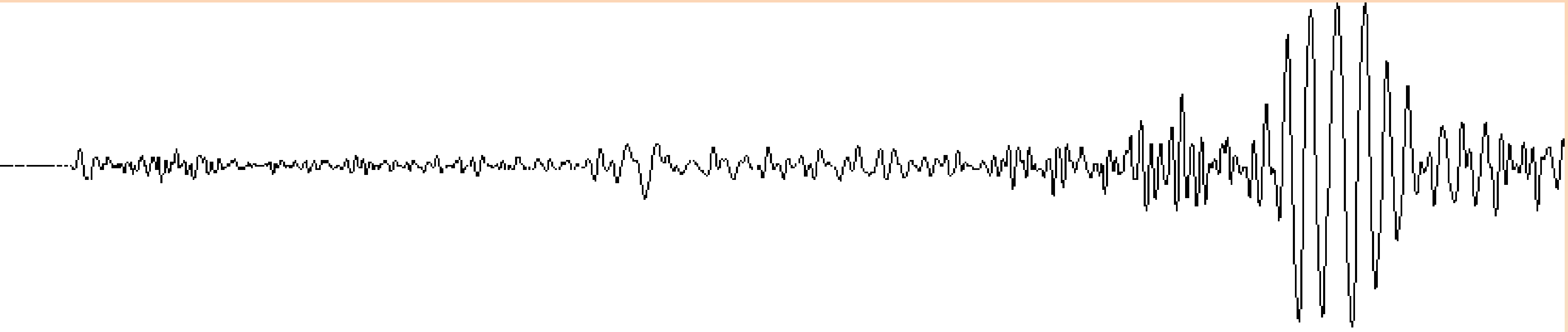


Broadband Seismic Characterization of the Arabian Peninsula Using 3-C Seismic Array

Abdullah M. Alamri
Seismic Studies Center, King Saud Univ.

