Seismic Array Processing with ***Antelope***

November, 2008
Antelope User Group Meeting
Geoscience Australia, Canberra

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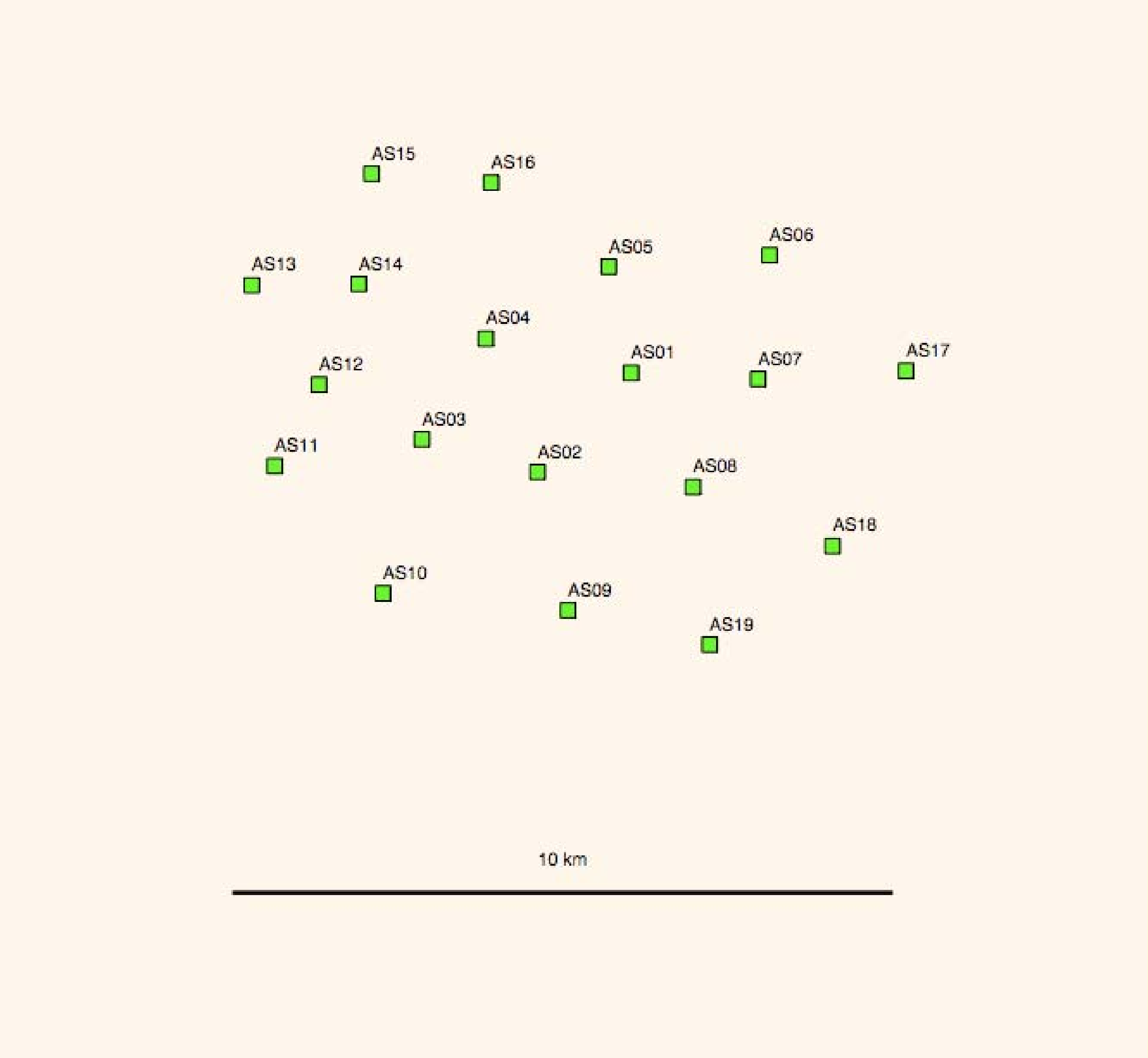
BOULDER REAL TIME TECHNOLOGIES, INC.

What is the Advantage of Seismic Array Processing?

- Seismic arrays are geographic distributions of matched seismic sensors whose data can be used to infer certain seismic wavefield properties
- The spatial aperture of seismic arrays has traditionally been small in extent
- There are a number of these small aperture seismic arrays around the world including two in Australia
- Small aperture seismic arrays have been used to estimate the horizontal vector slowness of the impinging wavefield from a seismic event
- Estimates of horizontal vector slowness can be used to provide approximate event locations using only data from a single array
- Horizontal vector slowness estimates from multiple arrays have been used to refine event location estimates and, more importantly, to provide a means for estimating fault propagation characteristics for large events
- Fault propagation models can be used to determine overall energy release and as a starting point for modeling Tsunami propagation
- All of this can be done quickly using only the P-arrival part of the waveform, thereby supporting Tsunami Early Warning

Alice Springs Seismic Array



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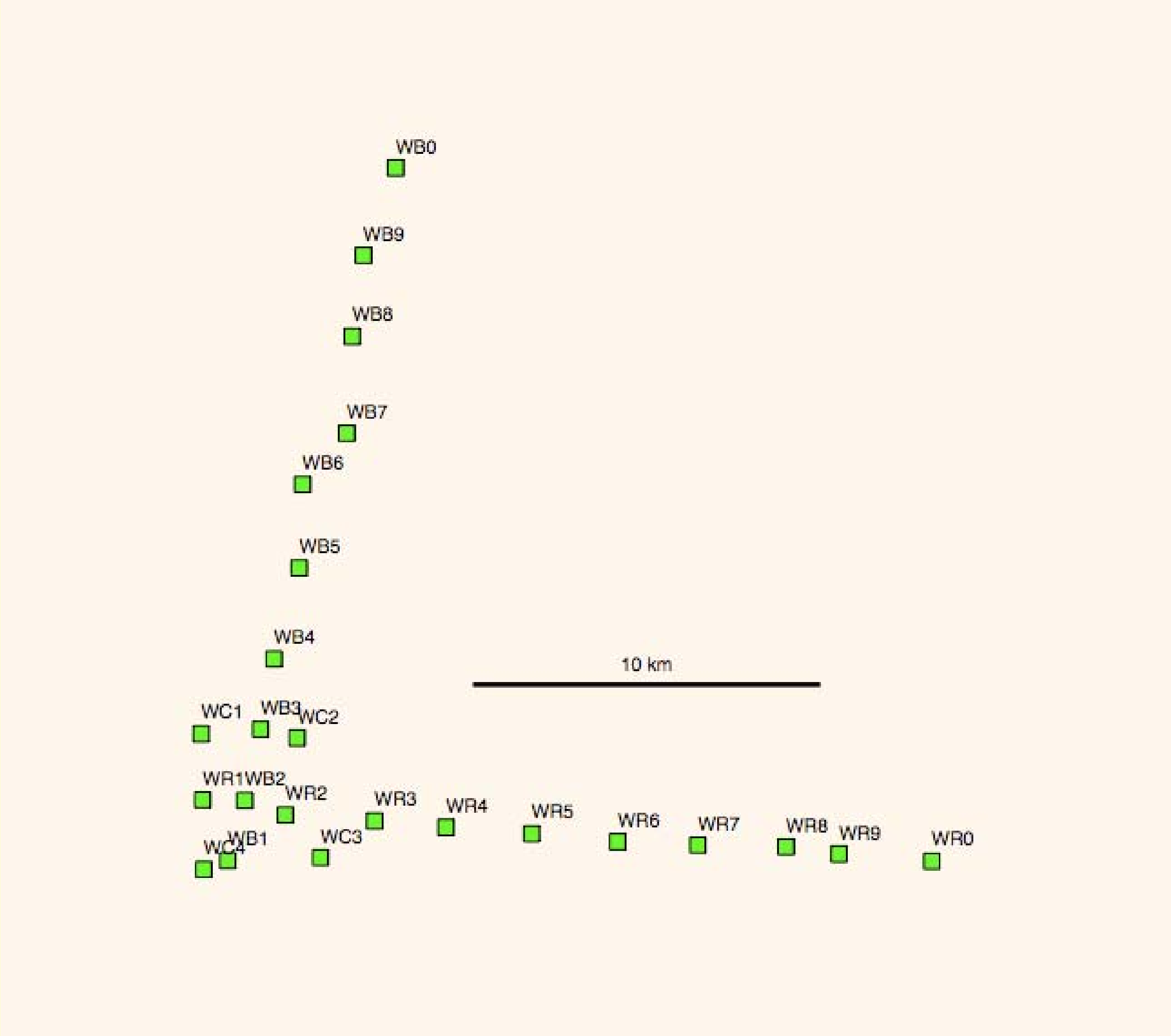
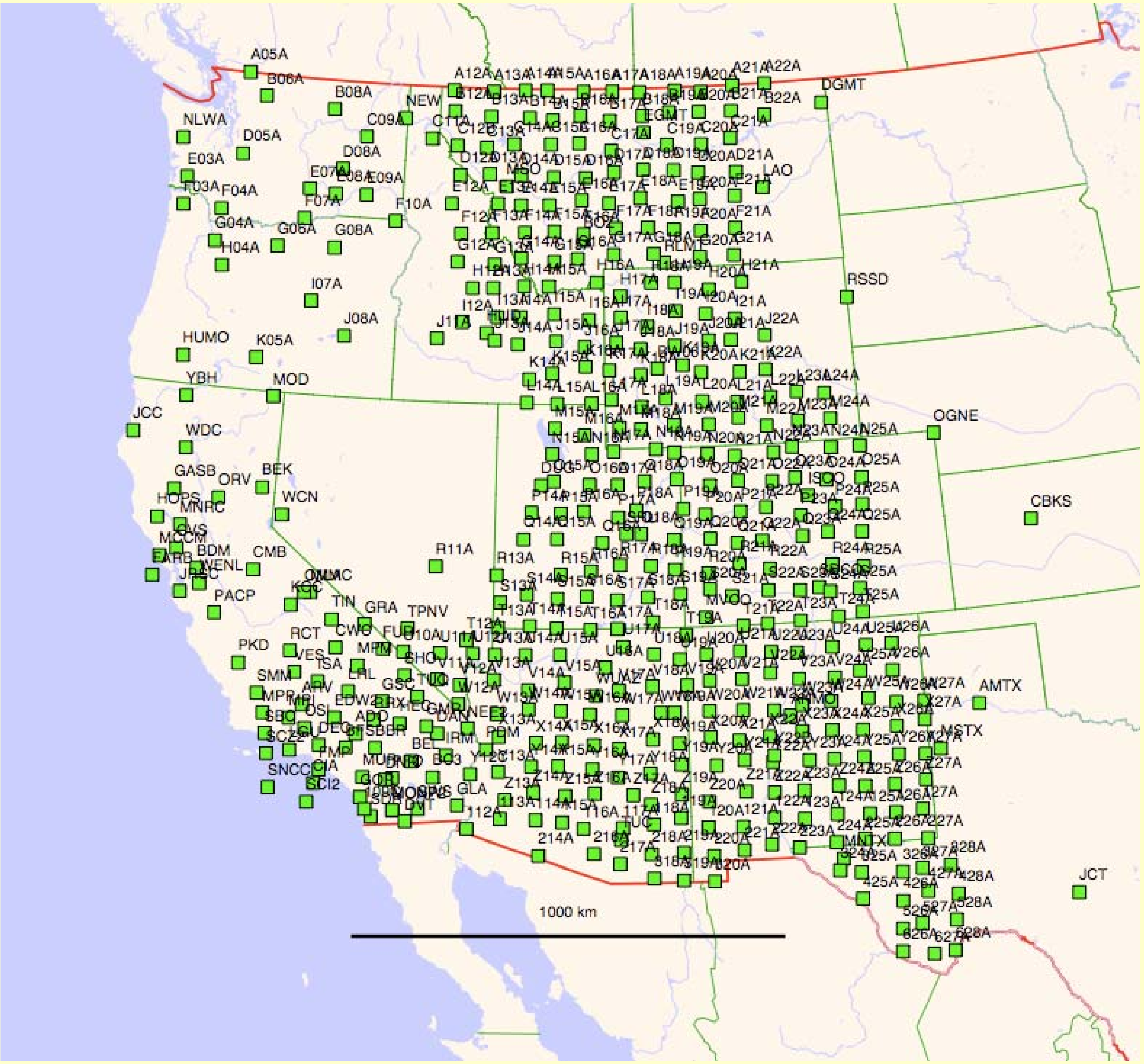
Warramunga Seismic Array



