Wave propagation across the US: Exploiting the quality of TA data

Göran Ekström
Lamont, Columbia University

Quality - the greater challenge

The TA in 1998: 100 stations
20 6-month deployments

USArray - Probing the Continent

Göran Ekström, Harvard University; Gene Humphreys, University of Oregon; Alan Levander, Rice University

USArray is the working name for an envisioned facility for the seismological probing of the North American continent. The facility is currently conceived to consist of two main parts: (1) a densified network of permanent broad band stations providing uniform coverage across the contiguous US, and (2) a collection of more than one hundred seismometers configured in a transportable telemetered array. This tool is needed for a new style of systematic mapping of the continental lithosphere and upper mantle, with the goal of revealing structures which tell us about the evolution of the continent from the Precambrian to the present.

The scientific and technical design of USArray evolves from the successes of the IRIS PASSCAL program and a growing understanding of the value of combining local and regional, and short- and long-term observations in seismological imaging. A project of systematic seismological mapping of the

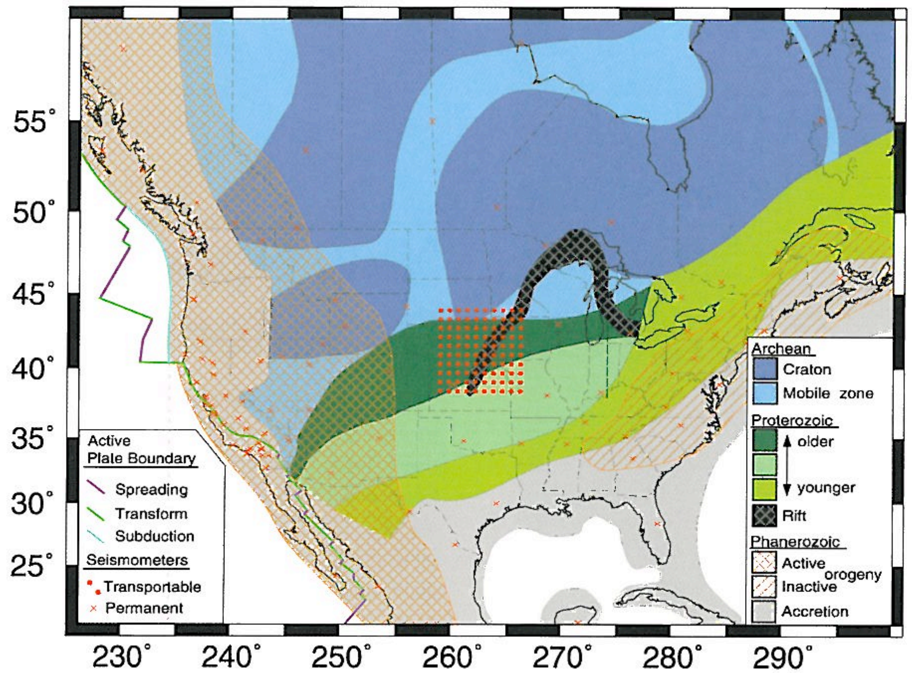

Figure 1. Idealized tectonic map of North America. Many structure boundaries are gradational and poorly understood. The permanent station locations are the existing sites of the Canadian, Mexican and US national broadband networks, the California broadband networks and the IRIS/USGS GSN.

IRIS newsletter, v.16, 2-6, 1998

USArray Initiative

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Consider what our understanding of North American tectonics would be like if our best image of the continent's topography was as blurred as that in Figure 1. First-order features like the Cordillera are barely resolved, and the characteristic topography within provinces like the Basin and Range and Great Valley are obscured beyond recognition. Yet it is precisely such a fuzzy view of the lithosphere and deeper mantle that we currently bring to the four-dimensional problem of understanding the structure, evolution, and dynamics of the North American continent.

At a workshop in Albuquerque, New Mexico, in March 1999, jointly sponsored by the National Science Foundation and IRIS (Incorporated Research Institutions for Seismology), seismologists and geologists discussed an ambitious plan to

transportable array so that a range of specific targets can be addressed; and (3) several dozen permanent high-quality seismic stations administered largely by the U.S. Geological Survey within the context of the national seismic network. The goal of this layered design is to achieve imaging

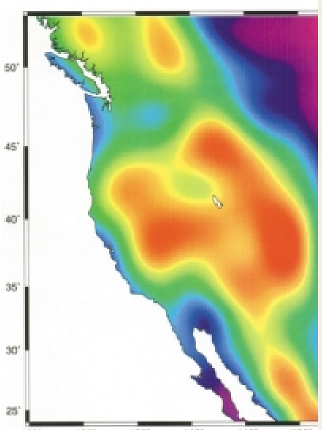


Figure 1. Topography of the western United States at d... tomographic models. Right: At resolution of 1 km (Simp... the order of tens of kilometers.

EOS, 1999

Eos, Transactions, American Geophysical Union, Vol. 80, No. 22, June 1, 1999, Pages 245, 250–251

Proposed Project Would Give Unprecedented Look Under North America

An unprecedented examination of the Earth's deep interior and investigation across a broad range of scales of the structure of the North American continent and the processes that formed it would be among the undertakings of a proposed 10-year Earth Science project called USArray. Now in the planning and development stage, the project would permit a three-dimensional (3-D) systematic investigation of North America, improving the resolution of lithospheric images by an order of magnitude.

For the Earth sciences, the project would be the seismological equivalent of the Hubble space telescope. A number of factors suggest that North America is particularly suited for this project, including the states of current knowledge and technology, the availability of a sophisticated infrastructure, organization in the seismological community, scientific economy, and widespread scientific interest.

The past decade and a half have seen major advances in structural seismology—imaging complex Earth velocity and impedance structures and making valid inferences from them on the physical state within the Earth. Similar advances in the other solid Earth sciences have poised us for important breakthroughs in our understanding of continental dynamics and evolution. In the past, whenever seismic resolution is dramatically improved, the Earth sciences have significantly advanced the understanding of the dynamics of our planet, changing the way we think about geologic processes. Deep crustal reflection images of crustal thickening and collapse, for example, have provided a new understanding of the orogenic cycle. Global tomograms have provided evidence for whole mantle convection in the recognition of deeply subducted plates.

USArray's current design has three seismic components: an expansion of the U.S. National Seismic Network (USNSN) in coordination with the U.S. Geological Survey and U.S. regional networks; a fixed design uniform array of up to 400 telemetered, observatory-quality, transportable seismographs that will be systematically deployed to cover the entire lower 48 United States; and a flexibly designed array of a similar number of broadband and short-period instruments that is used to field complementary experiments within the footprint of the fixed array. This would allow very high resolution of the continent in tectonically important areas. The data from the transportable array and the fixed stations would be available in near real time, ensuring timely analysis.

An education and outreach component would capitalize on the attention that would be focused on one region of the country after another, linking schools and the general public with area-related geologic issues and making the roving array an exciting, nationwide affair. Specific programs would be developed for all levels of education and the media. Using USArray to focus public attention on the geological sciences would increase public awareness and interest in geology and in science in general.

The plan continues to evolve as we seek and respond to community input. Since a primary goal, to design a strategy for studying the structure and ongoing deformation of North America, requires a far more comprehensive set of measurements than can be provided by seismology alone, a framework would be needed for other branches of the geological sciences to address important geological problems in different regions of the continent. These might include the investigation of the San Andreas fault, orogenesis in the western United States, the structure of the craton, or the assembly of the continent.

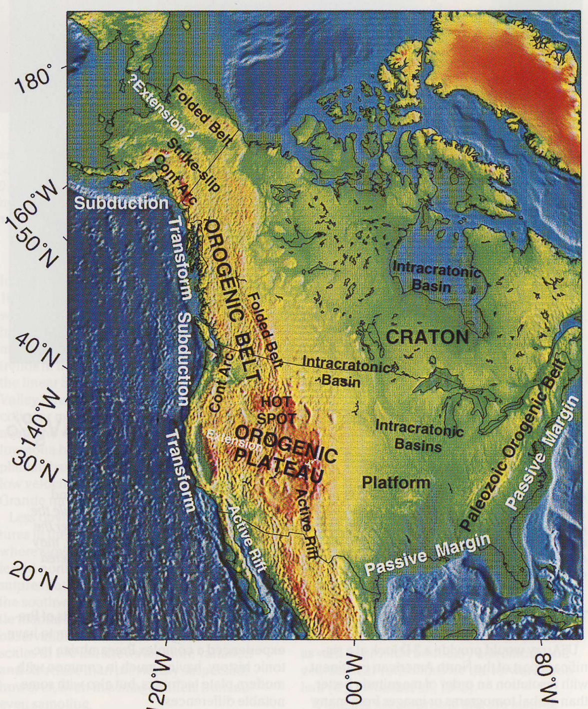
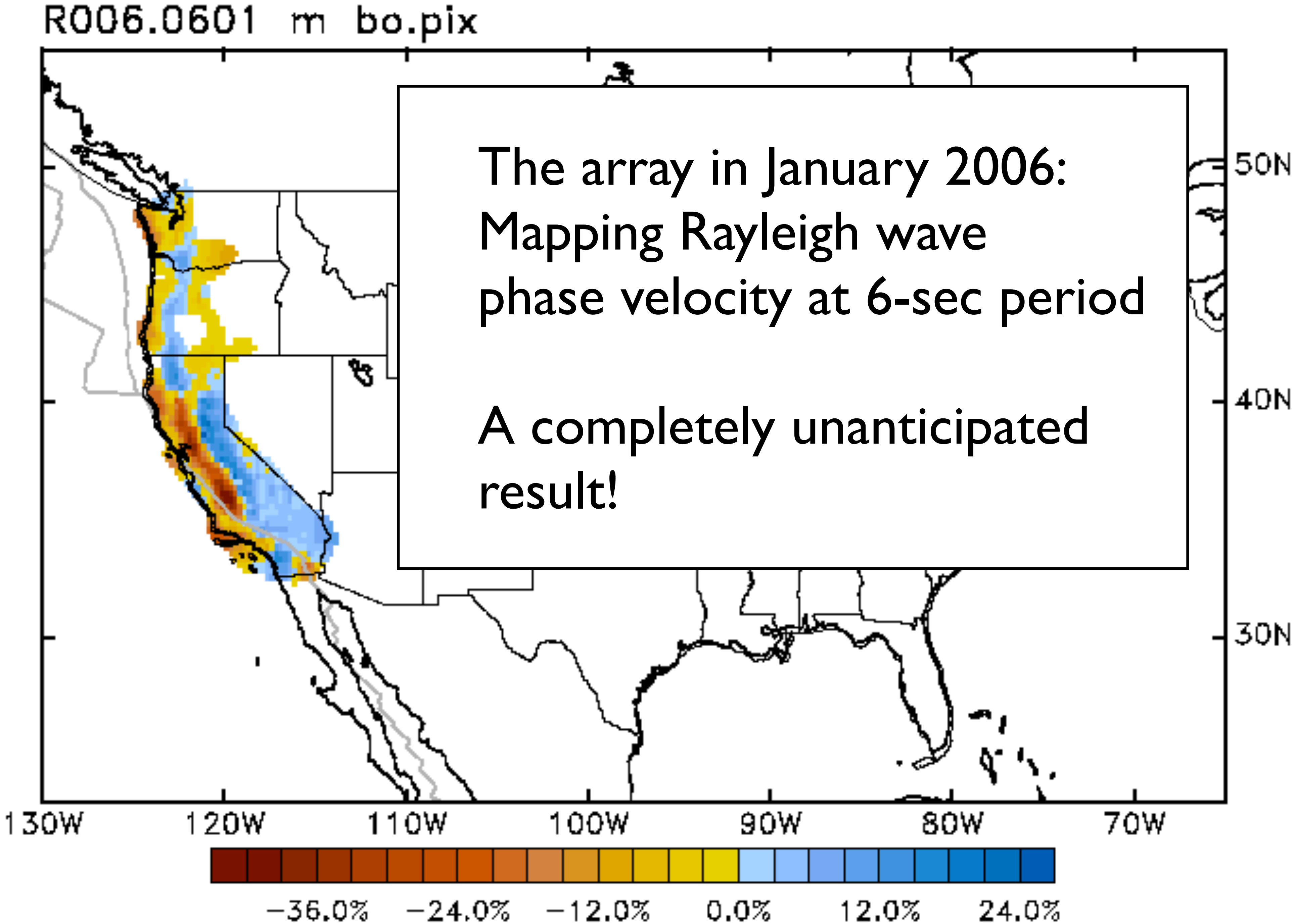


Fig. 1. Shaded relief map of North America showing current topography and tectonic regimes.