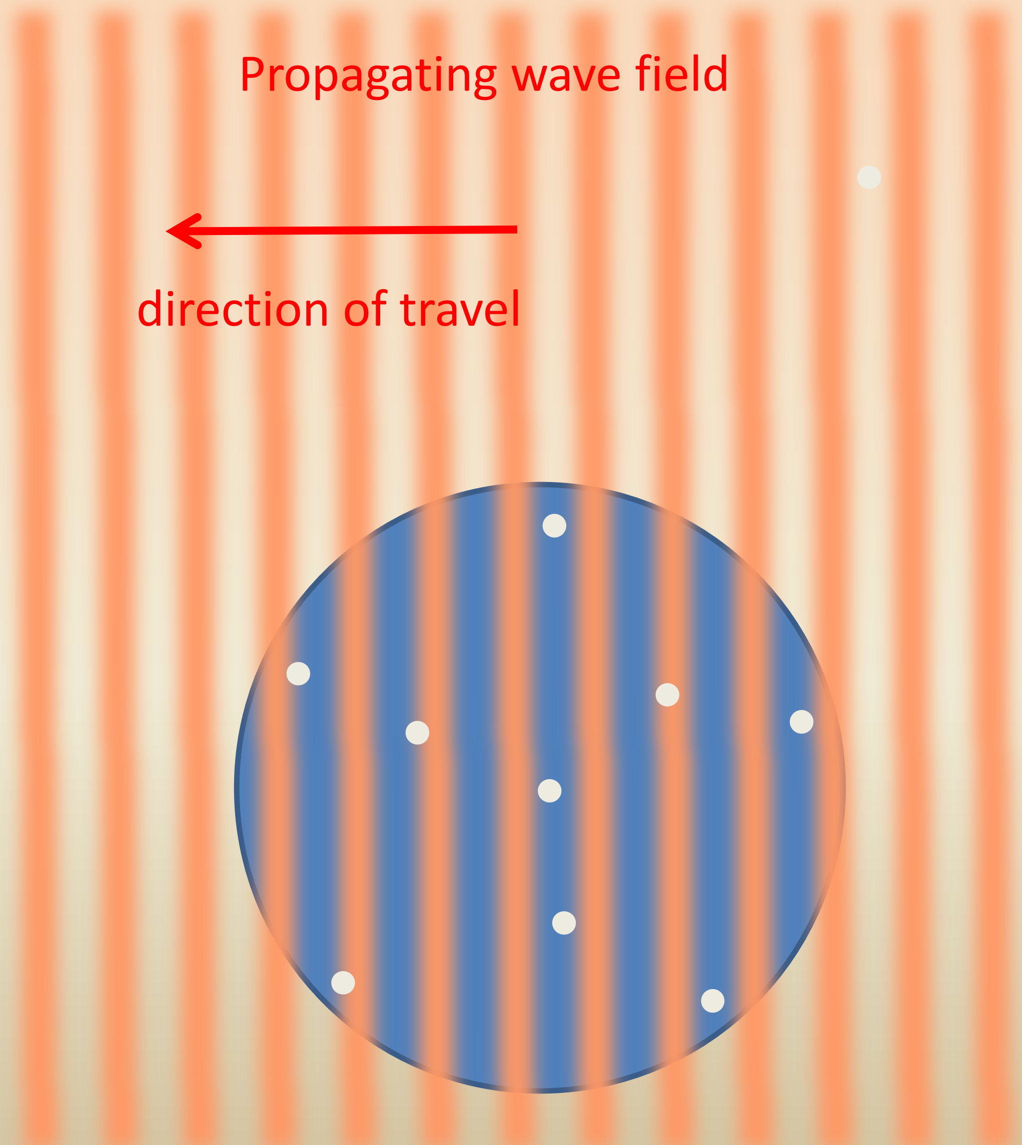
•

Sensor arrays provide processing gain to detect, locate and characterize (weak) signals

Seismic Array: term used to describe network of seismometers that allow time-series stacking to increase signal-to-noise ratio of coherent energy

- Received signals are combined coherently (and noise incoherently) to detect and image weak signals

Seismic arrays are groups of sensors sampling the wave field across a coherent aperture



Single seismic station samples the wave field at one point

An array samples the wavefield across an aperture
- 3 or more sensors
- uniform instrumentation
- common time base
- ensemble signal analysis

Can estimate direction and speed of the waves

Sensor recordings can be combined to detect weak signals

Types of Seismic Arrays

- Conference of Scientific Experts (1958)
  - New instrumentation for monitoring nuclear test ban treaties
- Early arrays
  - Medium aperture (~< 10 km) research arrays, up to 31 sensors
    - Tennessee (Cumberland Plateau, CPO)
    - Oregon (Blue Mountain, BMO)
    - Utah (Uinta Basin, UBO)
    - Arizona (Tonto Forest, TFO)
- Large aperture arrays (10 – 200 km) designed to detect and locate signals at teleseismic distances; low frequency
  - British arrays: Eskdalemuir (EBA, 1962), Gauribidanur (GBA), Yellowknife (YKA), Warramunga, Brasilia
  - LASA, project VELA (525 element array, ~200 km aperture; 1964)
  - ALPA Alaska Long Period Array
  - NORSAR (132 element array, ~120 km aperture; 1970)

More recent array research has focused on regional arrays

- Small aperture arrays (1 – 5 km) designed principally to detect and locate Pn, Pg, Sn and Lg at ranges <~ 2000km; higher frequency

- NORES (25 elements, ~3 km aperture; 1984)

- ARCES   (25 elements, ~3 km aperture; 1987)