USArray Transportable Array



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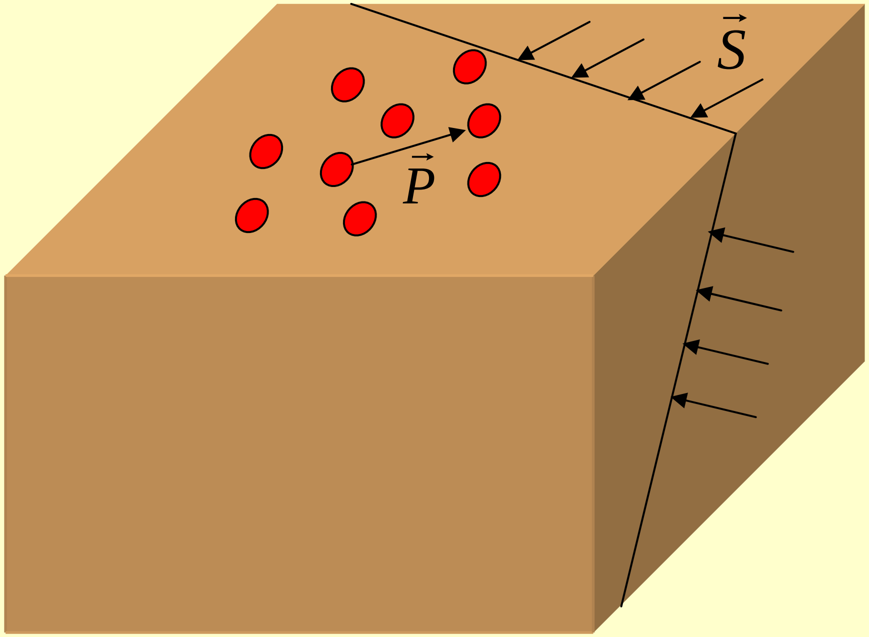
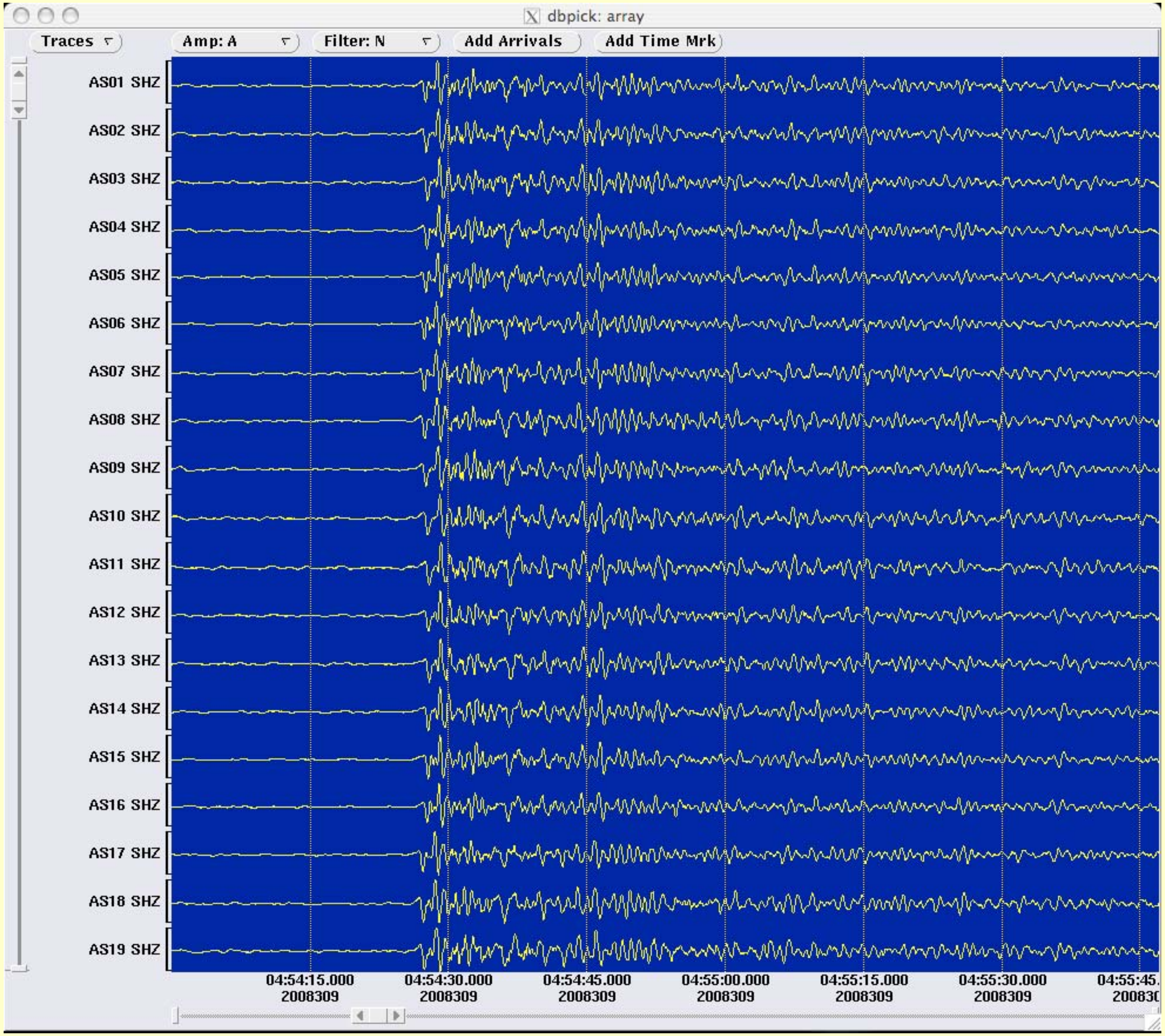
Array Processing 101

- Consider a seismic wavefield from a P-arrival impinging upon a small aperture array