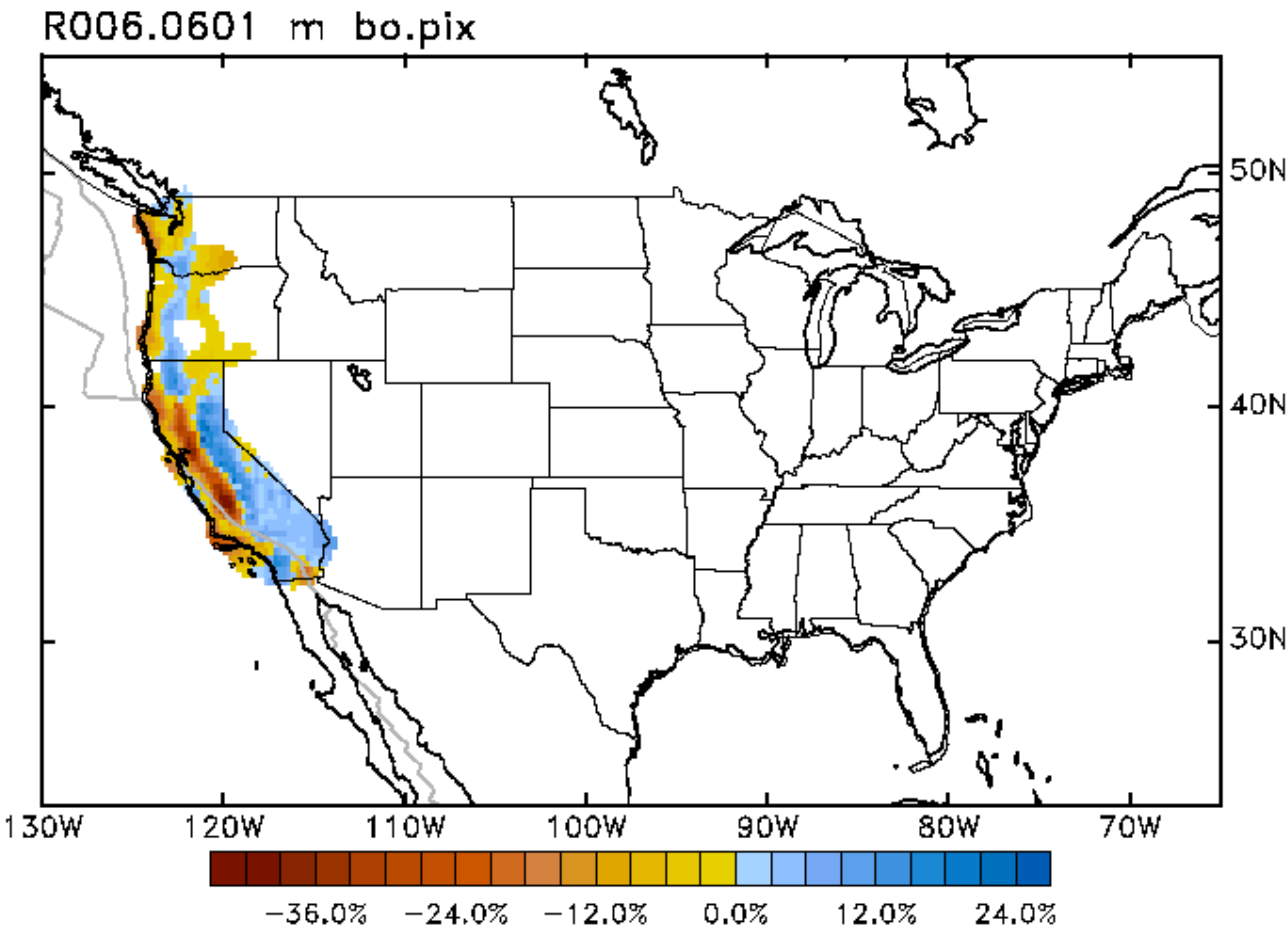
GSA Today, 1999

By 1999 it was 'settled':
400 stations
one- (or two-?) year deployments?



The array in January 2006:
Mapping Rayleigh wave phase velocity at 6-sec period

A completely unanticipated result!


R006.0601 m bo.pix
50N
40N
30N
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80W
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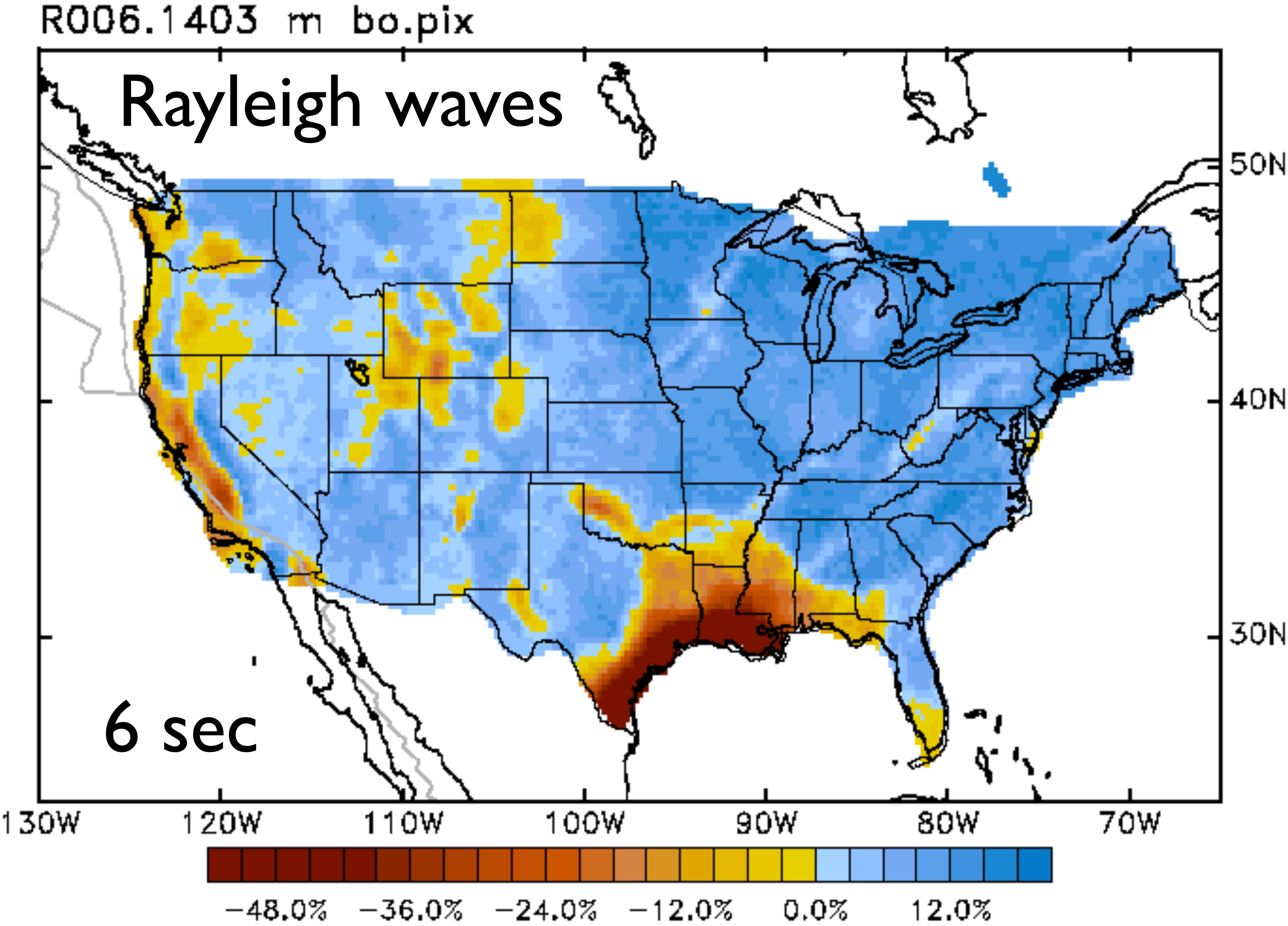
0.0%
12.0%
24.0%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Rayleigh waves
6 sec
50N
40N
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120W
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−48.0%
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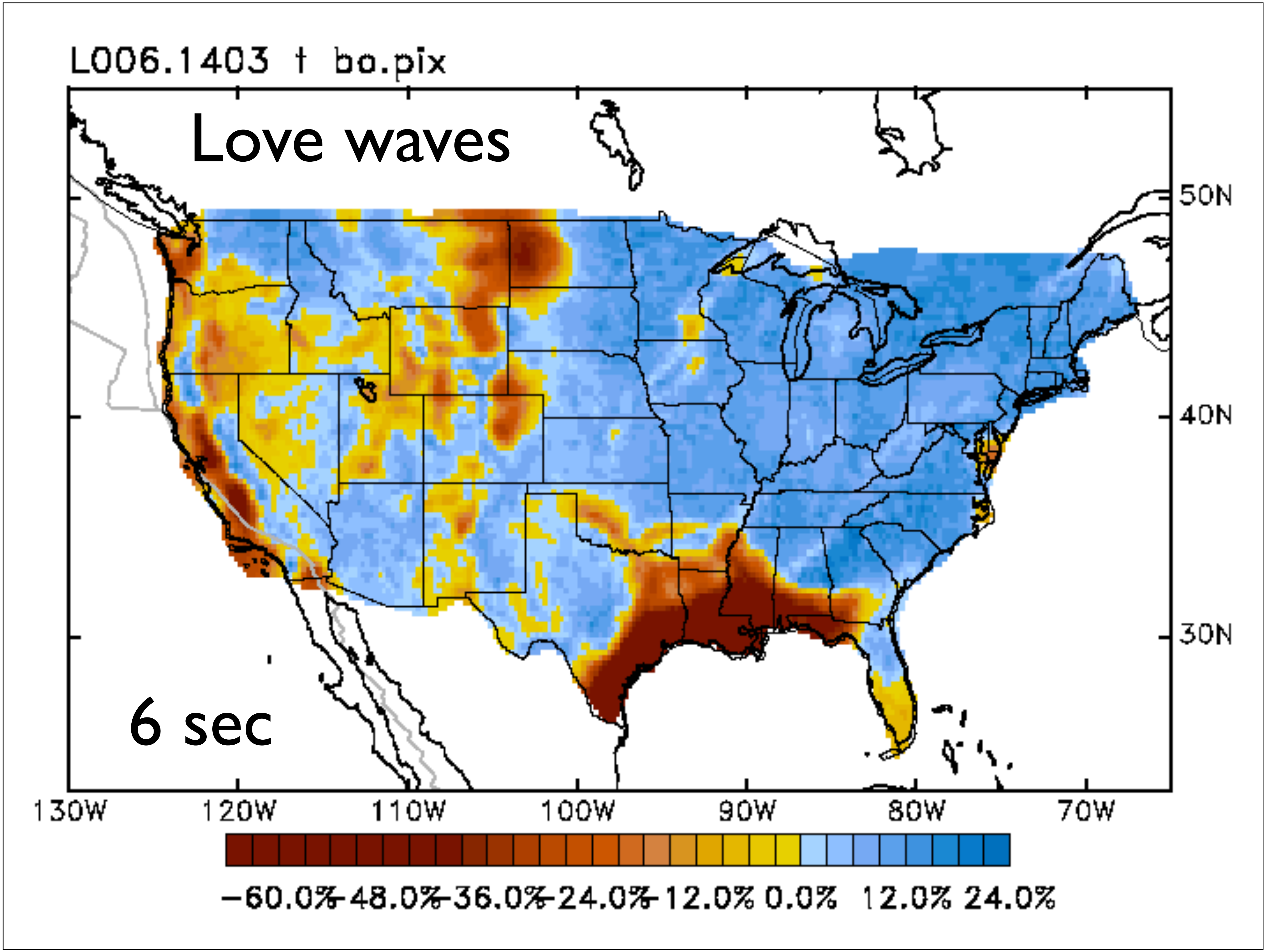
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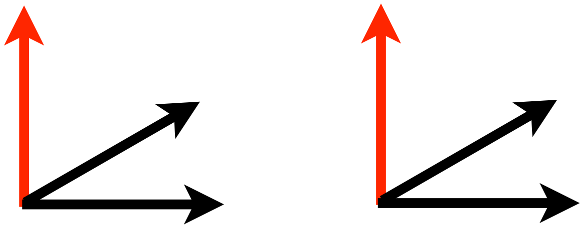
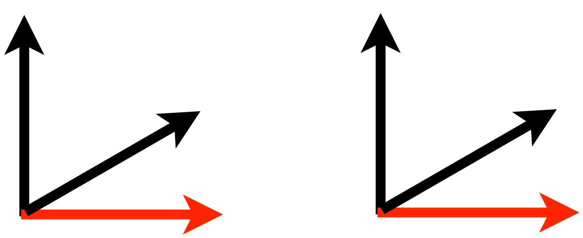
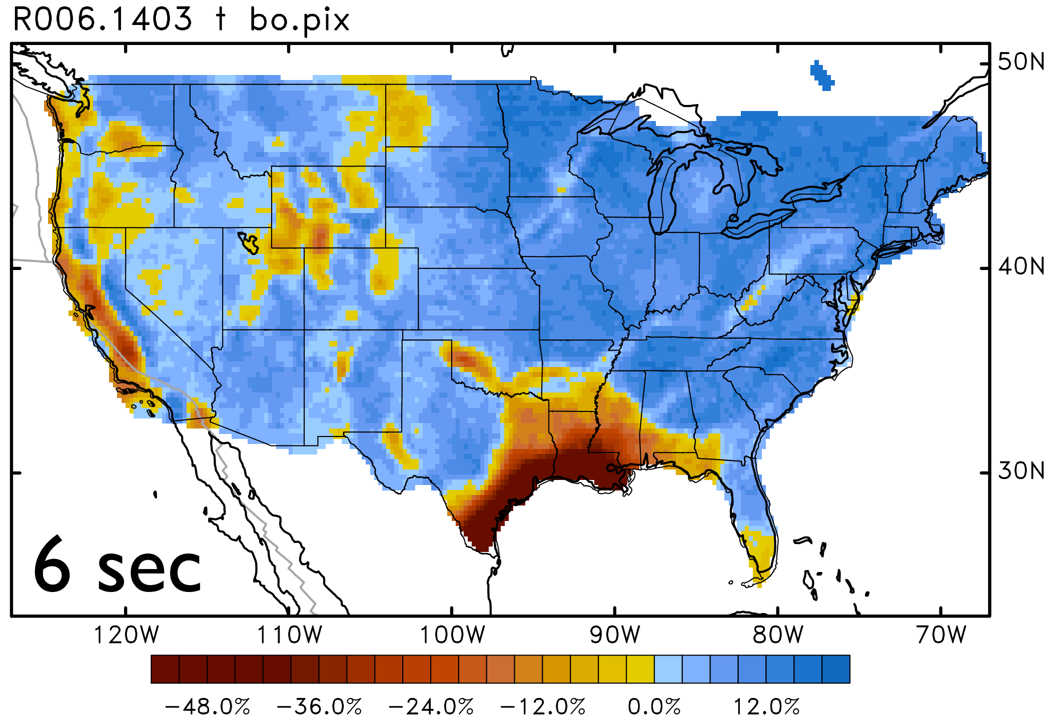
Robust maps