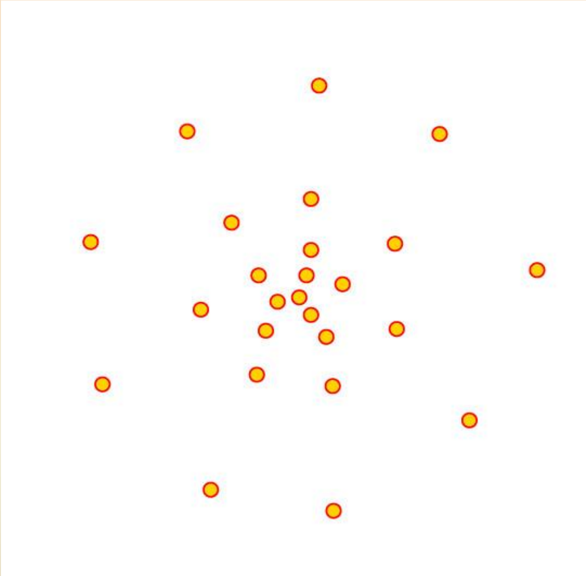
- CTBT IMS arrays   (9 elements, 3-5 km apertures; since 1995)

- There has not been a lot of research on arrays of three-component sensors (Pinon Flat, PFO)

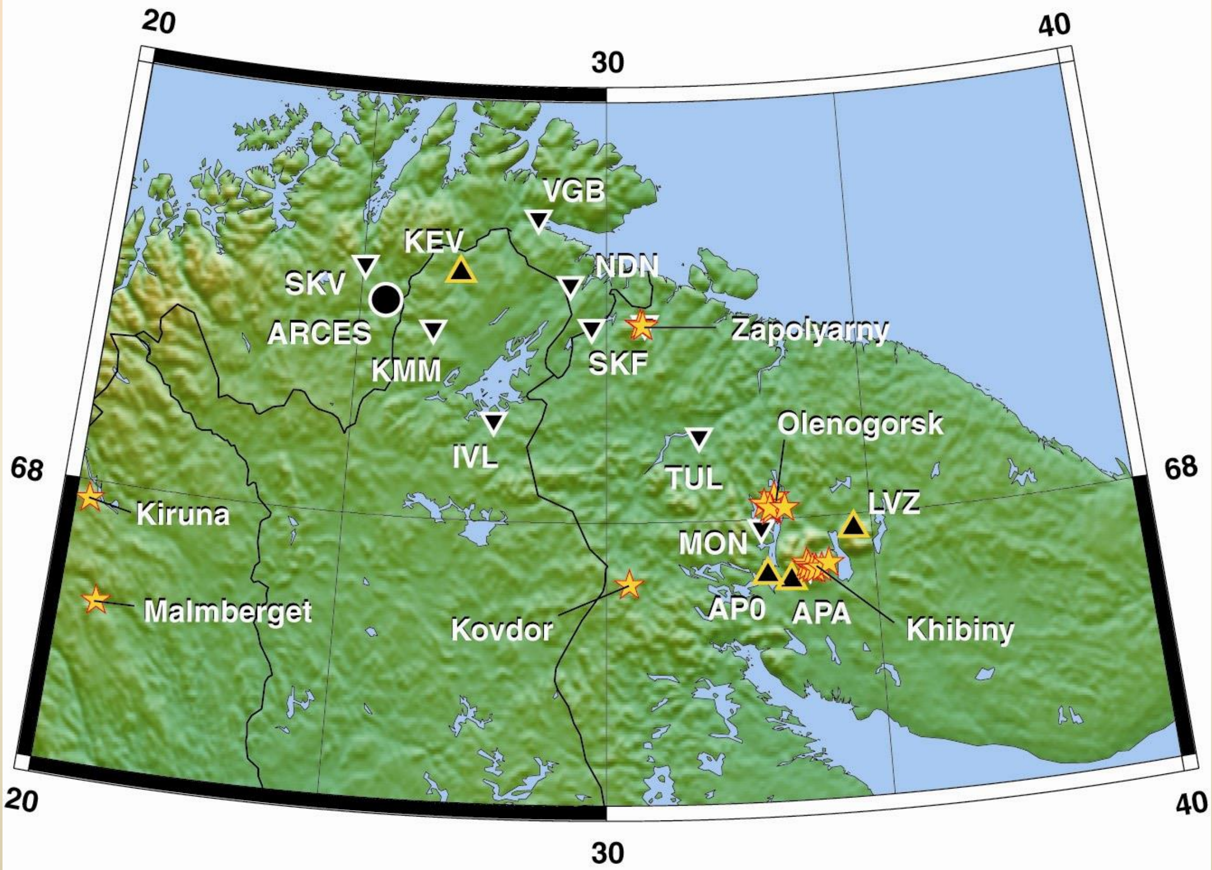
- Not much research outside of Fennoscandia on high-frequency propagation (> 5 Hz)