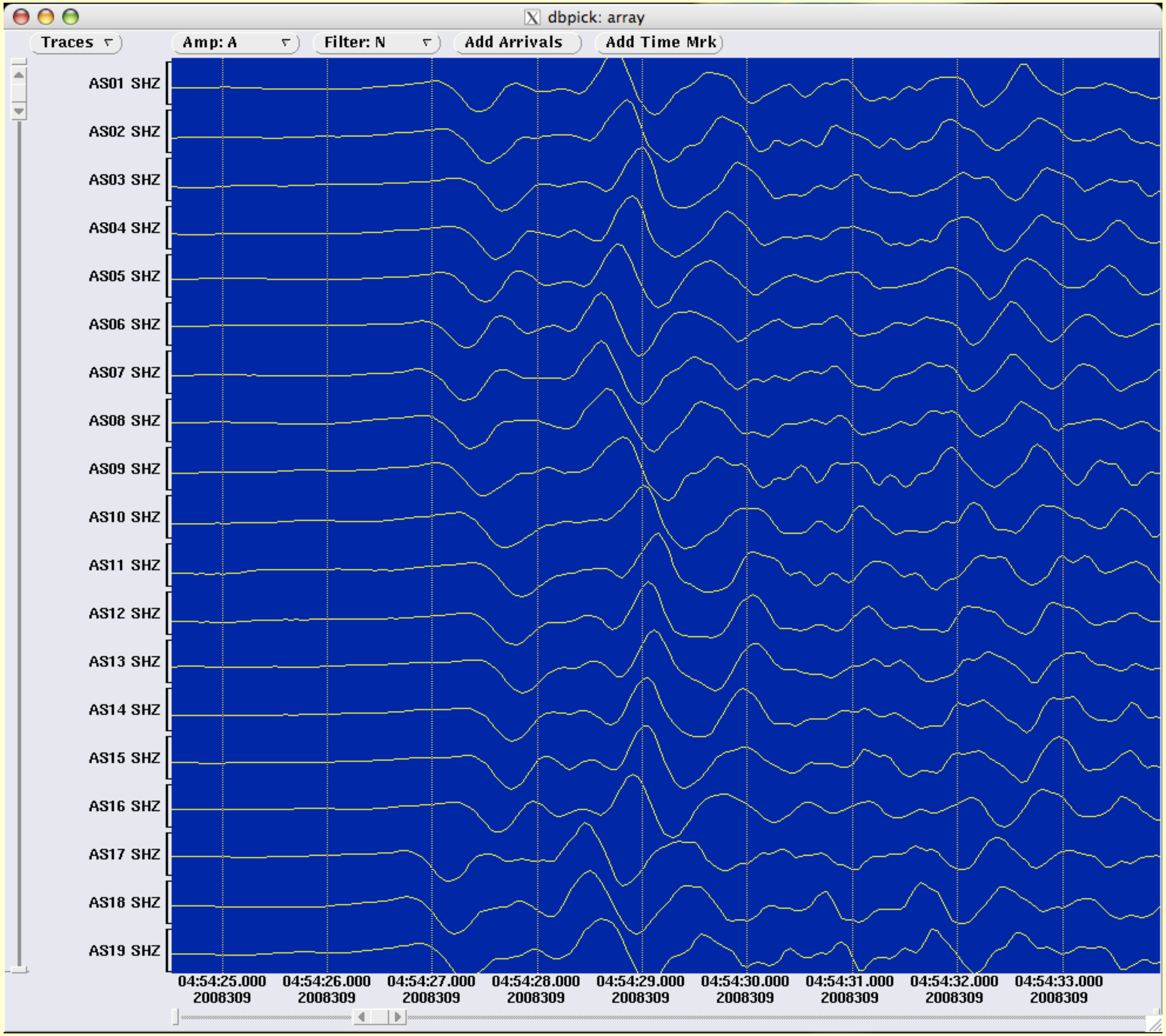


This seismic wavefield is planar which is a reasonable approximation for a wavefield across a small aperture array from a distant event

Alice Springs Example



Alice Springs Example



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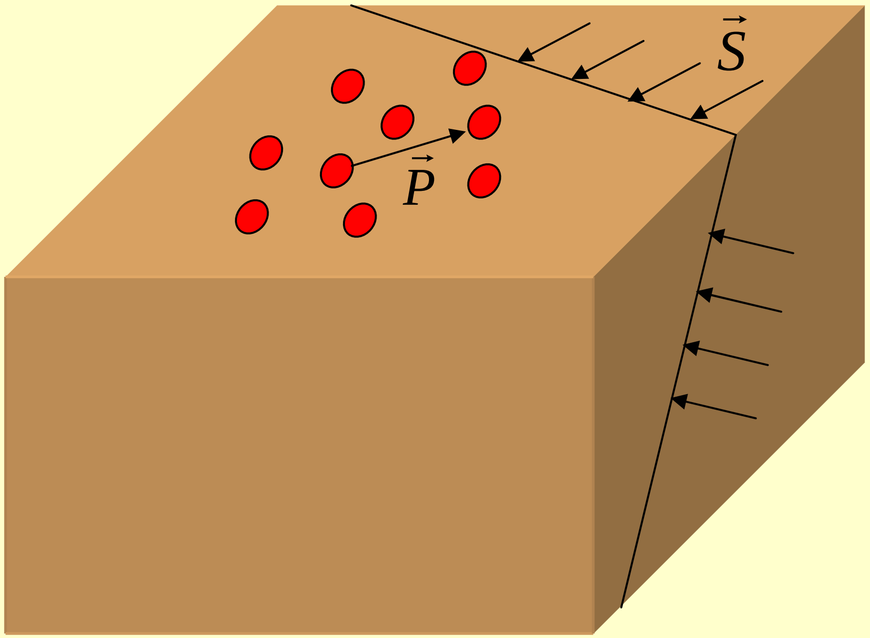
Array Processing 101

- Consider a seismic wavefield from a P-arrival impinging upon a small aperture array



This seismic wavefield is planar which is a reasonable approximation for a wavefield across a small aperture array from a distant event

- A planar wavefield like this produces a time shift to an otherwise approximately coherent seismogram at each station
- If $\vec{P}$ is the horizontal relative position vector between any two stations
- And $\vec{S}$ is the horizontal slowness vector of the impinging wavefield in sec/km
- Then $\Delta t = \vec{S} \bullet \vec{P}$ is the time it takes for the wavefield to propagate between the two stations
- If we assume a value of $\vec{S}$, we can compute Δt for each station relative to some reference station
- We can apply the Δt time shift to each station which should time align the waveforms if the value of $\vec{S}$ corresponds to the actual wavefield value
- All of the station waveforms can be summed together to produce a "beam". This process is also known as "stacking"
- We can repeat this "beamforming" procedure over a grid of $\vec{S}$ values and look for the beam with the largest power, thereby inferring the value of $\vec{S}$ for the wavefield; this process is known as seismic array processing

Array Antenna Patterns

- Seismic arrays behave in a manner similar to certain electromagnetic (RF) arrays; such electromagnetic arrays are sometimes referred to as “antennas”
- RF antennas have directional focusing characteristics; similarly seismic arrays also have directional focusing characteristics
- Antenna focusing gain patterns are common for RF antennas and can also be computed for seismic arrays; these antenna patterns show the array resolving power, for seismic arrays the ability to estimate $\vec{S}$, the wavefield horizontal slowness vector
- Consider a periodic seismic wavefield of form $\mathrm{Re}\left(e^{i\left(\omega t-\vec{k}\bullet\vec{x}\right)}\right)$
- If we define antenna gain as the stack power average over a wave cycle we get

$$A(\omega,\vec{S})=\frac{1}{n}\sum_{i=1}^{n}\cos^2\left(\omega\vec{S}\bullet\vec{P}_i\right)$$

- Where n is the number of stations in the array and $\vec{P}_i$ are the station horizontal positions relative to a reference station