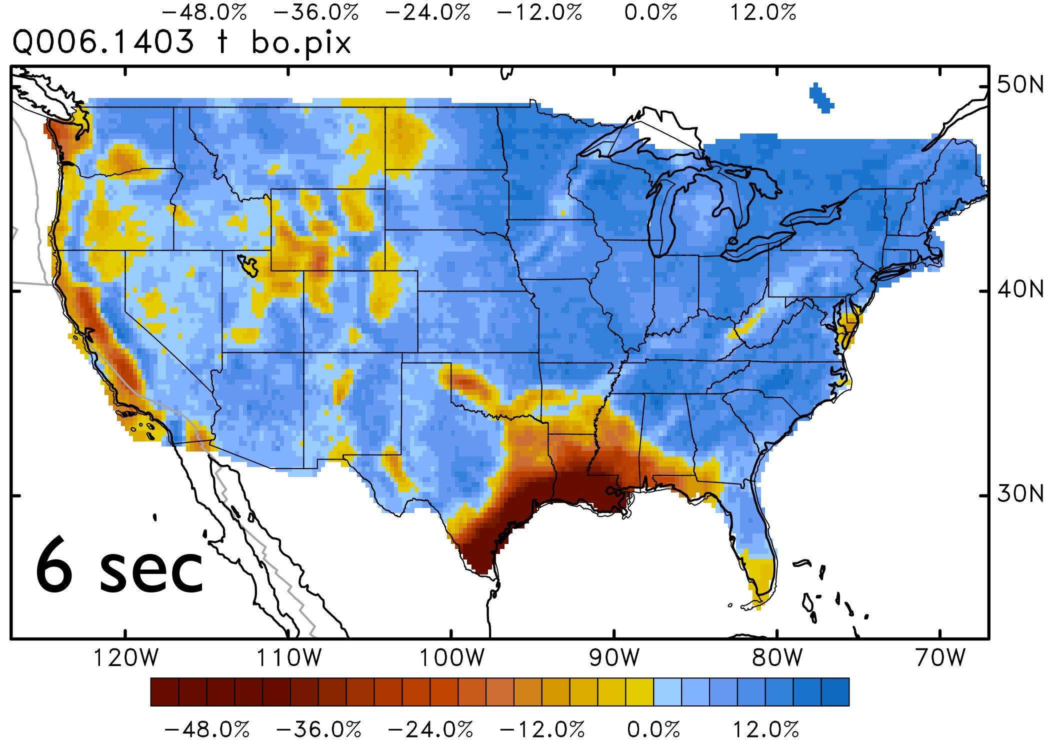
Vertical correlations



Radial correlations

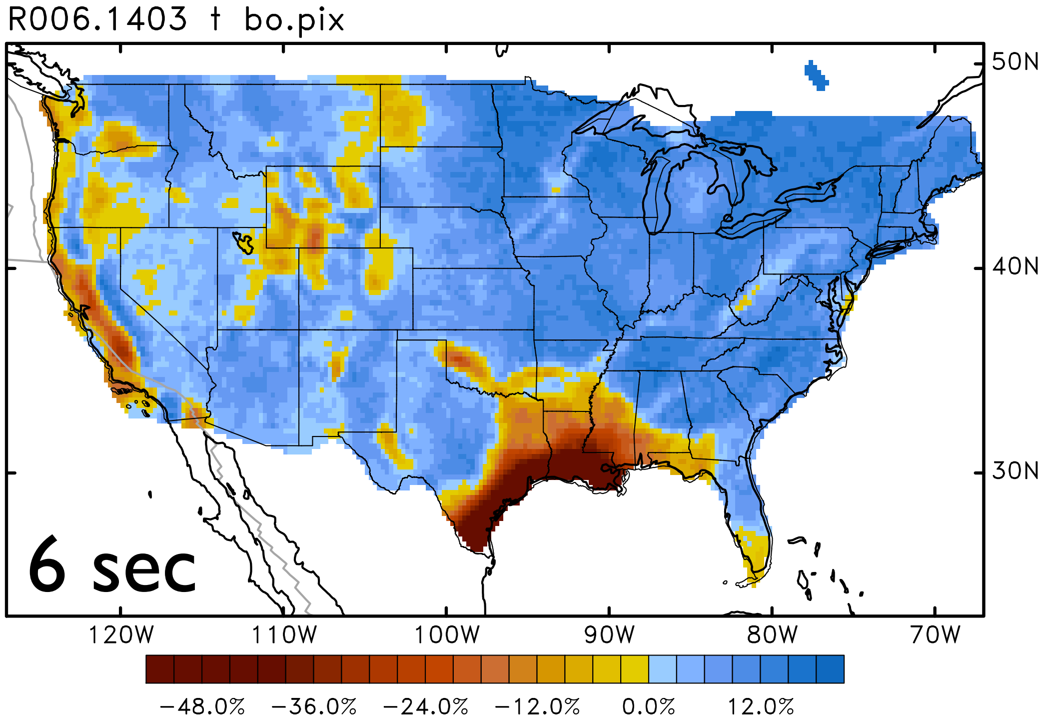




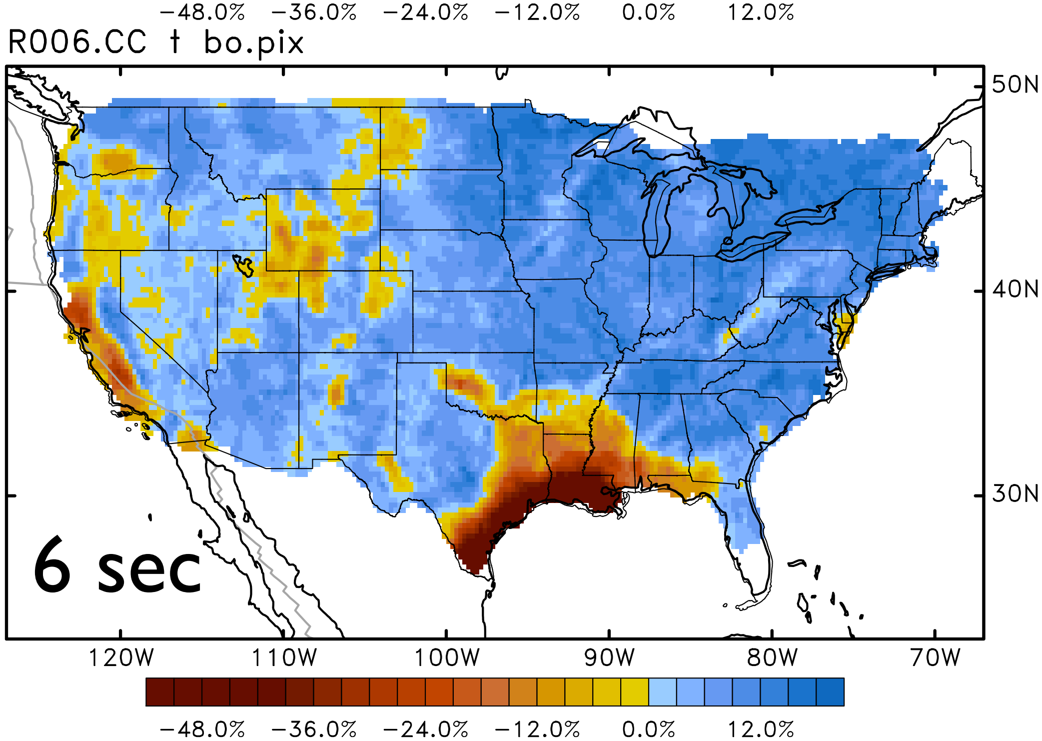


Robust maps

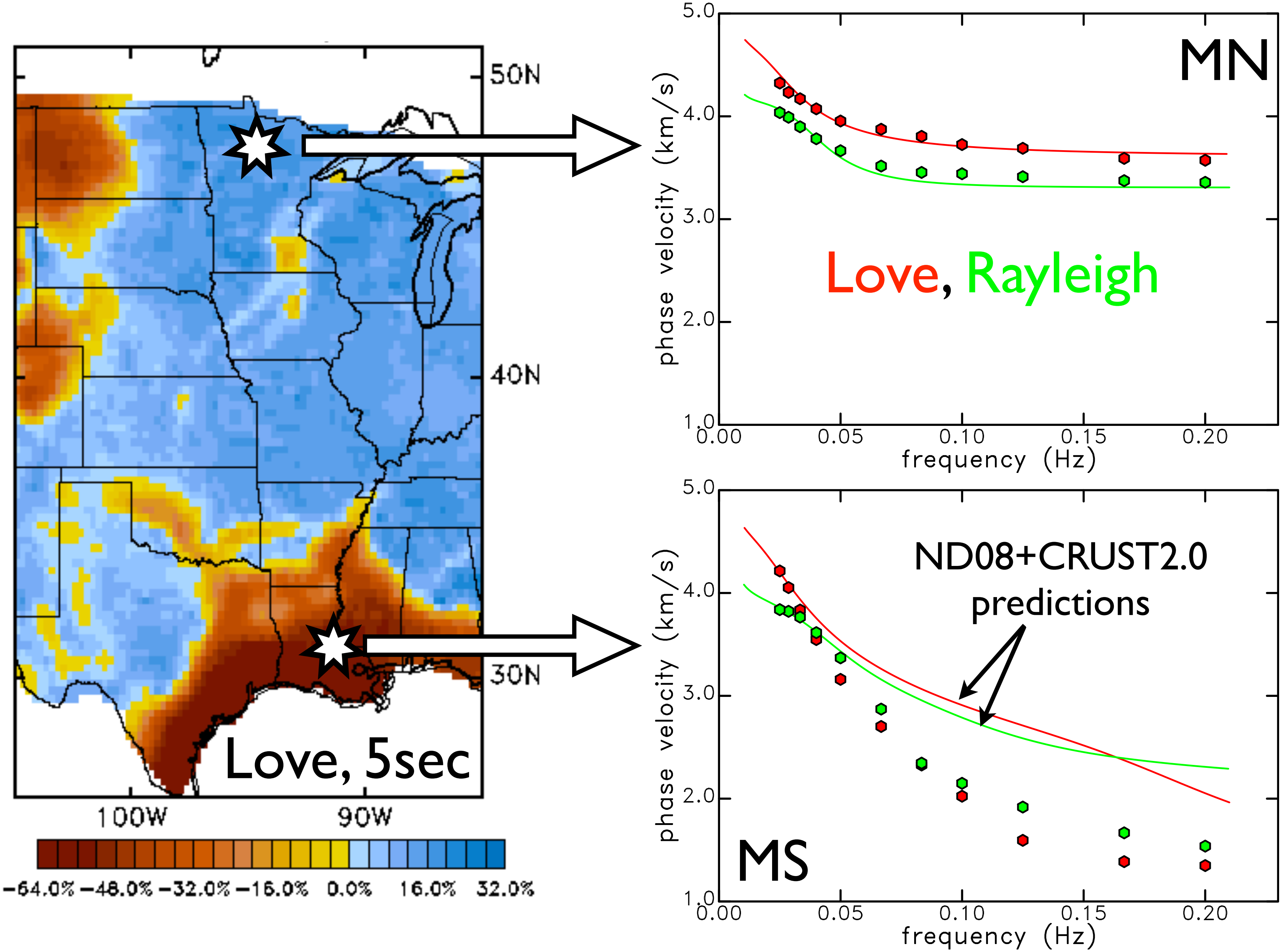
Standard two-station correlations



Correlations of correlations



Observed and predicted dispersion



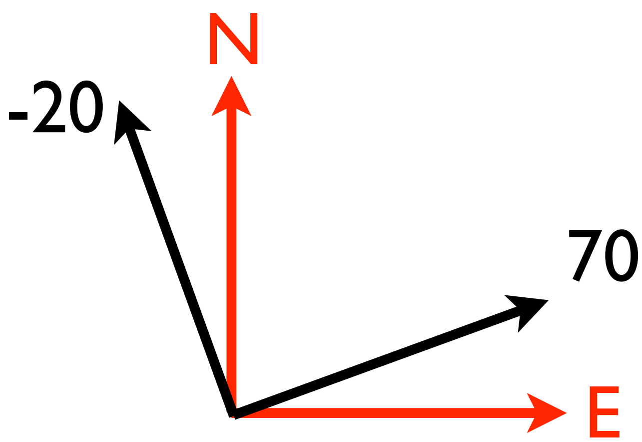
What about the quality?

