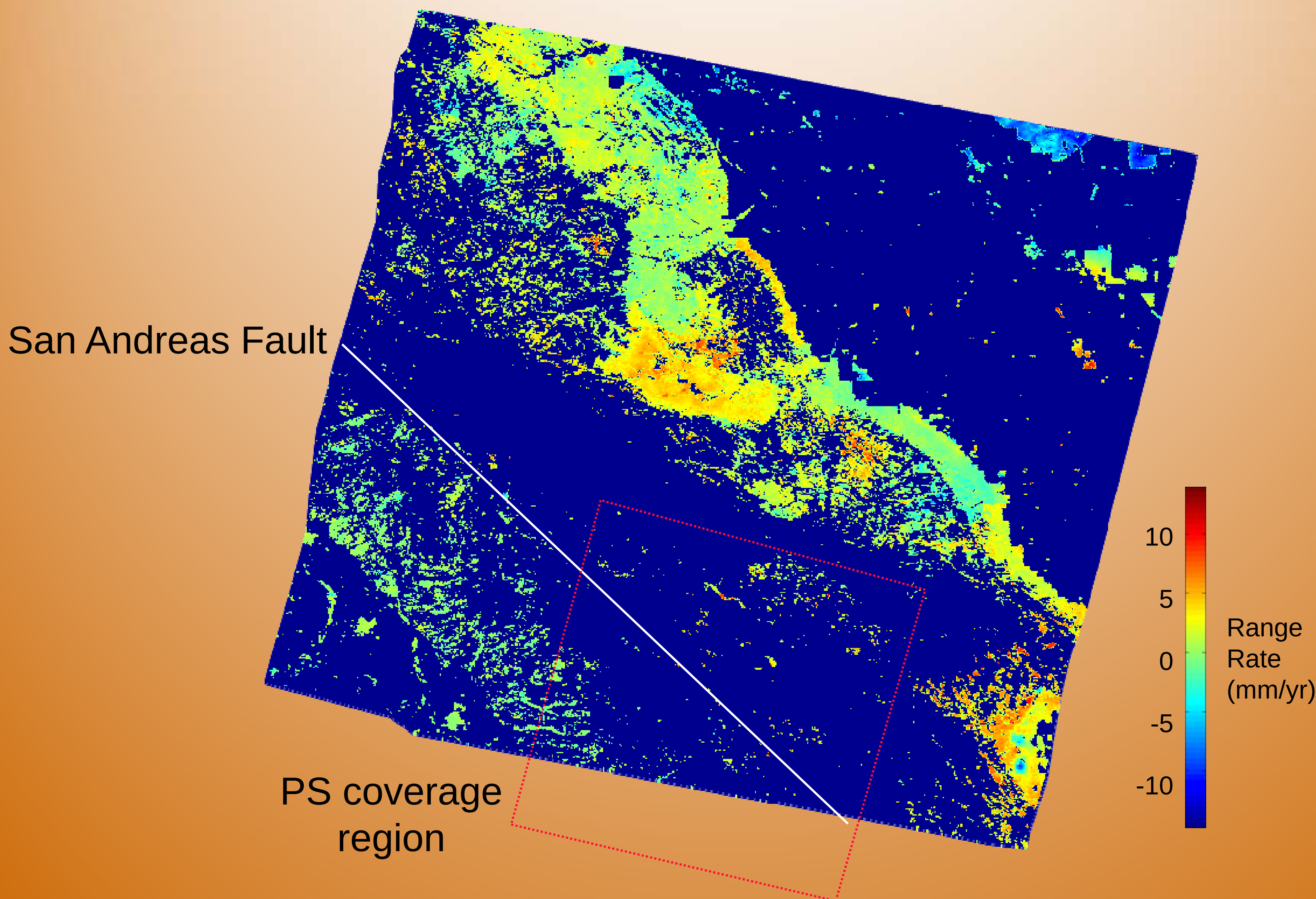


Tizzani et al., RSE 2007

Mean velocities

Dome growth and subsidence with time

SBAS reduction of CSAF region at C-band



Resolution requirement for more PS points

- Prefer PS point density ~100-500 m spatially
- Fine resolution helps in two ways