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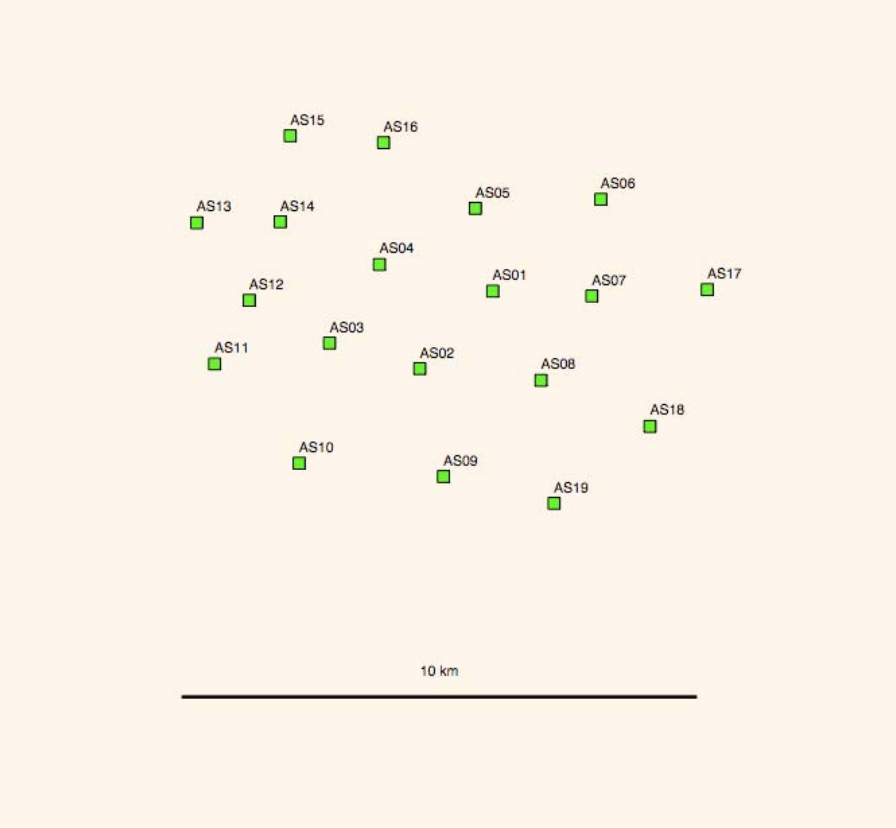
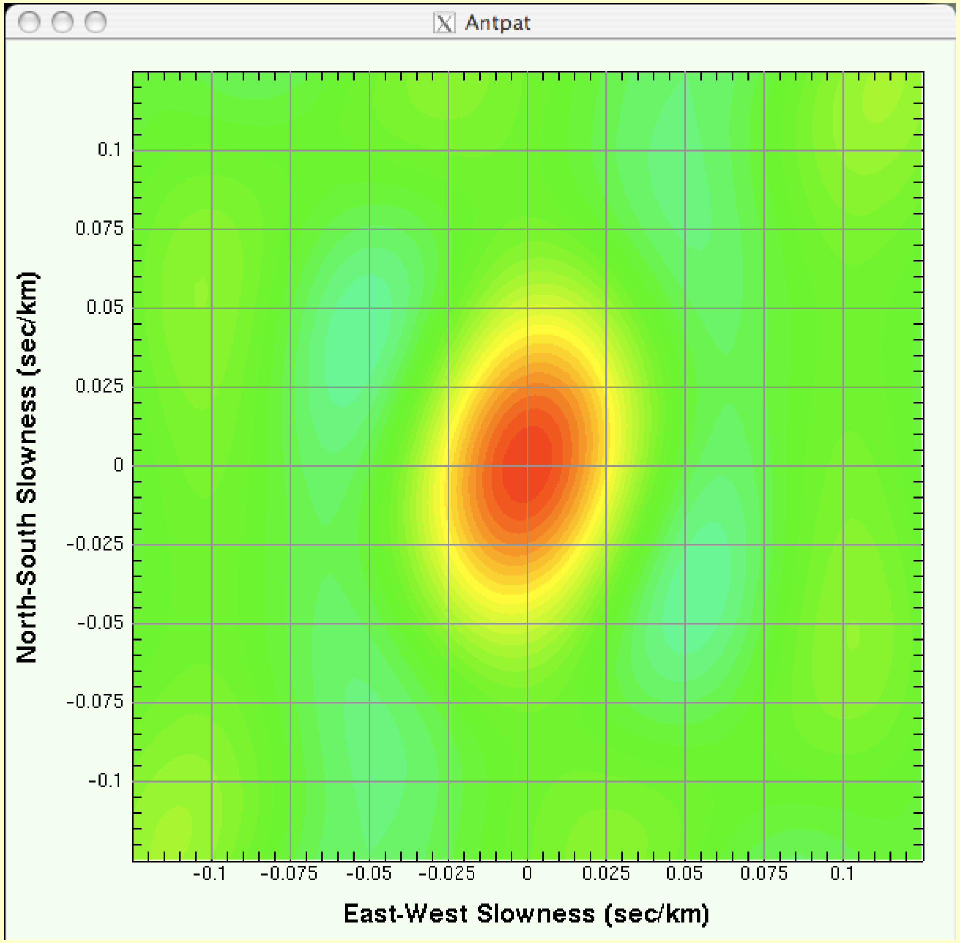
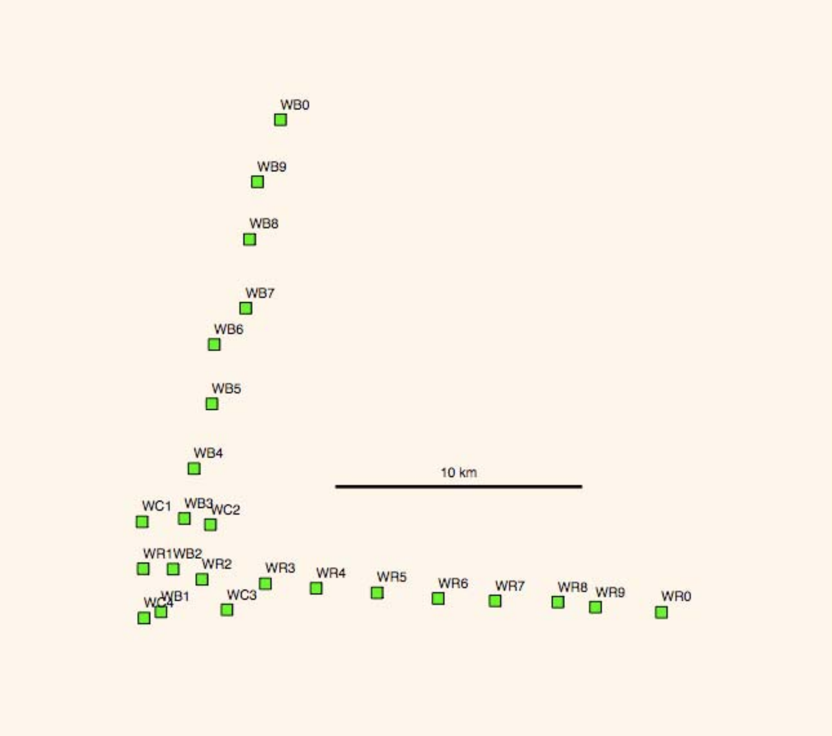
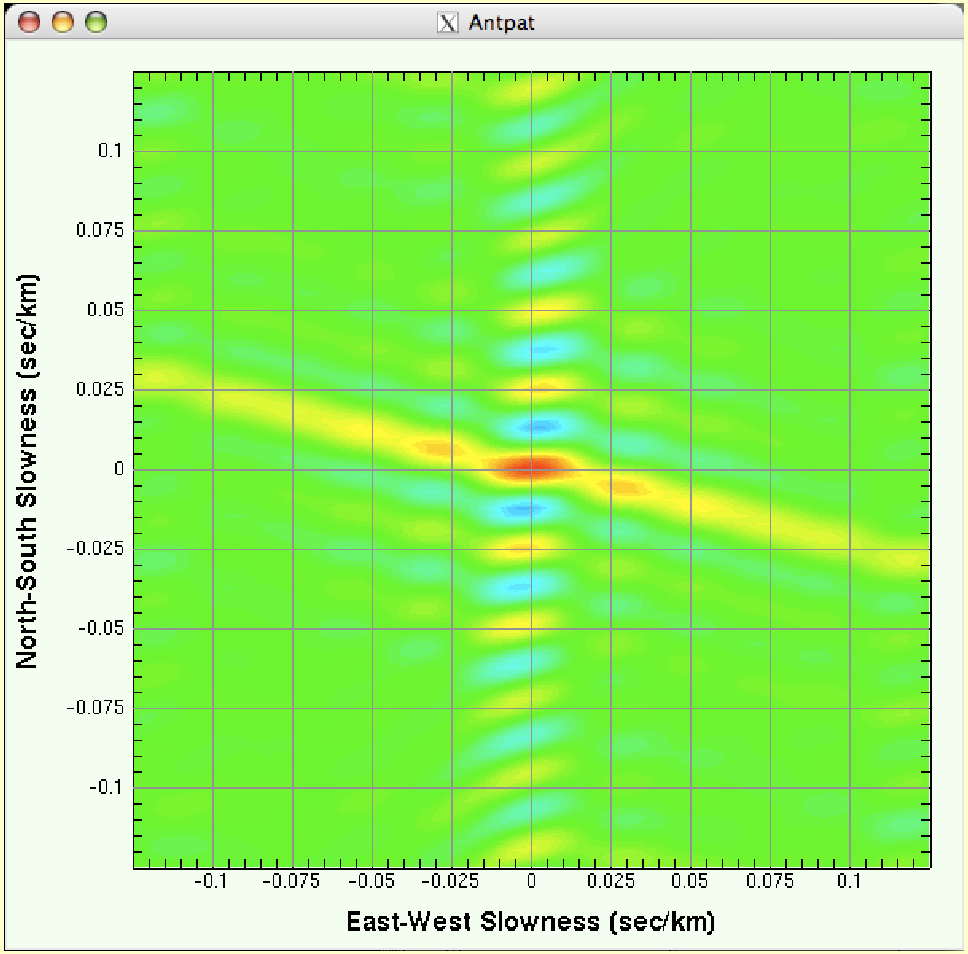
Alice Springs Antenna Pattern (1 hz)





Warramunga Antenna Pattern (1 hz)





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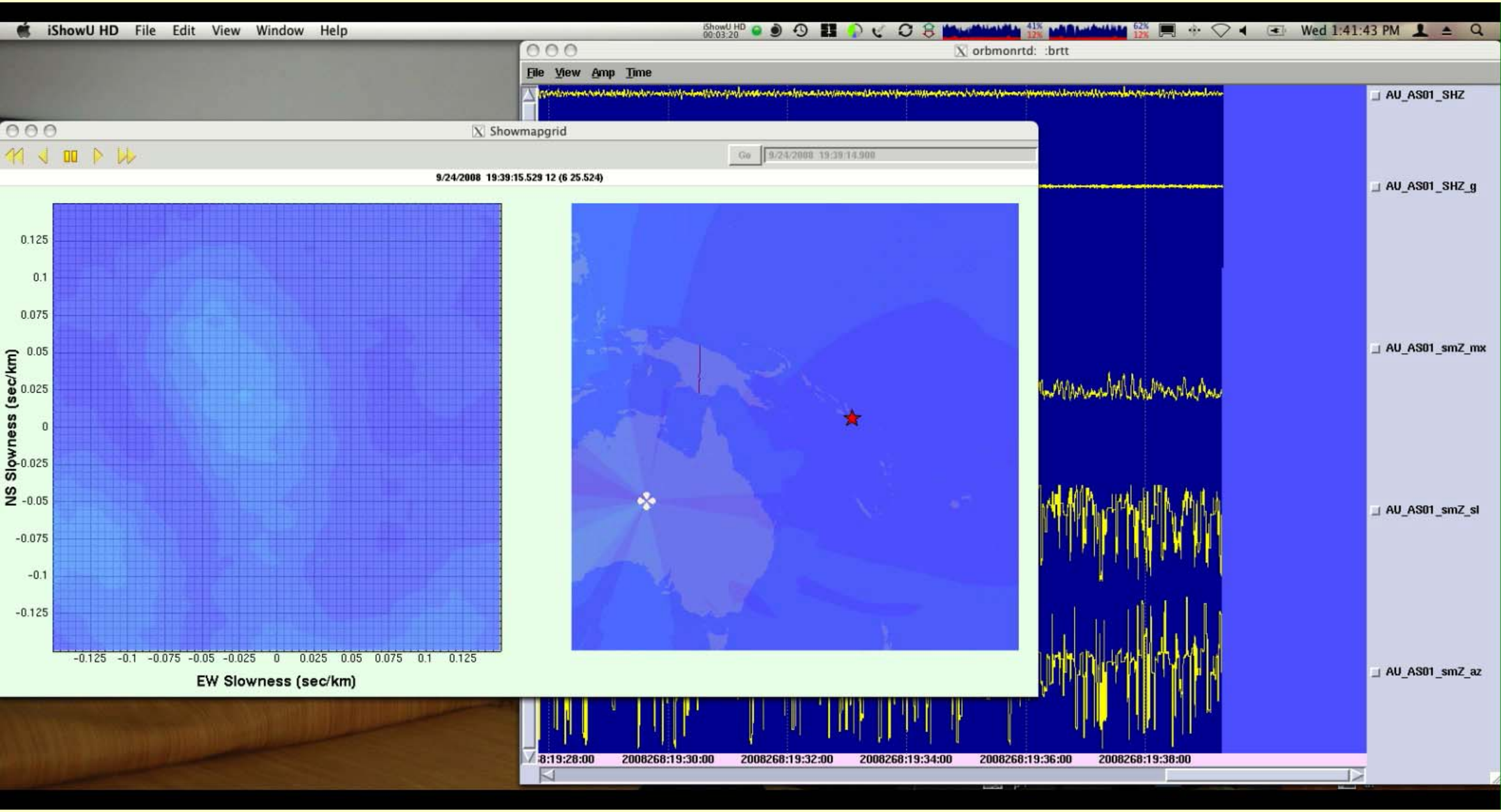
Array Processing in Antelope