1. Sensor orientation
2. Sensor calibration

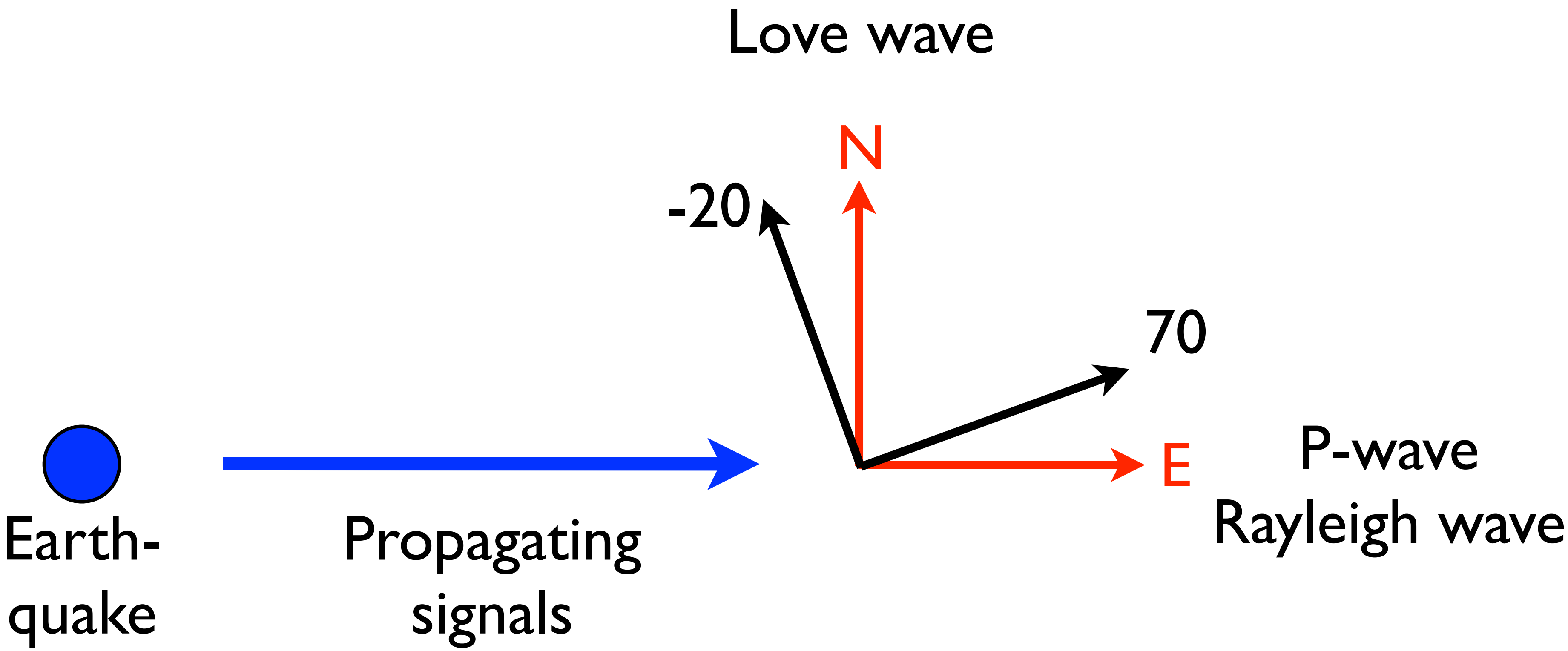
Horizontal Polarization Problems

Desired (assumed) orientation of seismometer

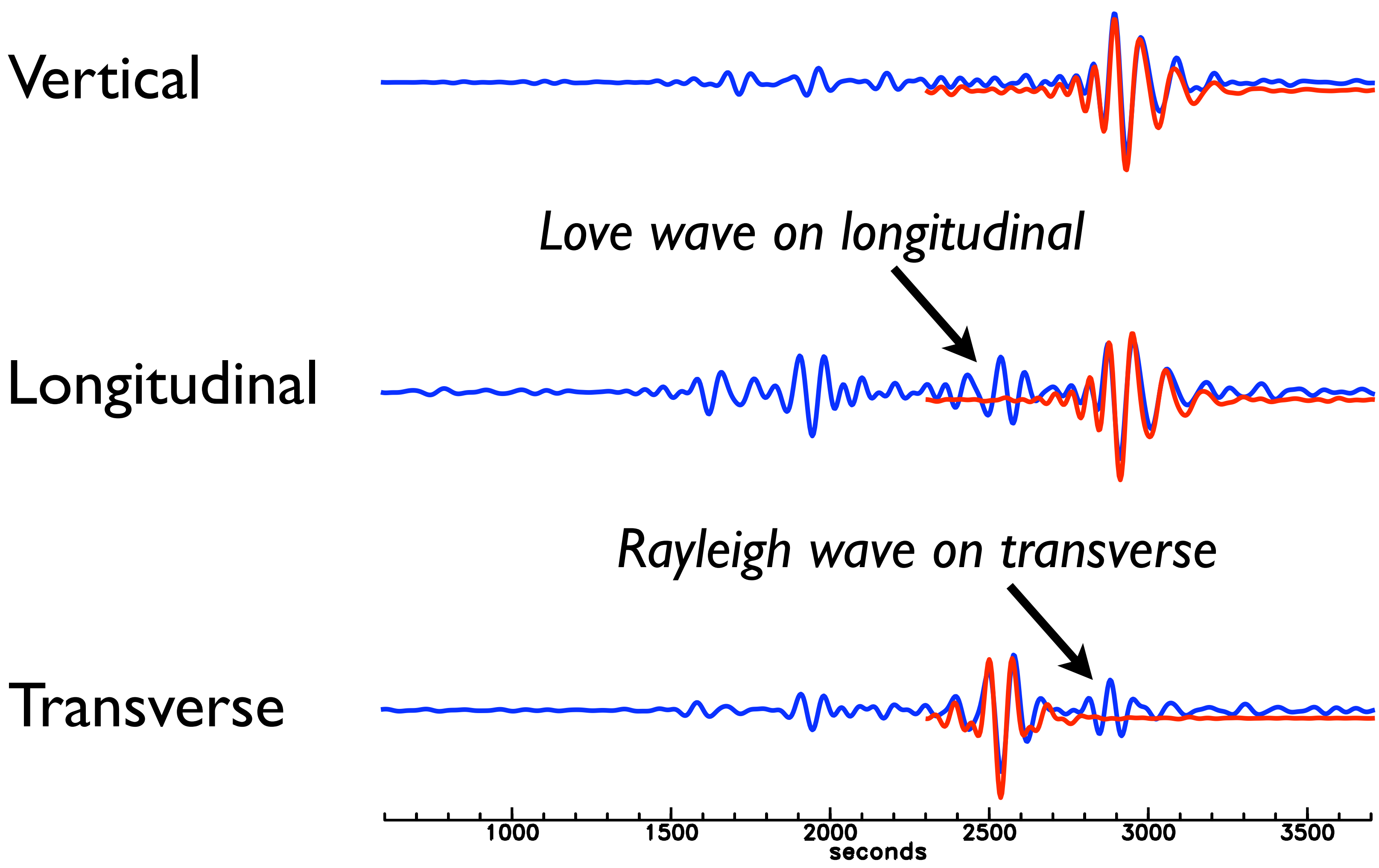
True orientation of seismometer



Natural Polarization of Earthquake Signals



Symptoms of a misoriented sensor



Station D09A, earthquake on 08/20/2007

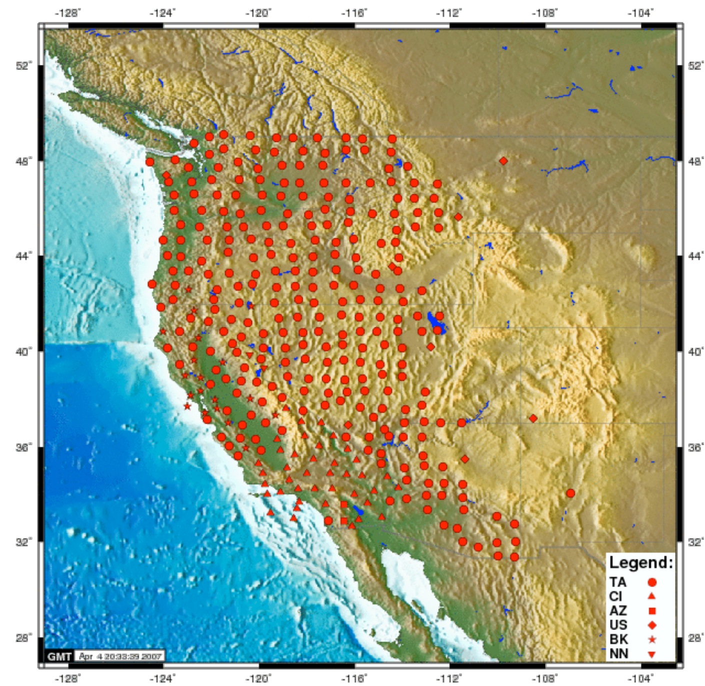
Polarization analysis of USArray data using earthquake signals recorded in 2006-2007

400+ USArray stations

Result:

> 5% misoriented > 10 degrees

> 10 % misoriented > 5 degrees

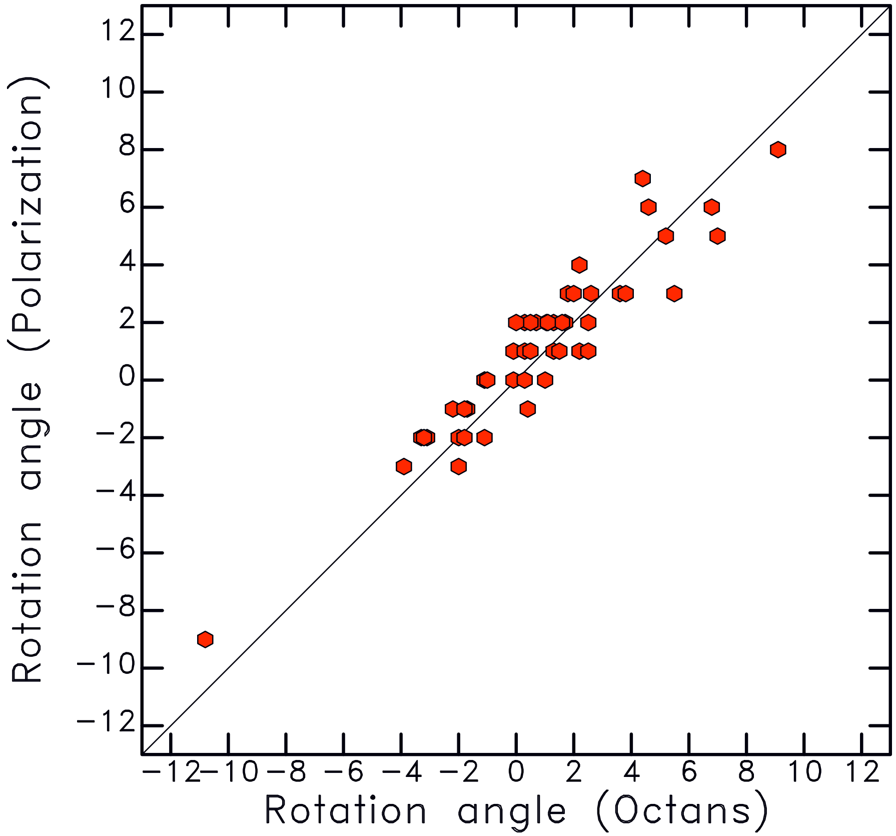


Ekström & Busby, SRL, 2008

Octans interferometric laser gyro

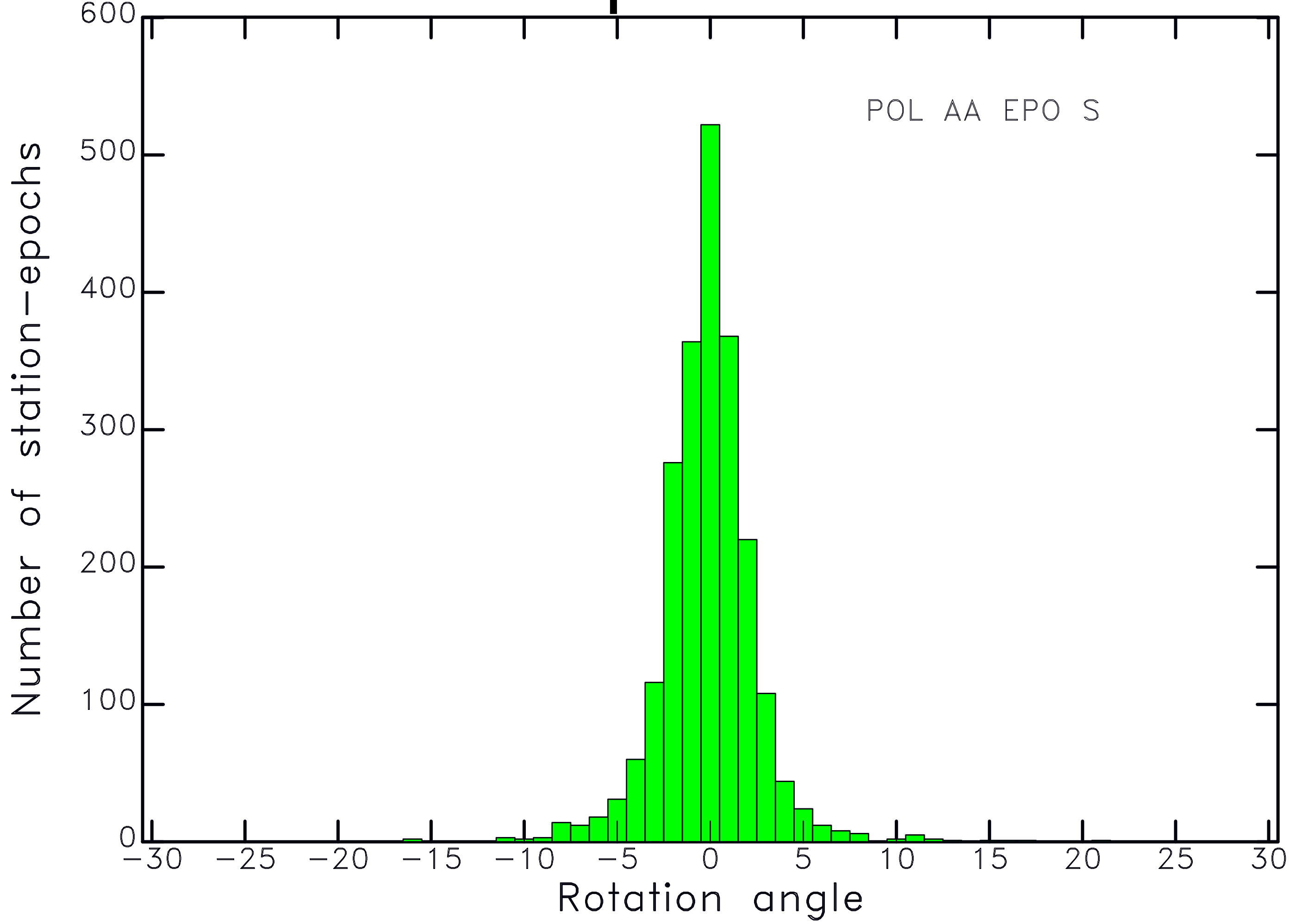
New procedures!