Examples drawn from the ARCES array in northern Norway

ARCES



~ 3 km



OBJECTIVES

- To collect and analyze continuous three-component waveform data with a seismic array in Saudi Arabia.

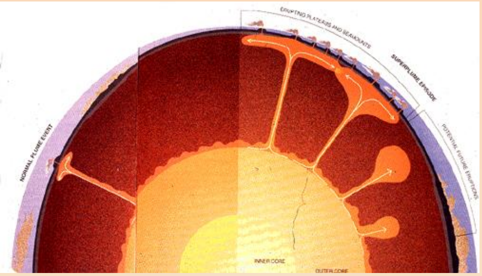
- To characterize background noise, signal characteristics and slowness-azimuth-polarization behavior of regional and teleseismic signals.

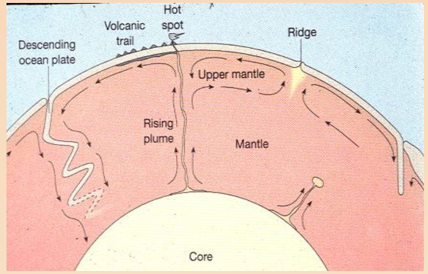
- To characterize regional phases (Pn, Pg, Sn, Lg) .

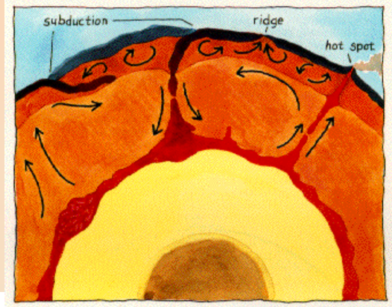
ACHIEVEMENTS

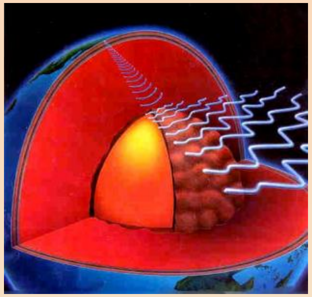
- Providing observations of seismic waves in the Arabian peninsula .
- Improving models of crust and upper mantle structure .
- Monitoring of seismic events and shed light on broad structural features such as the volcanism of the western peninsula.
- Providing better estimates of signal waveforms, and allowing direct estimation of propagation parameters such as the slowness and azimuth of signals.
- Improving detection and location performance.