- A new Antelope program, **`orbwfproc`**, has been developed that will provide real-time array processing capability
- A pre-release version of **`orbwfproc`** is being tested at Geoscience Australia; the first production version will be available in the next Antelope release scheduled for Spring 2009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orbmonrtd: :brtt
File View Amp Time
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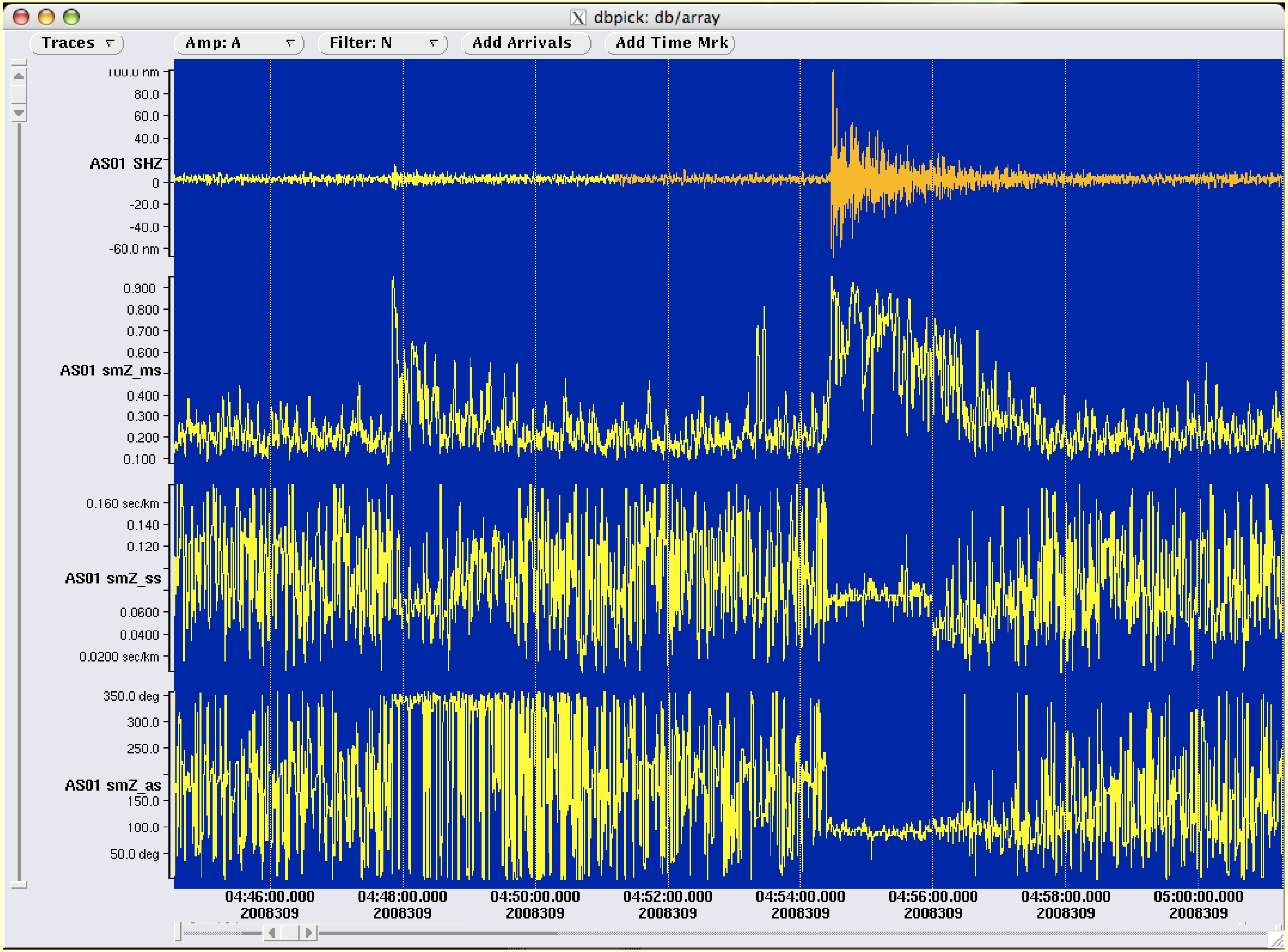
What does **`orbwfproc`** do?

1. Import raw waveform data from real-time ORBs from one or more seismic arrays
2. Form pre-filtered “gathers” of waveform channels for each array into regularized channel-sample grids
3. Compute beams (stacks) over grids of horizontal vector slowness values assuming planar wavefield characteristics; this is done for each time sample over a grid of slowness values
4. Also compute power averages for each beam at each time sample (power of the stack) plus power averages for each of the individual array channels plus an average of the individual array channel powers (stack of the powers)
5. Also compute “semblance” by dividing the beam power averages by the stack of the individual channel power averages
6. Scan the semblance grids for the slowness vector that corresponds to maximum semblance for each time sample
7. Compute azimuth and scalar slowness corresponding to maximum semblance
8. Export beams as waveforms plus maximum semblance, azimuth and scalar slowness as waveforms plus the semblance grids themselves into ORB output packets

What is semblance?

- Semblance is the power of the stack divided by the stack of the powers
- Semblance ranges from 1/n for completely uncorrelated noise across the array channels to 1 for a completely coherent signal across the array channels
- Semblance is a normalized measure of array channel coherence
- Semblance provides a size-independent single-array event detector