Empirical measurements agree with Octans



Ekström & Busby, SRL, 2008

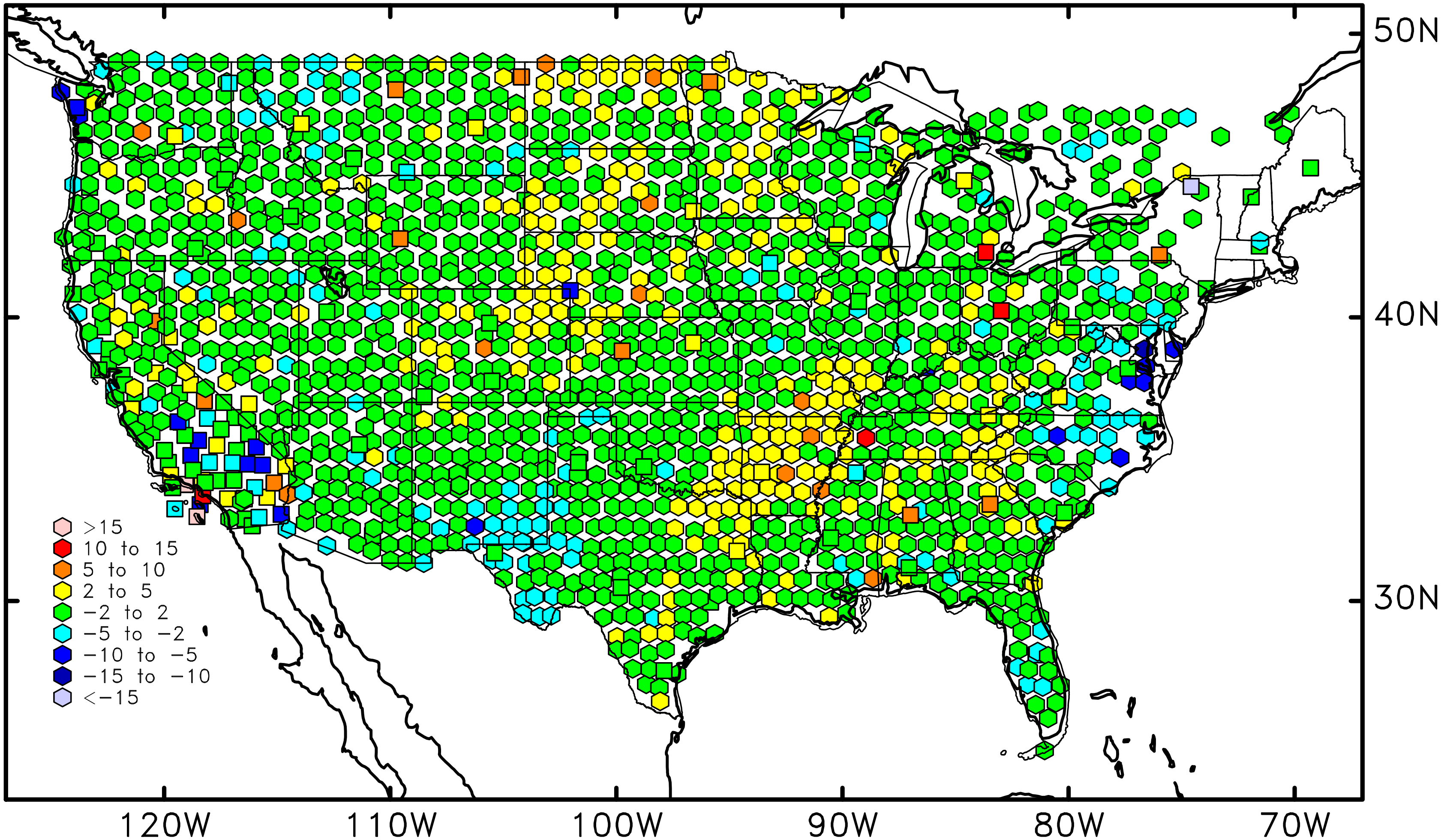
2013 UPDATE
Distribution of polarization anomalies



TA + USArray permanent (2227 station epochs)

cumulative, 2006-01-01 to 2013-12-31

Station polarization anomalies



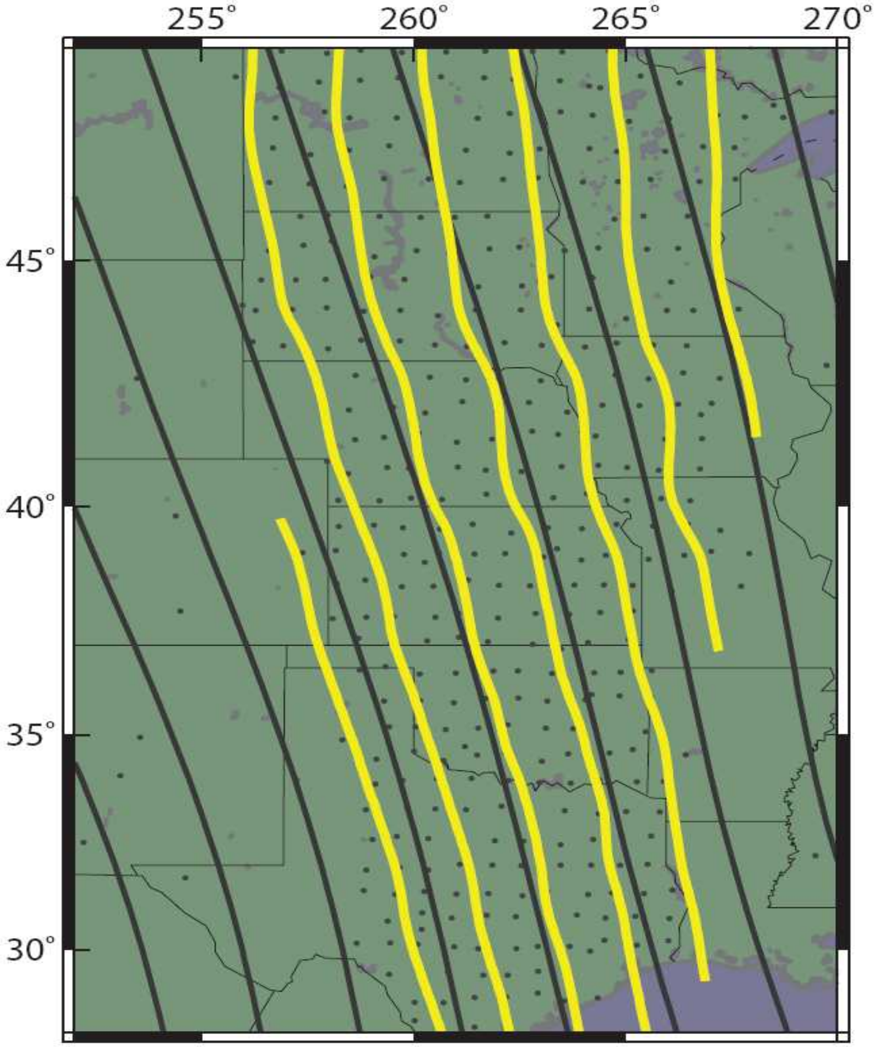
Intermediate-period surface waves
(squares are non-TA)

Statistics of absolute polarization anomalies

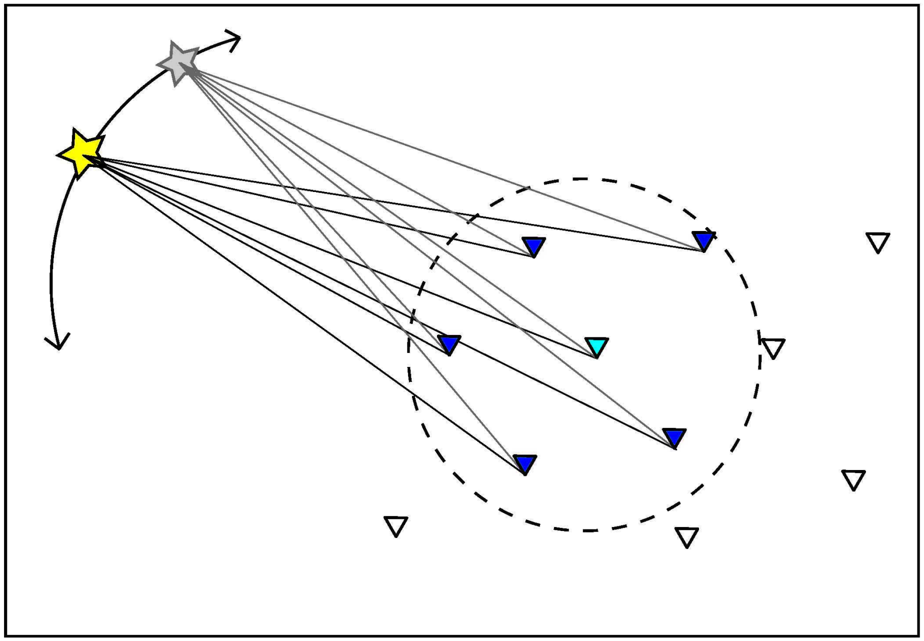
network	≤3 deg.	≤6 deg.	#epochs
TA	92.2%	98.9%	1829
US	69.6%	90.5%	158
BK	82.1%	100.0%	28
CI	58.2%	77.1%	122
II+IU	76.6%	91.1%	726
G	85.7%	98.7%	77