  -For constant probability of PS, more pixels in same geographic area yield more PS

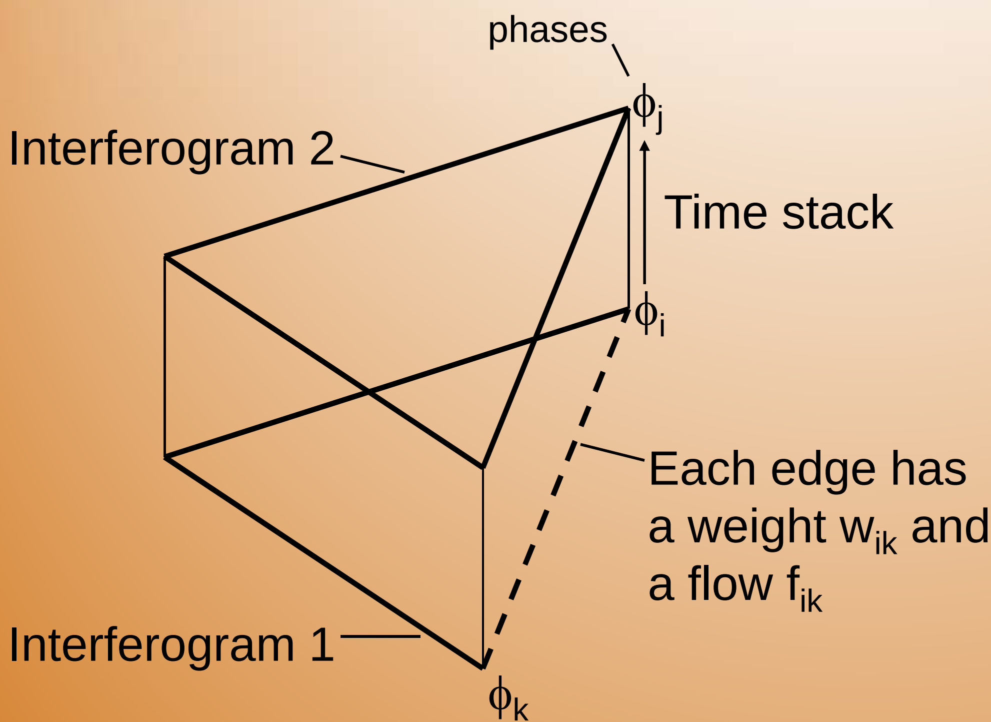
  -Finer resolution makes it easier for a single scatterer to dominate

- Resolution probably needs to be in the m-scale, need a better analytical model incorporating scattering and scatterer distribution

Phase unwrapping for PS analysis remains a problem

- Example existing methods
  - STUN algorithm from Delft
  - 3D unwrapping algorithms by Hooper and Zebker
- Current research
  - Minimum cost flow extension to 3D
  - Edge-based methods
  - Incorporation of external constraints

Edgelist phase unwrapping method



Rectangular facets in time, triangular facets in space

- Method:

  - Solve for n_i, missing cycles for each measurement ϕ_i

  - Minimize

  $$\sum w_{ik} \bullet f_{ik}$$

  - Subject to constraint

  $$n_i - n_k = [\phi_i - \phi_k]/2\pi + f_{ik}$$

- Additional constraints such as GPS points easily added by including more equations of same form

Enabling future sensors and systems

- Frequent, reliable and robust data acquisition
  - Longer sequences facilitate PS identification
  - Multiple measurements reduce atmosphere phase
- Fine resolution yields more PS points as smaller scatterers can dominate
- Longer wavelengths to improve correlation
- Controlled orbits to manage baselines, precise orbit determination
- 3D phase unwrapping: time series displacements still limited by phase unwrapping algorithms

➢ Technology wish list: short repeats, long wavelength, fine resolution, precise orbits, processing codes

Summary

- Time series InSAR invites significant new scientific investigations
- Known phenomena characterized by temporal effects and interactions
- Many new processes may be hiding in unobserved parts of time spectrum
- “Conventional” applications extended to challenging vegetated and other extreme terrain
- Accuracy much higher than present methods
- Time series of displacements today limited by phase unwrapping algorithms and lack of temporal data