dbpick: db/array
Traces
Amp: A
Filter: N
Add Arrivals
Add Time Mrk
100.0 nm
80.0
60.0
40.0
AS01 SHZ
0
-20.0
-40.0
-60.0 nm
0.900
0.800
0.700
0.600
AS01 smZ_ms
0.400
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0.100
0.160 sec/km
0.140
0.120
AS01 smZ_ss
0.0600
0.0400
0.0200 sec/km
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AS01 smZ_as
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100.0
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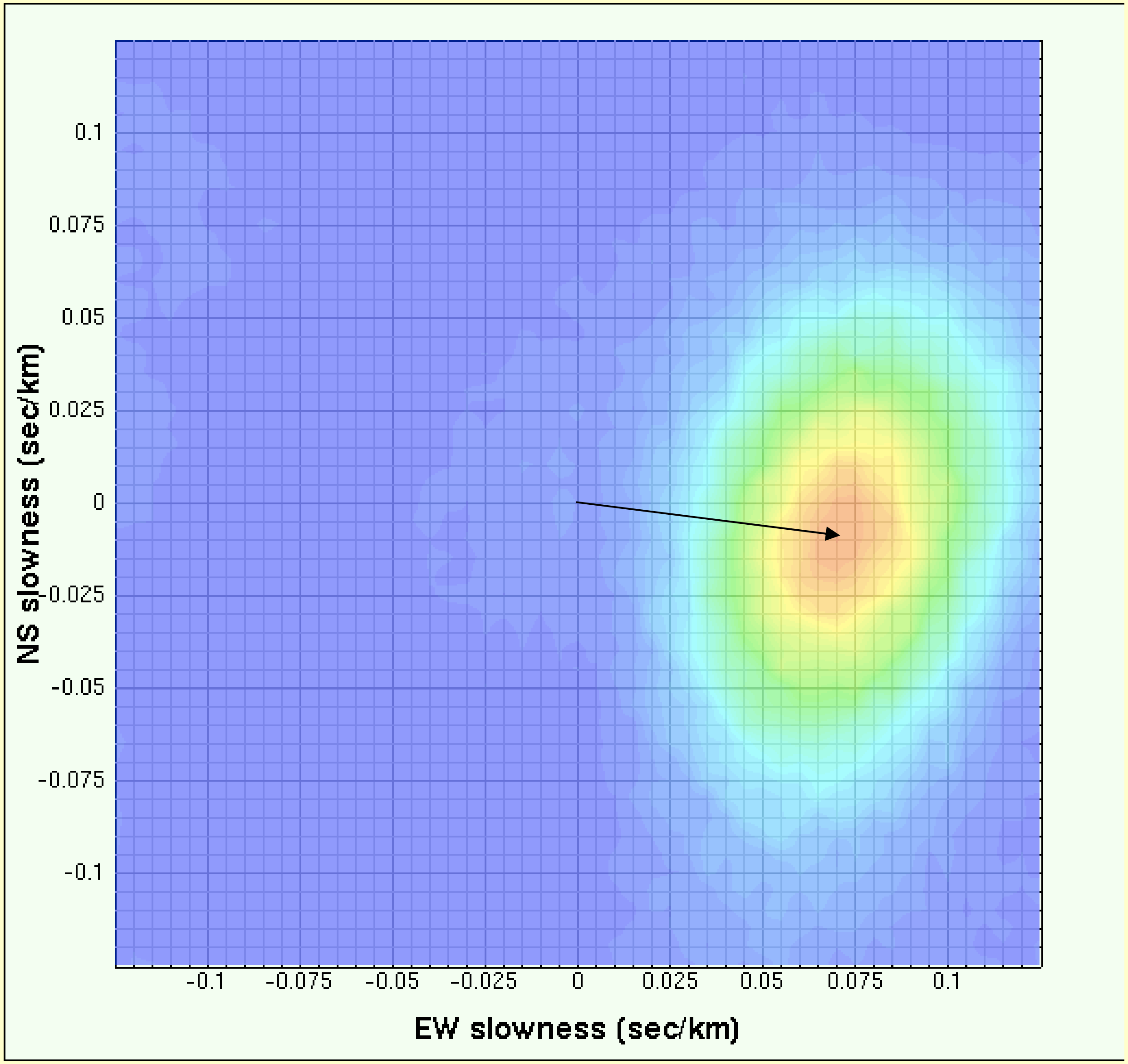
0.1
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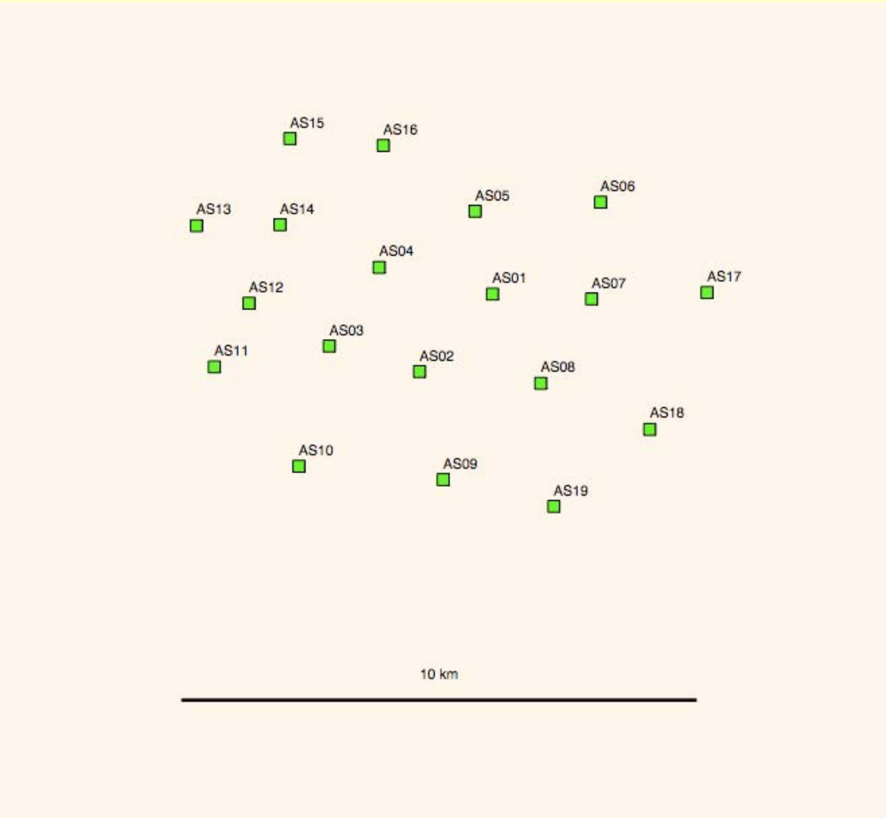
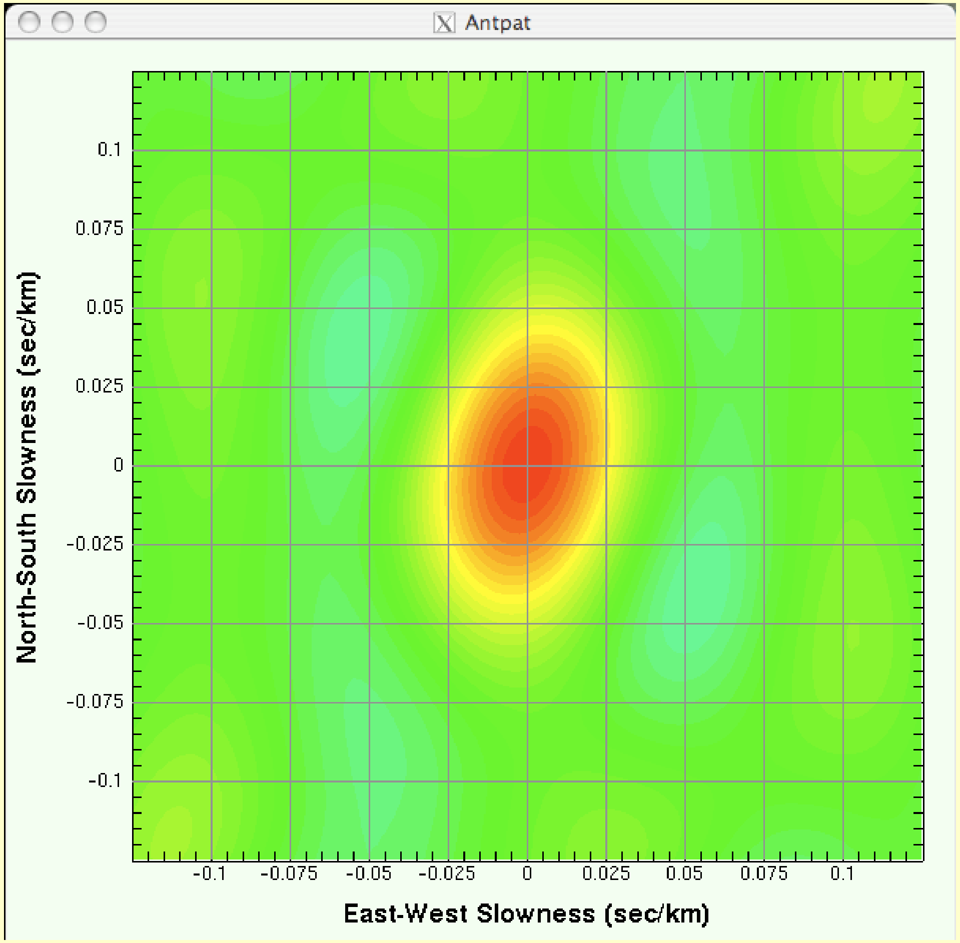
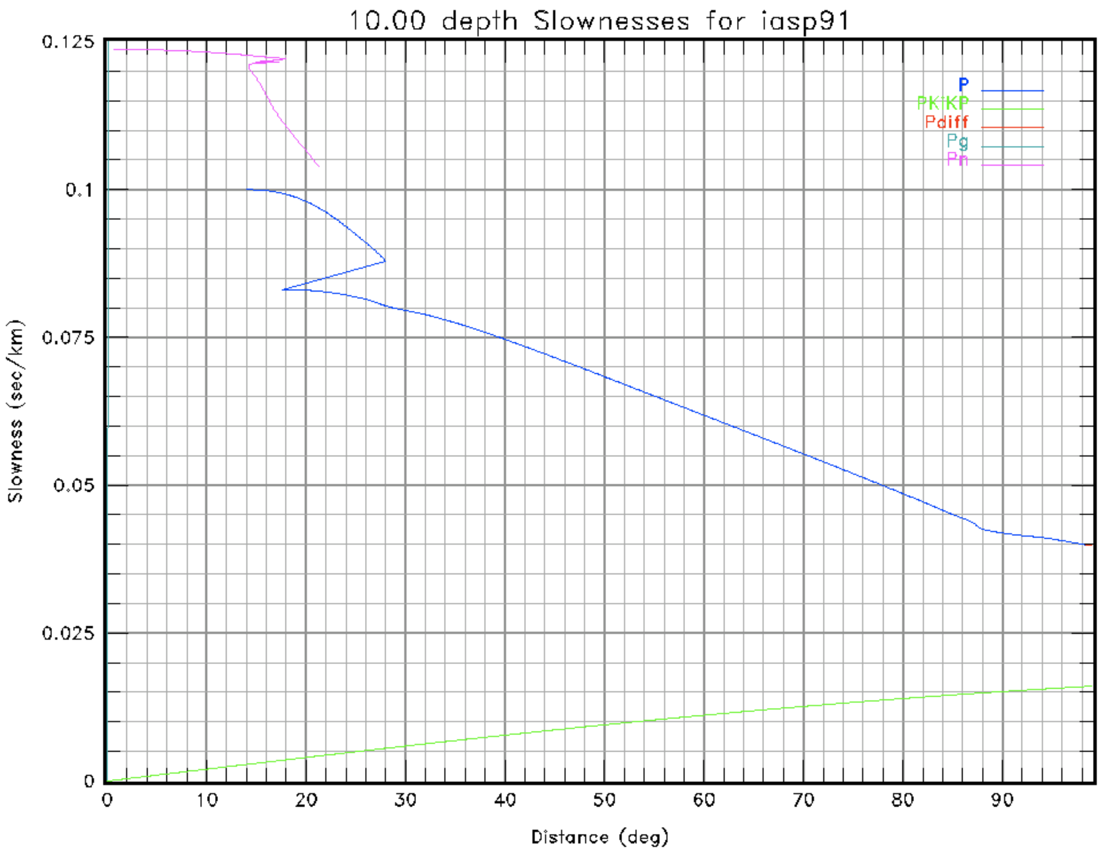
0.025
0
-0.025
-0.05
-0.075
-0.1
NS slowness (sec/km)
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
EW slowness (sec/km)