Mapping phase-front geometry across USArray

Single-station phase

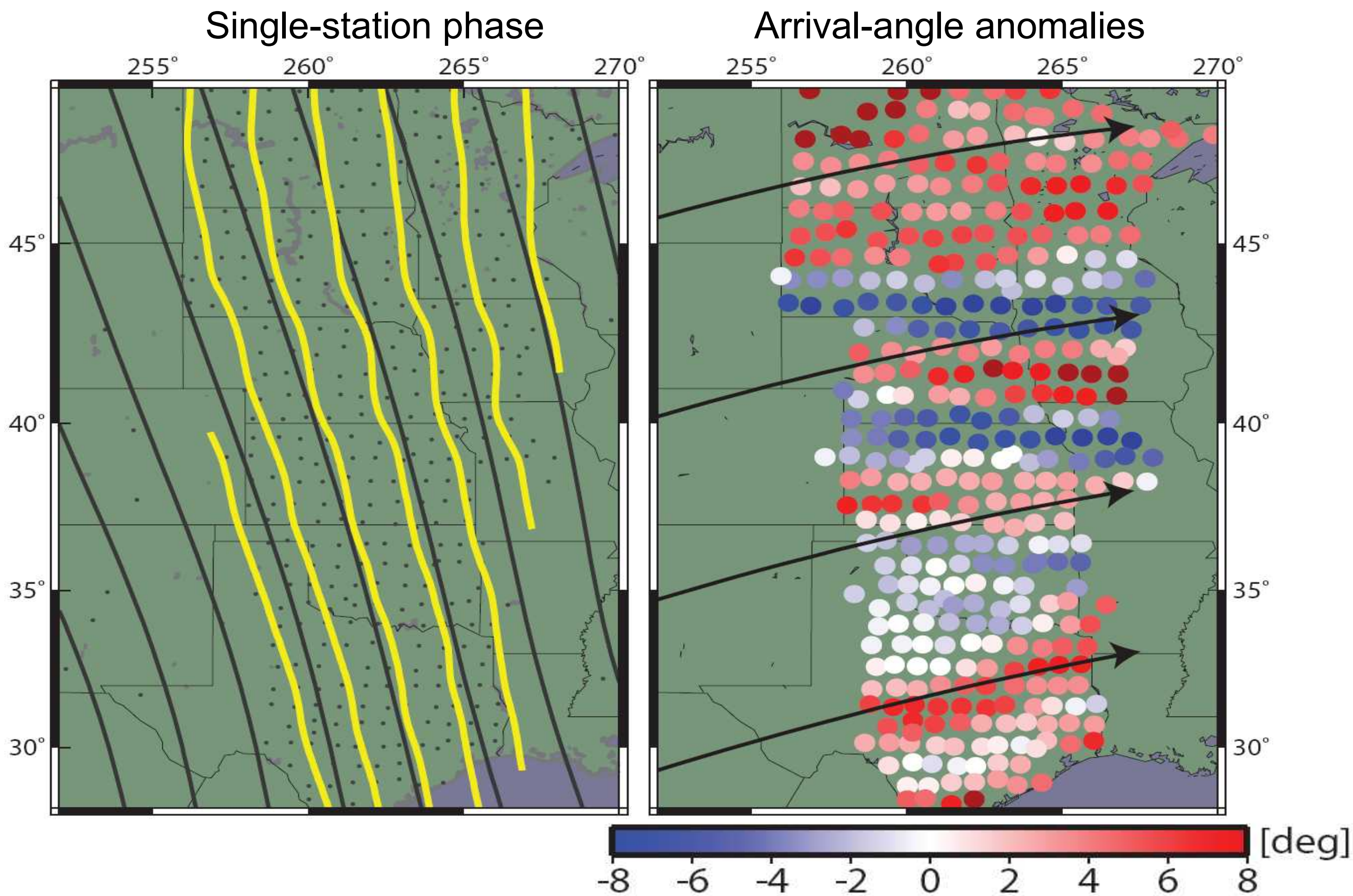


Mini-array back azimuth



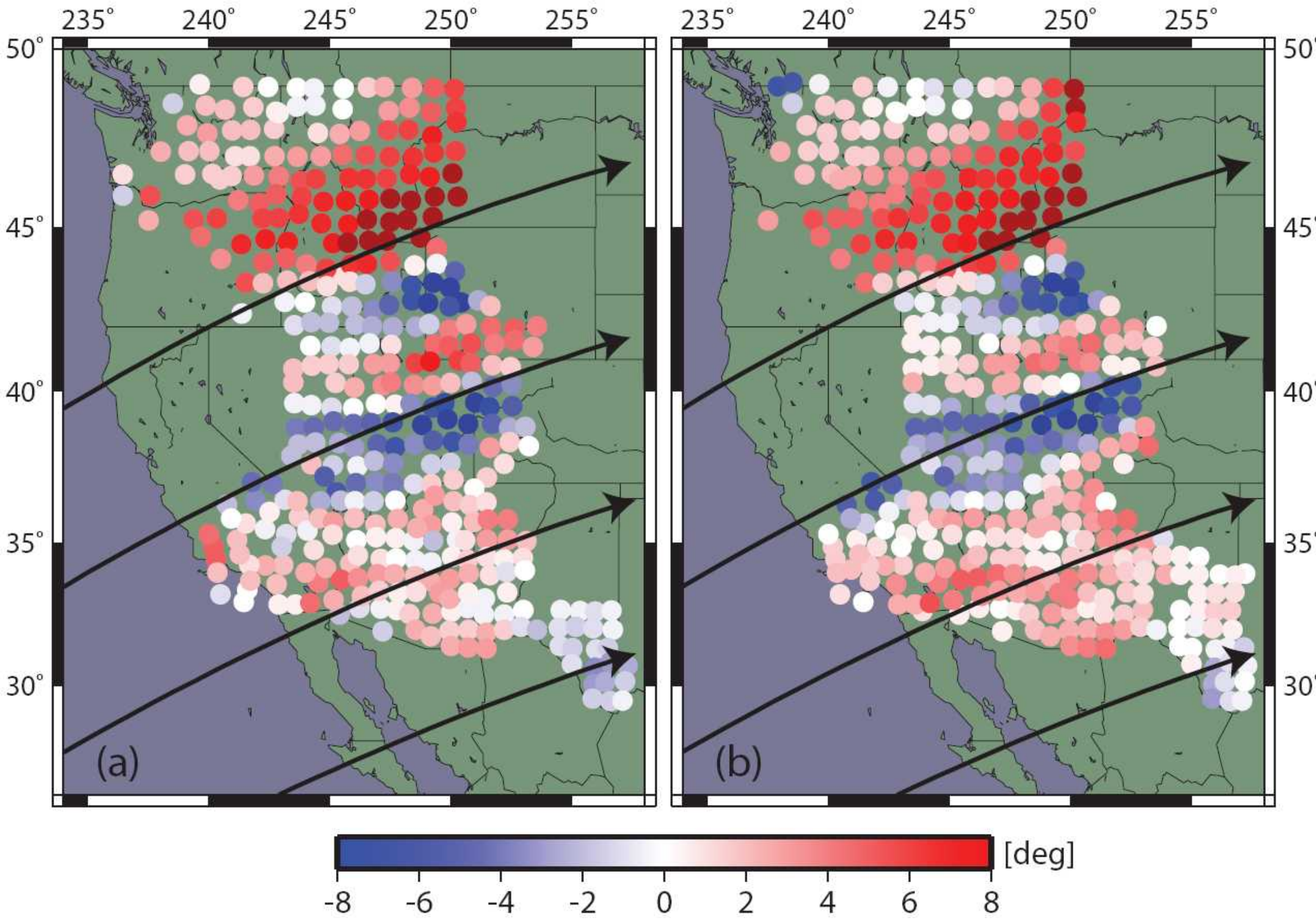
Foster et al., 2013

Mapping phase-front geometry across USArray



Foster et al., 2013

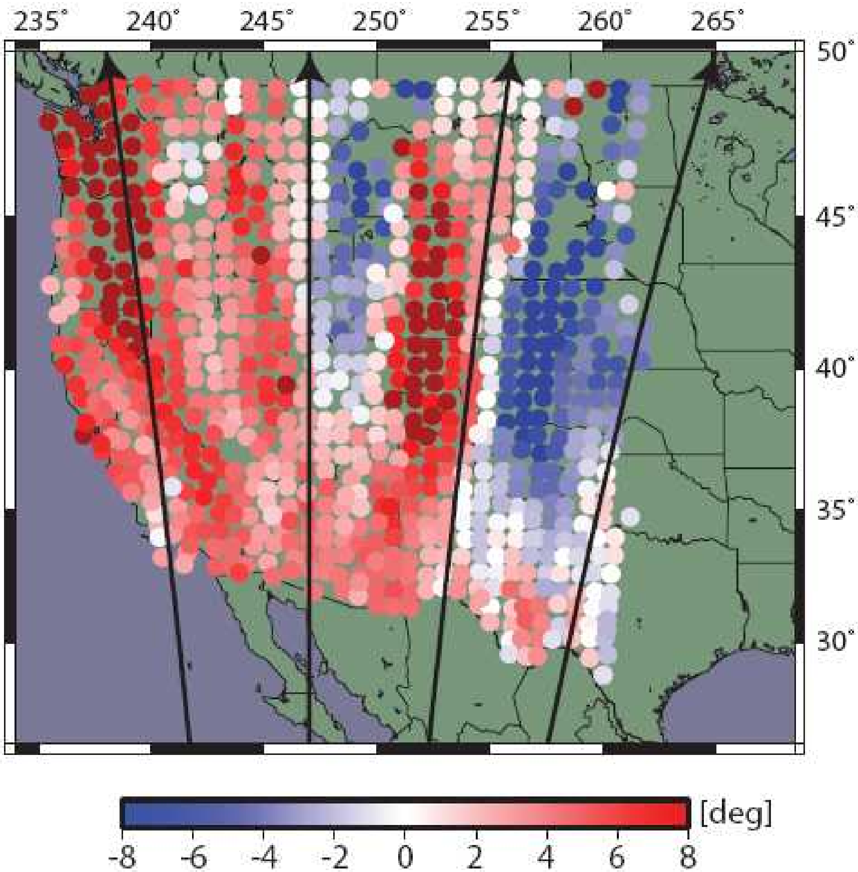
Two earthquakes - the same pattern



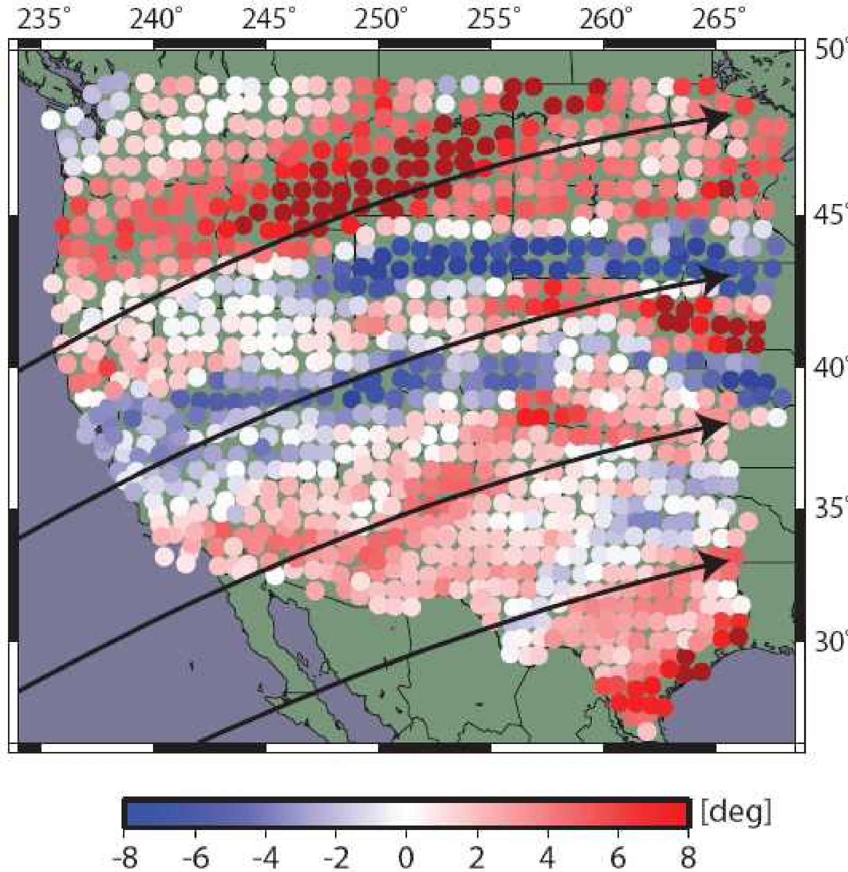
Foster et al., 2013

Composite events and anomaly maps

Easter Island

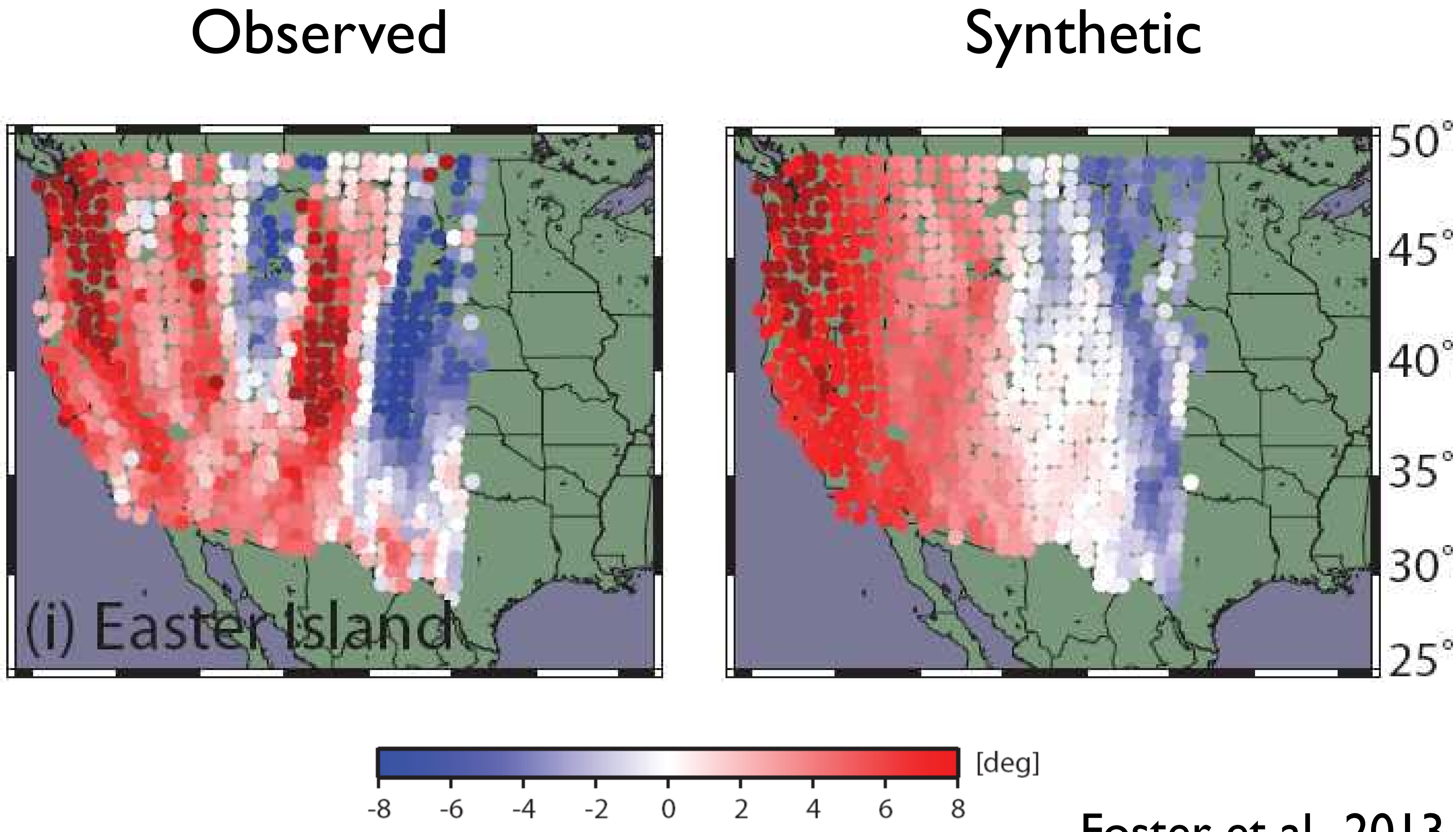


Loyalty Islands



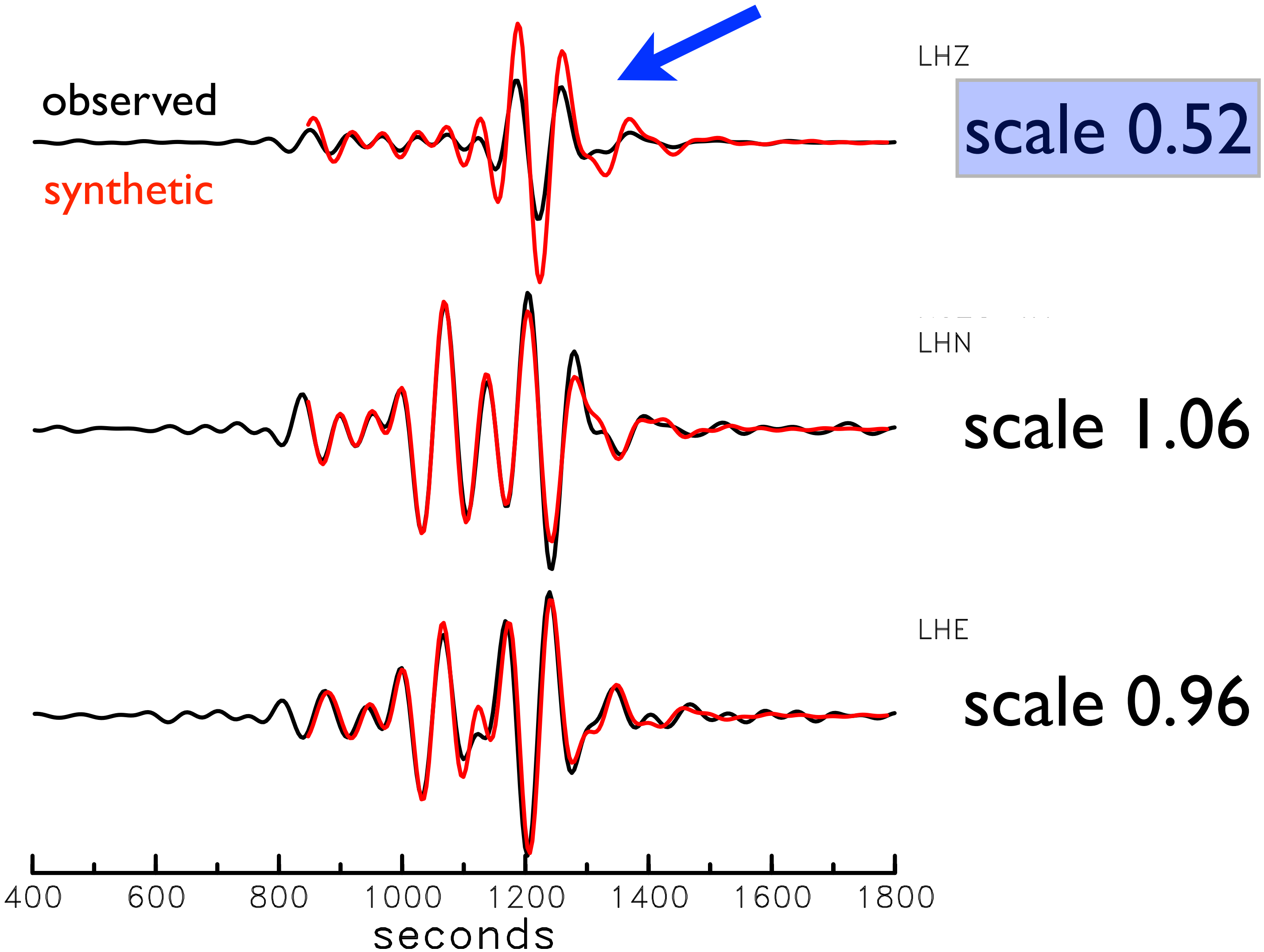
Foster et al., 2013

Comparison with measurements on SPECFEM synthetics (S362ANI + CRUST2.0)

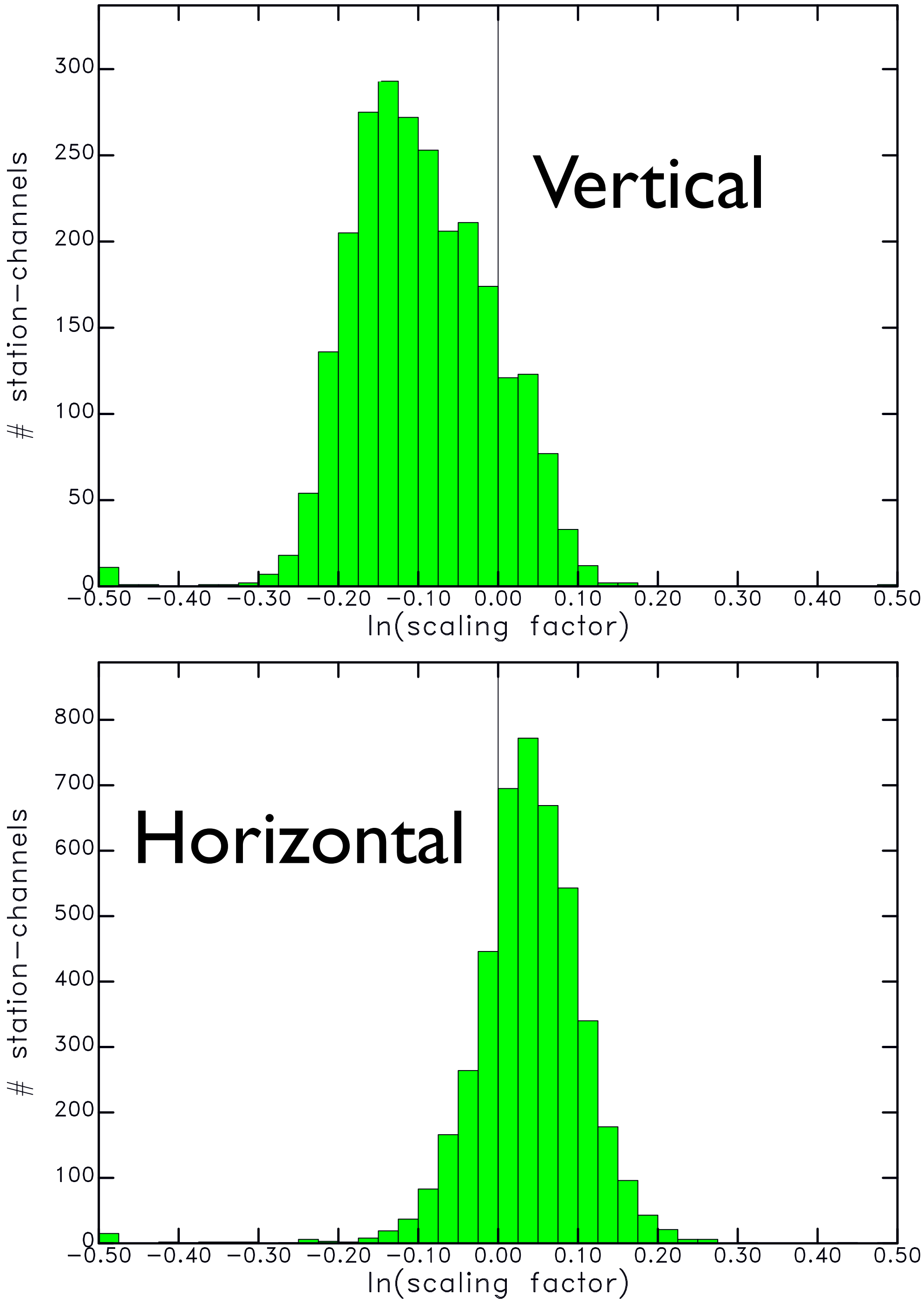


Foster et al., 2013

Symptoms of a seismometer with wrong gain



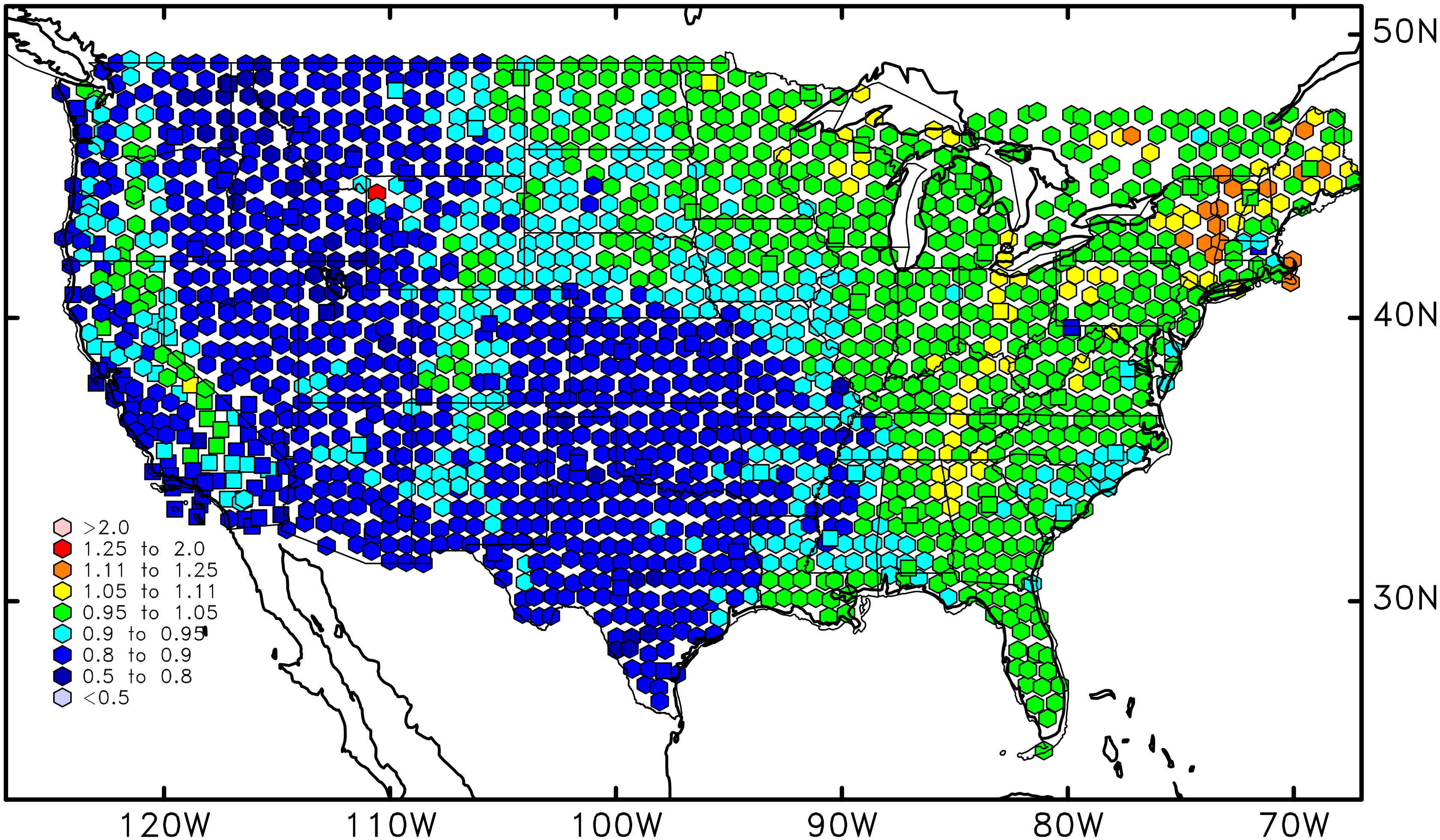
Station N02C, earthquake on 06/14/2006



Station scaling factors calculated from ~1,000,000 seismograms (50-sec body waves)

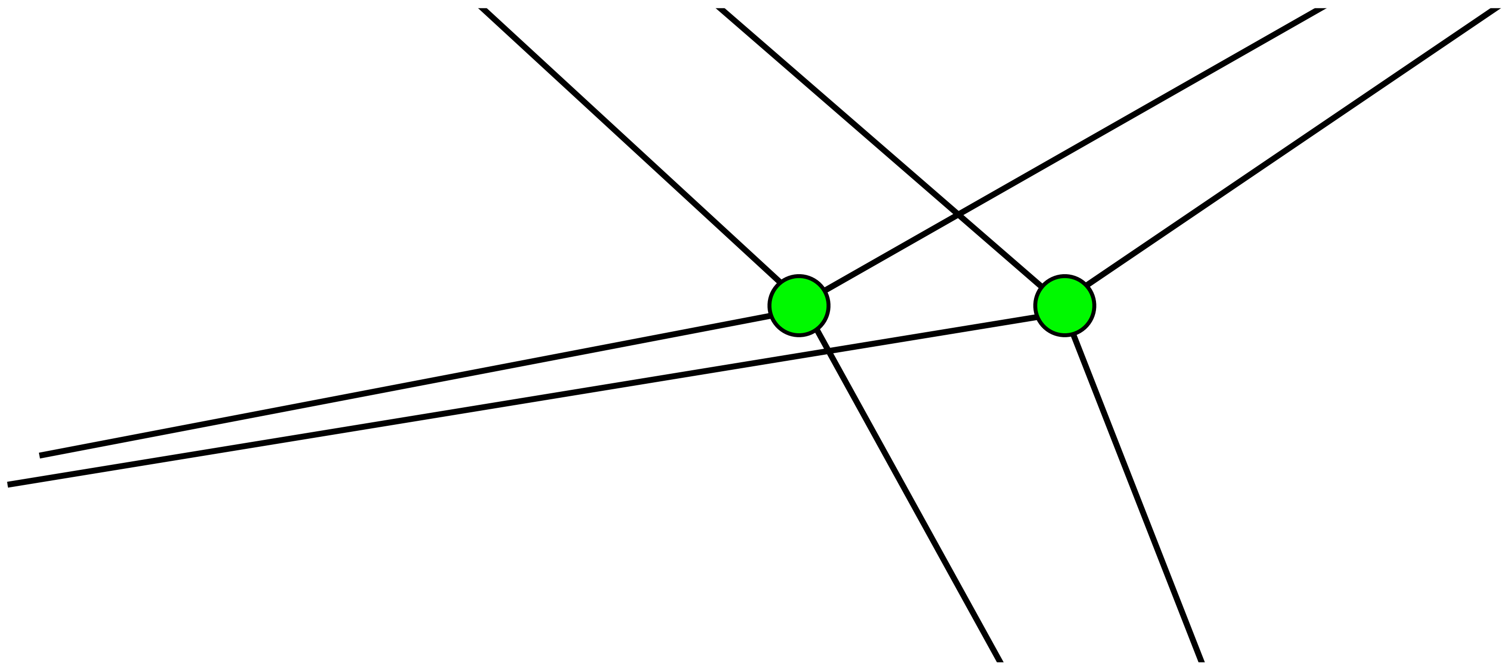
Large variability!