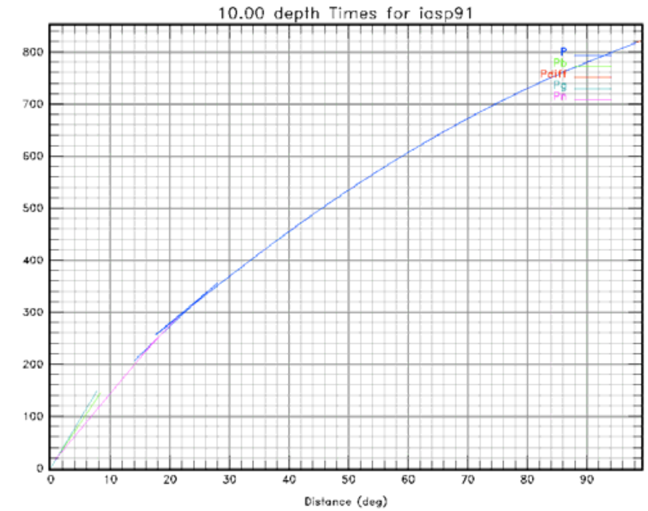
Alice Springs Antenna Pattern (1 hz)





Projecting slowness to event location





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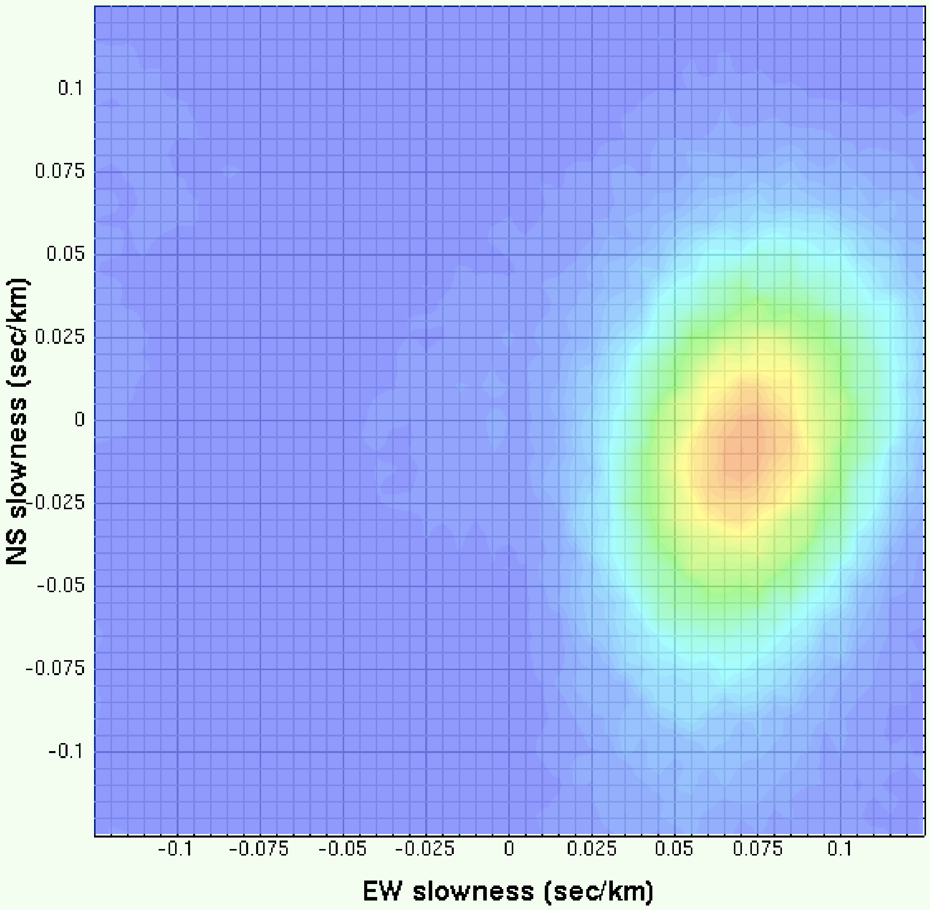
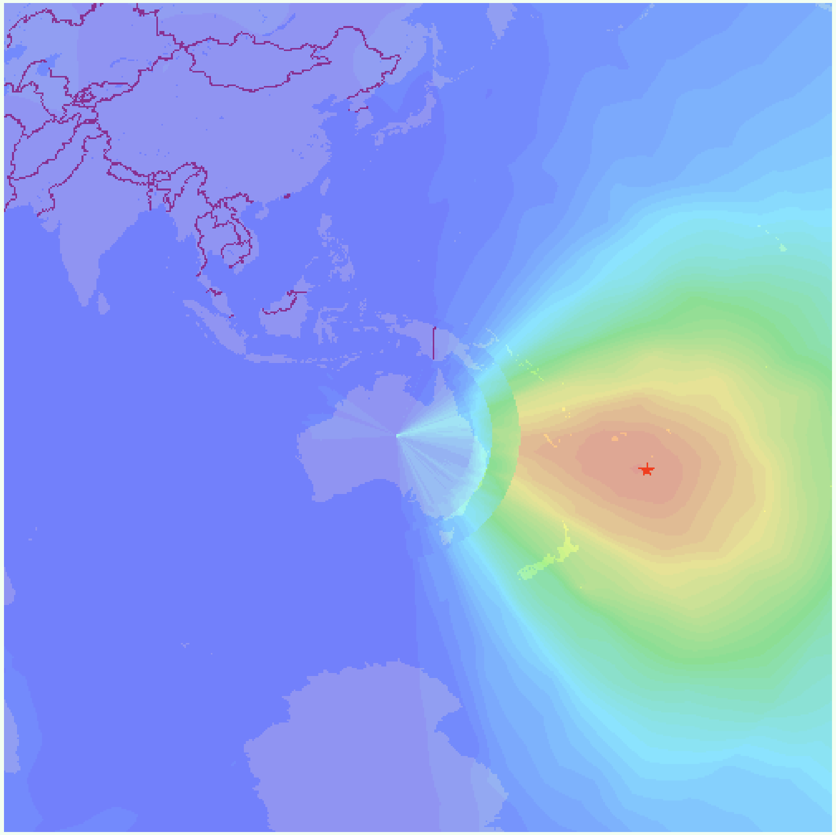
Projecting slowness to event location





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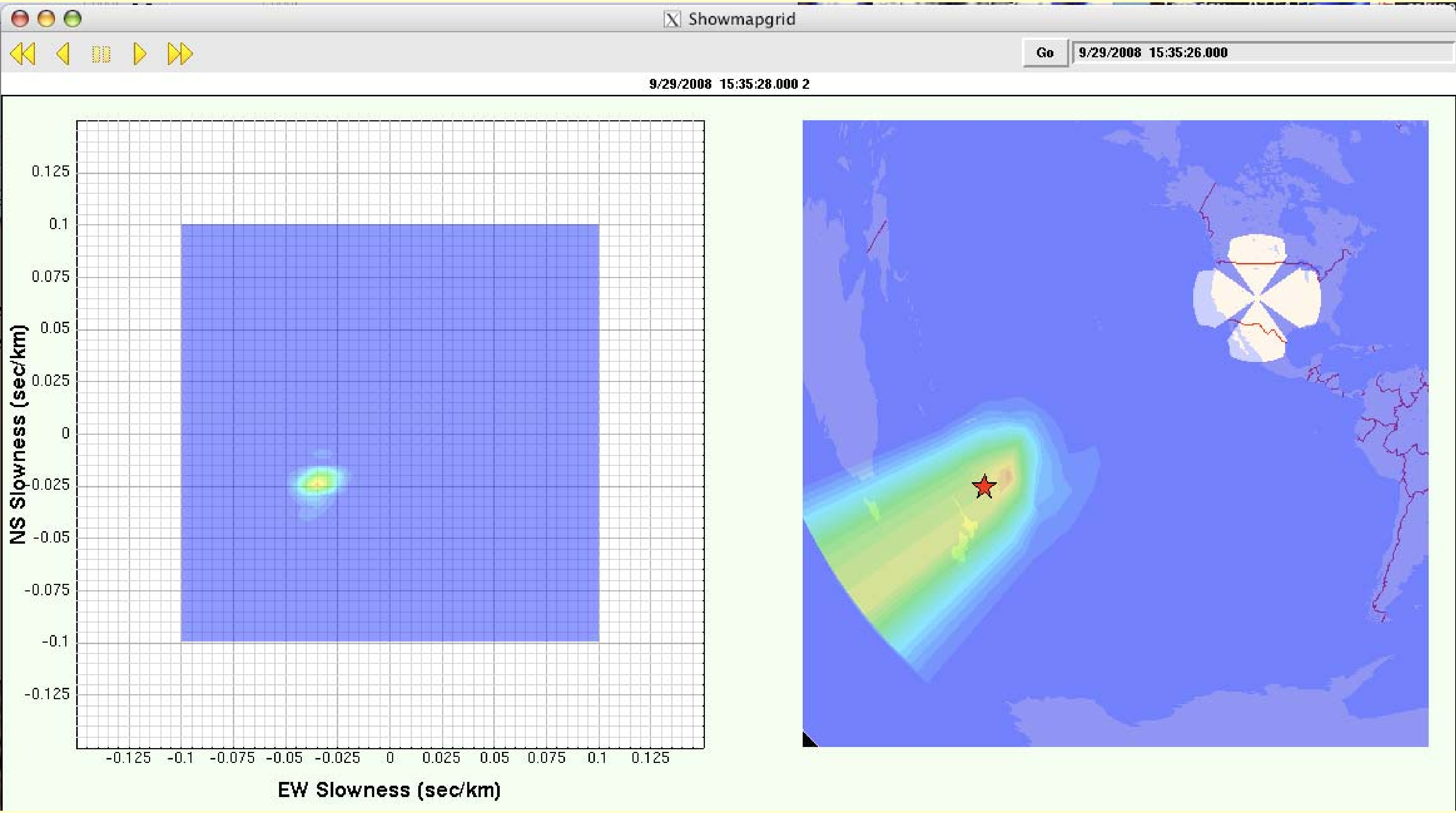
Using large aperture arrays

- 380 LP USArray stations and plane wave stacking



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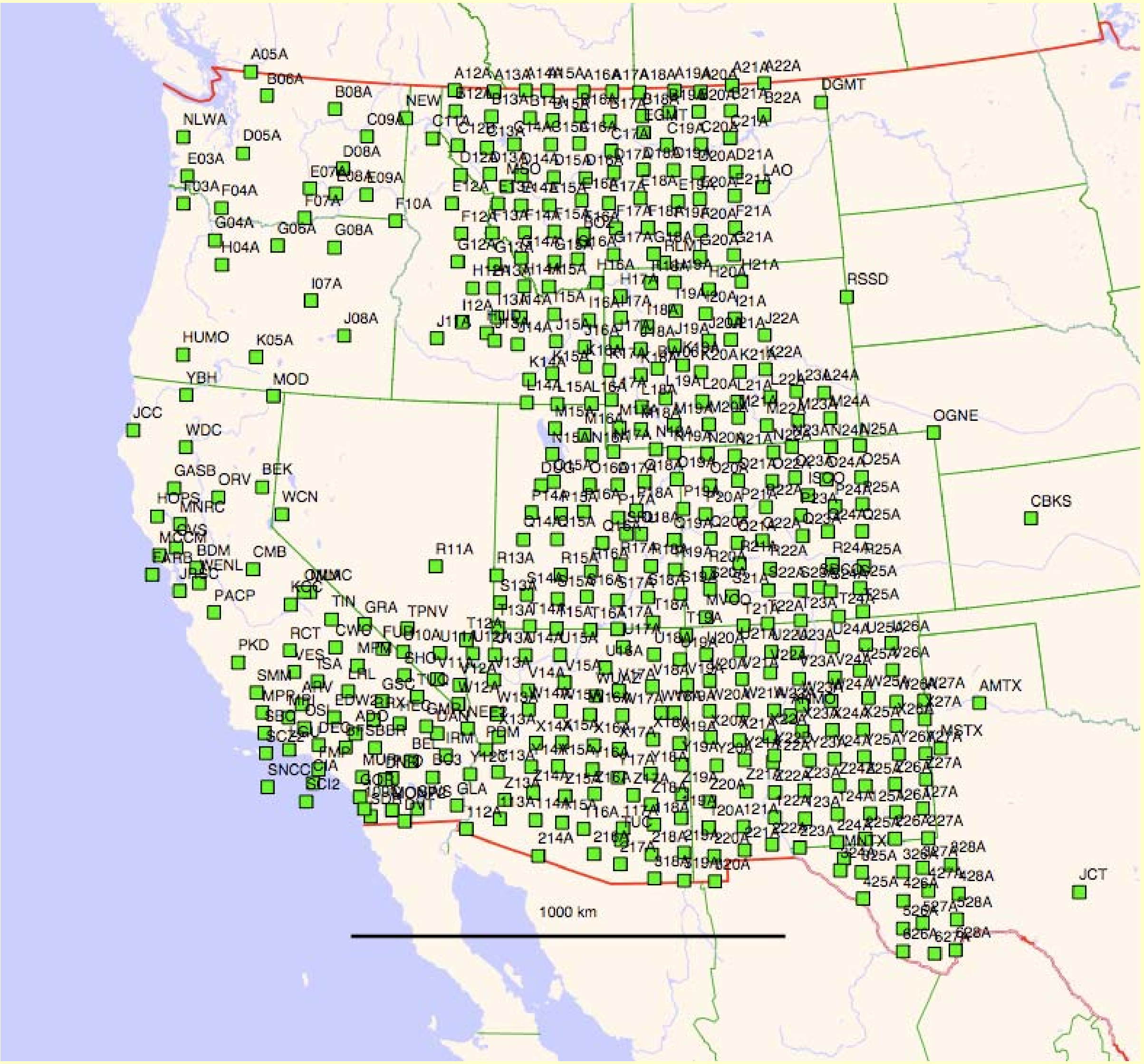
USArray Transportable Array



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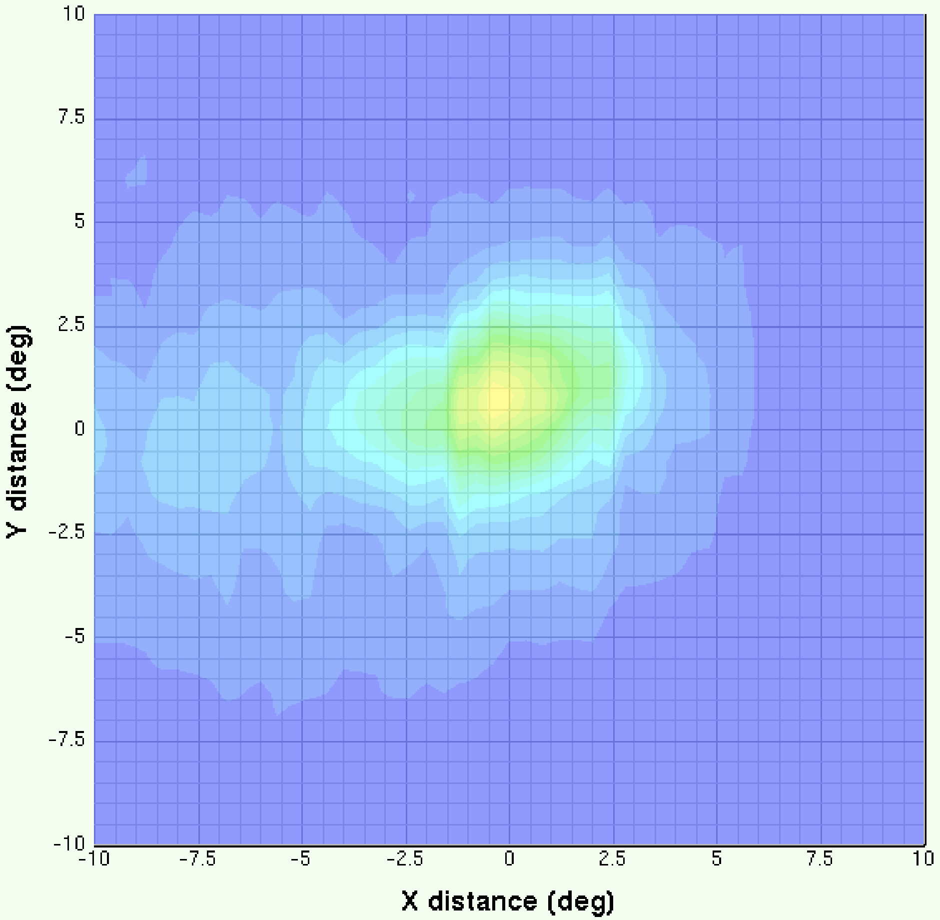
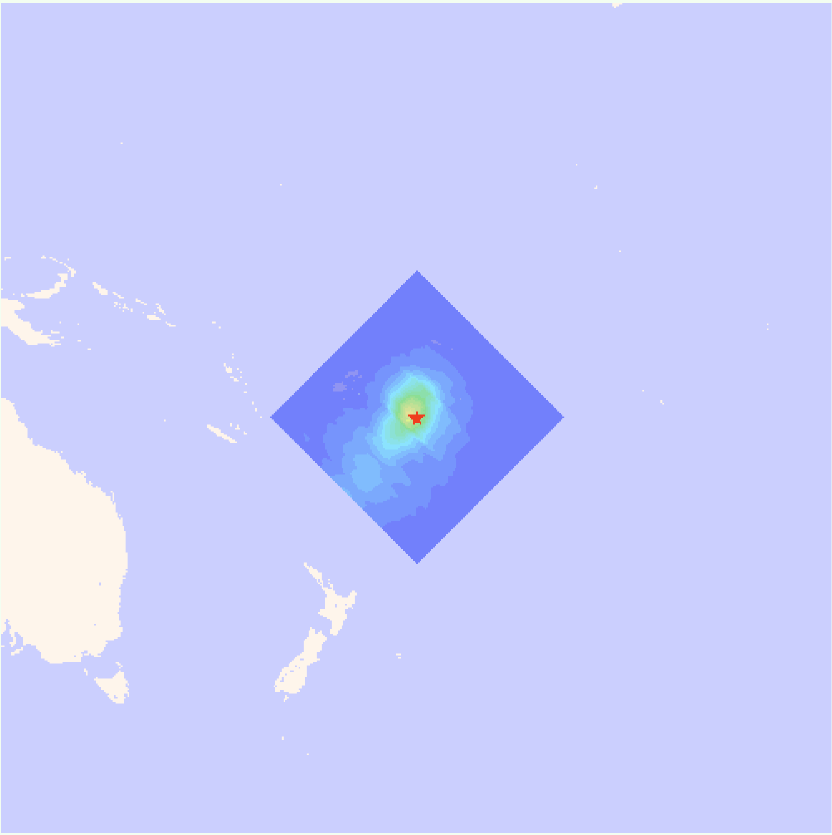
Stacking to geographic grids

- Consider defining relative time shifts of array channels using actual travel times to a grid of geographic coordinates
- Removes plane wave approximation
- Useful for large aperture arrays where the plane wave approximation is invalid
- **`orbwfproc`** can do geographic grid stacking

Stacking to geographic grids





Future developments for `orbwfproc`

- Semblance-based array detector
- Grid refinement for more finely determined peak slowness and azimuth
- Datascope version
- Integration into event associator
- Combining grids from multiple arrays in real time to produce forward source imaging in space and time