'Brute-force' scaling factors; variability but spatial coherence



(vertical body waves at 50 sec)

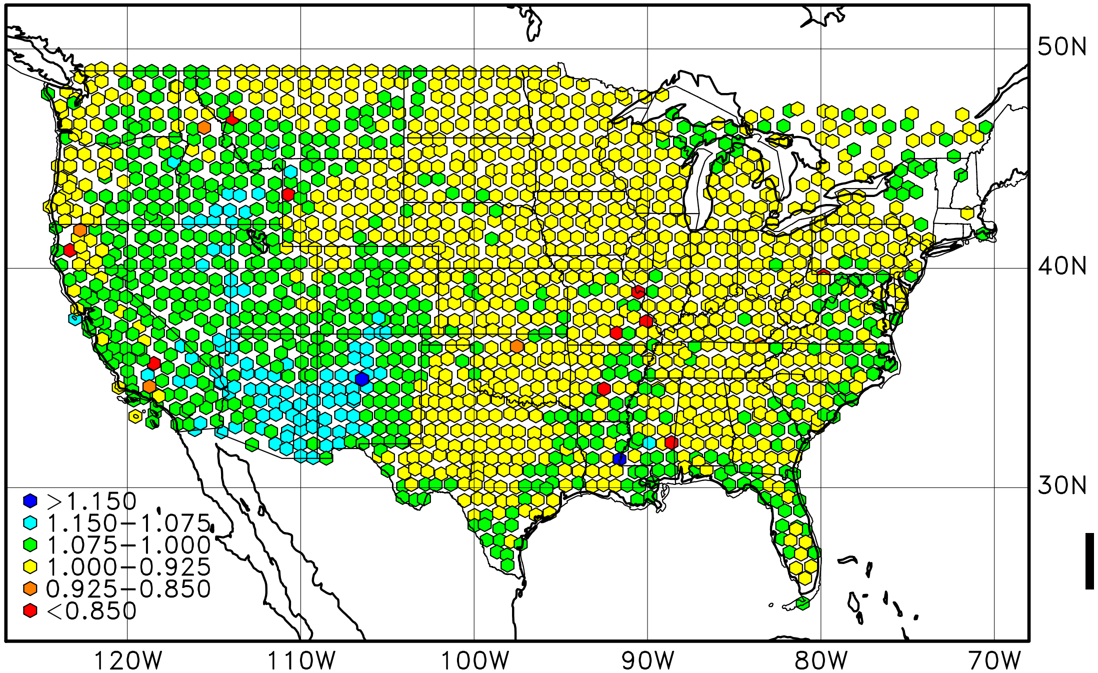
In-depth analysis of Rayleigh wave amplitudes:



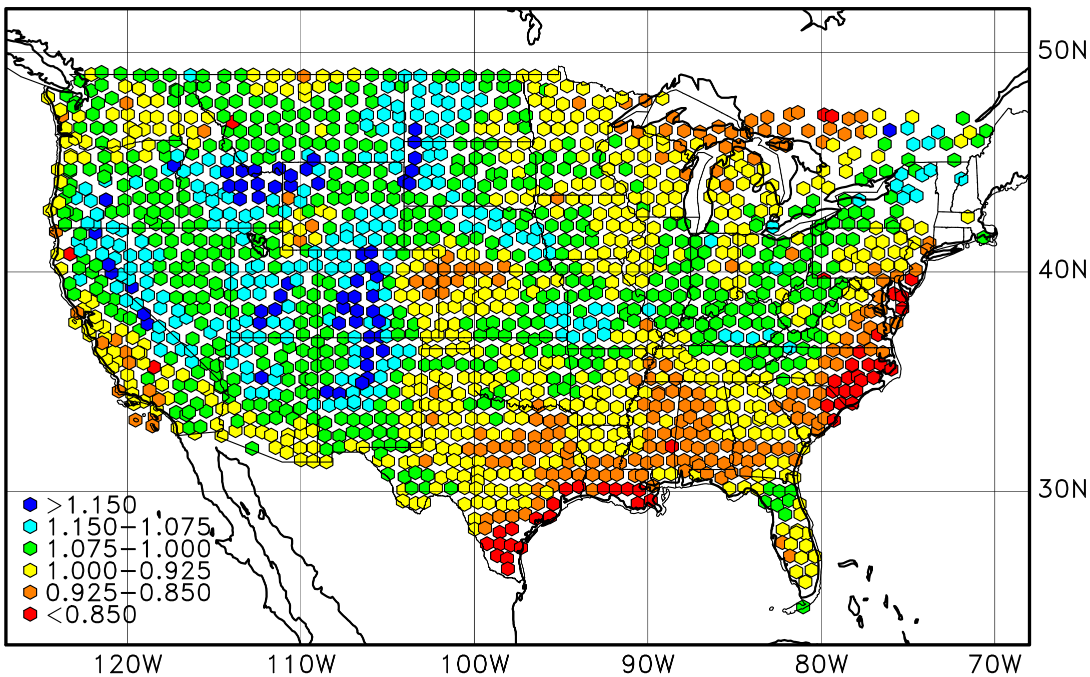
1. Measure Rayleigh wave amplitudes for many sources
2. Form amplitude ratios for adjacent stations
3. Average ratios over all events
4. Link all station pairs to determine amplitude factors across the entire array

Eddy & Ekström, 2013

Observed local Rayleigh wave amplitude factors



125 sec

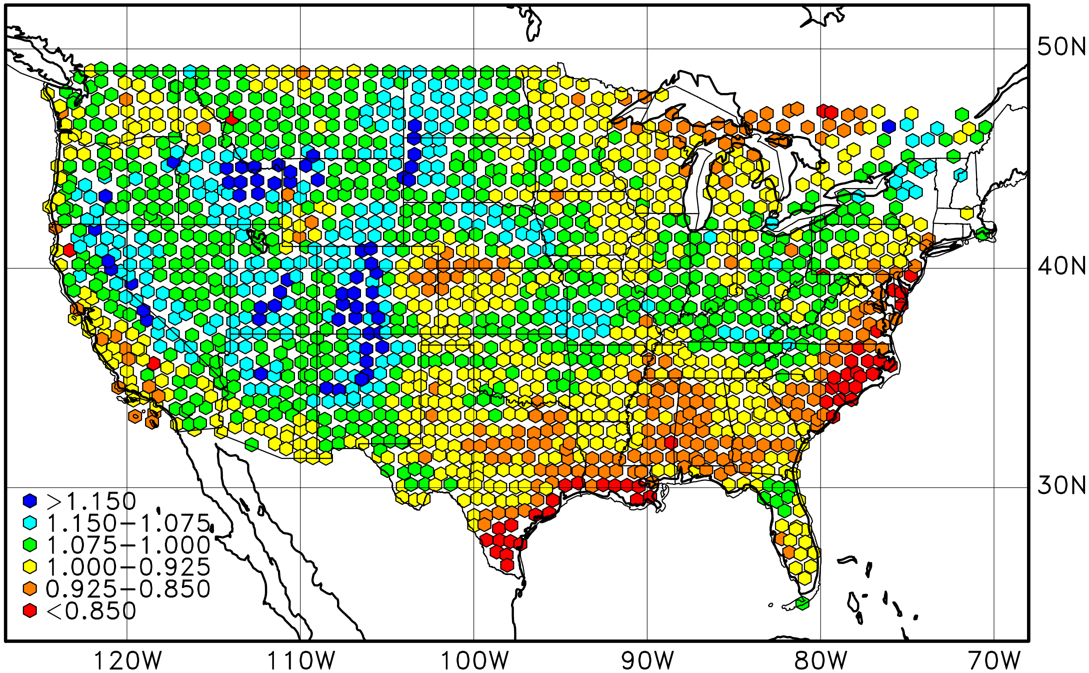


50 sec

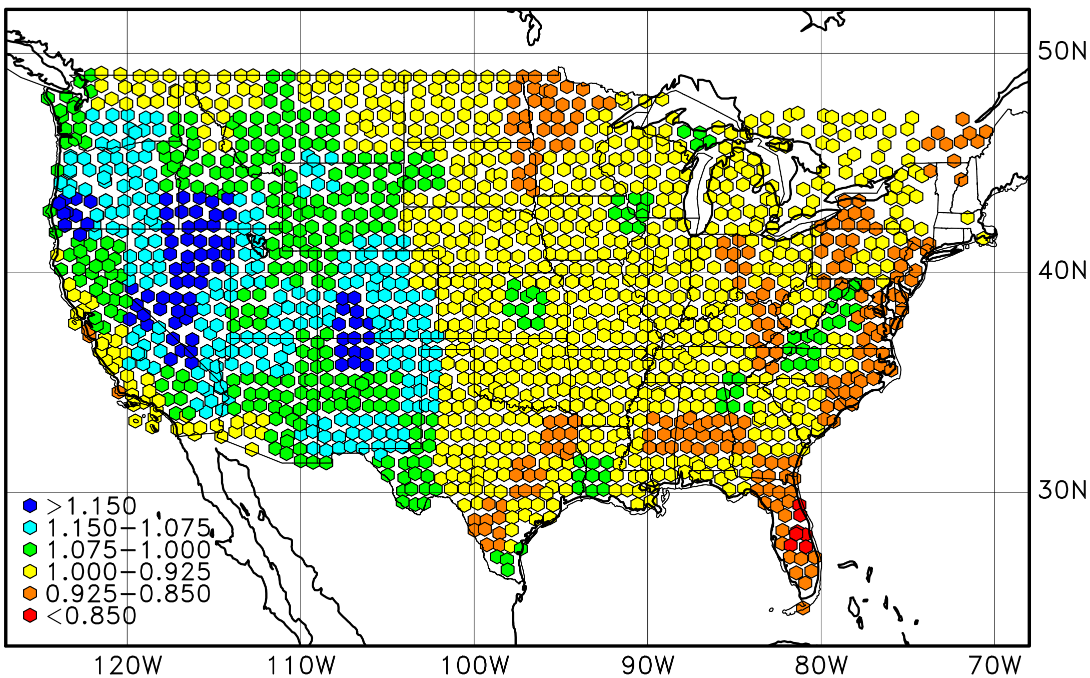
Eddy & Ekström, 2013

Rayleigh wave local amplification at 50 sec. at each USArray station

observed



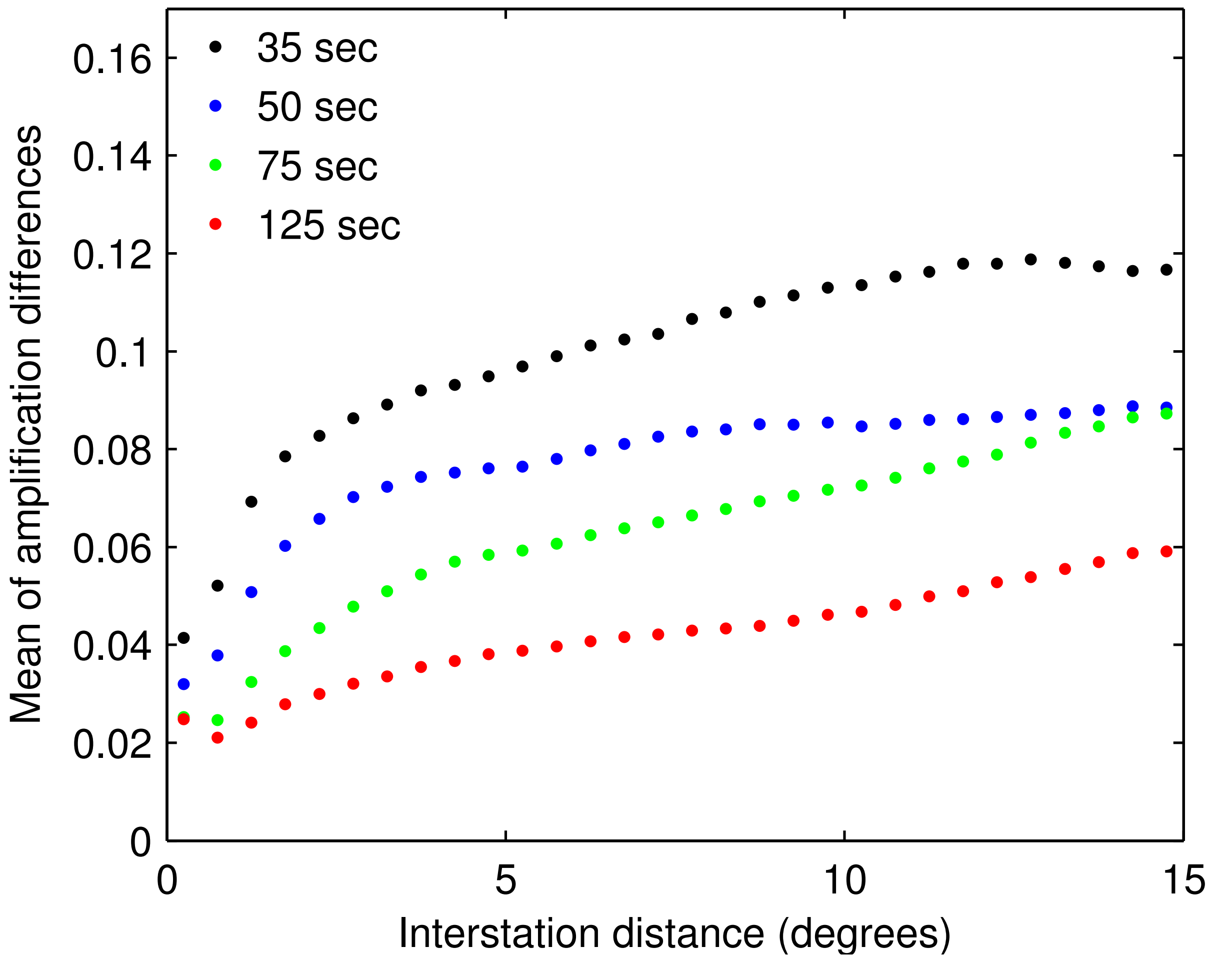
predicted



Predictions from ND08 mantle model
(Nettles and Dziewonski, 2008)
and CRUST2.0 (Bassin et al., 2000)

Eddy & Ekström, 2013

Spatial coherence reflect high-quality calibration: small-distance asymptote suggest errors < 2-3%



Eddy & Ekström, 2013

Conclusions:

The USArray TA instruments are oriented within ~2 degrees (one sigma)

---- unique opportunities for quantitative investigation of wavefield polarization

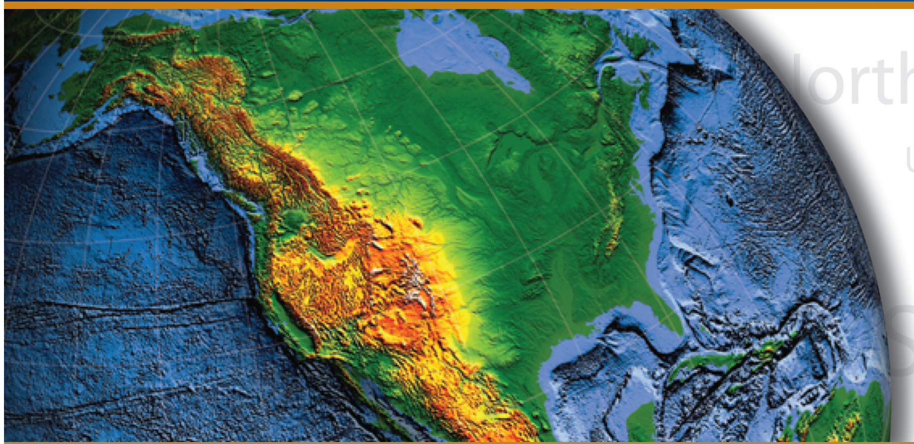
The USArray TA instruments are calibrated within ~2% (one sigma)

---- unique opportunities for investigations of wavefield amplitude and attenuation in the Earth

Quality -
the greater challenge

An even greater challenge!

earthscope



Unlocking the Secrets of the North American Continent

An EarthScope Science Plan for 2010–2020