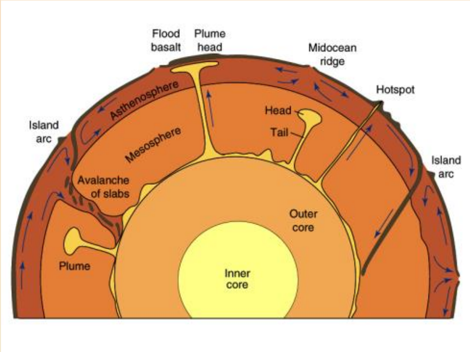
Hypotheses and Interpretations

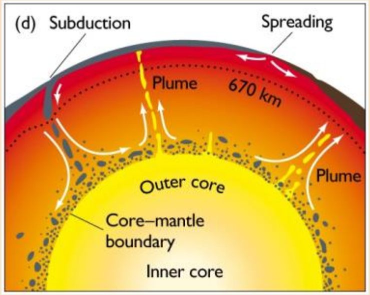


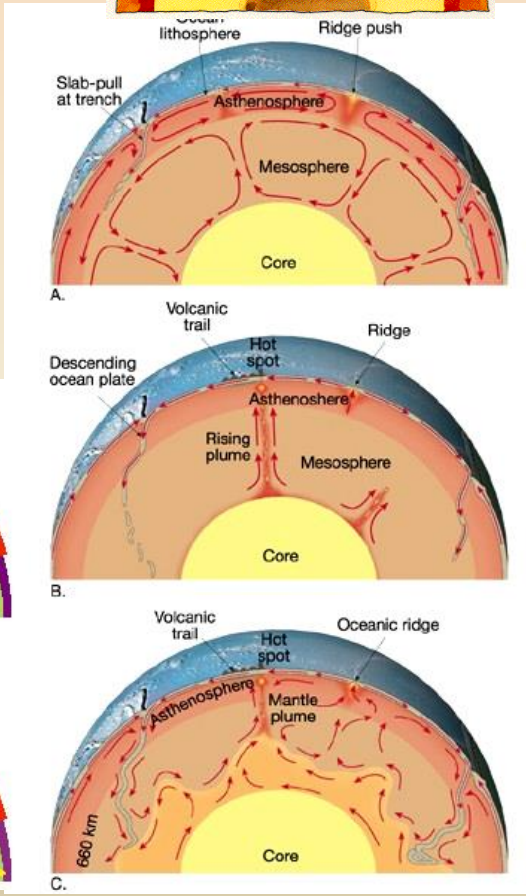


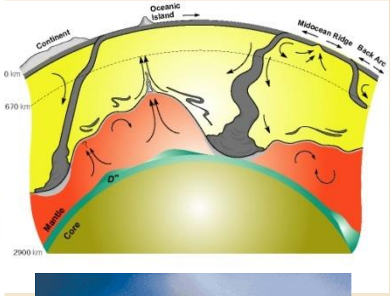


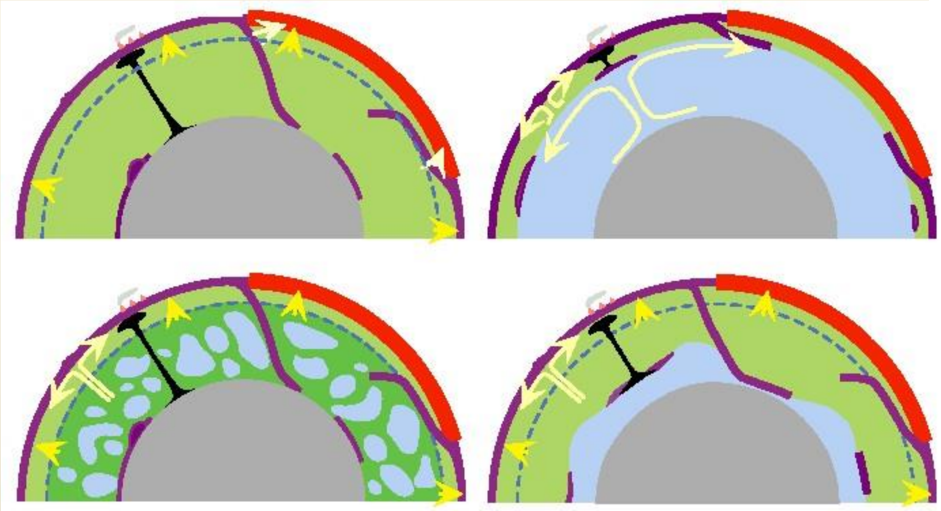


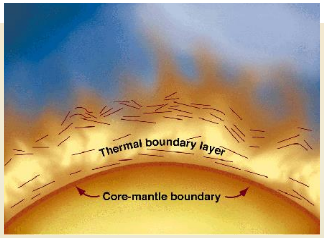


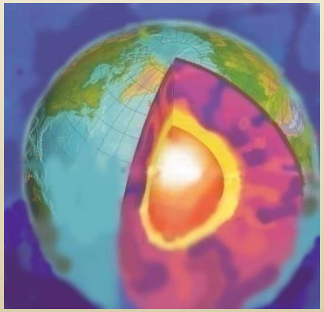






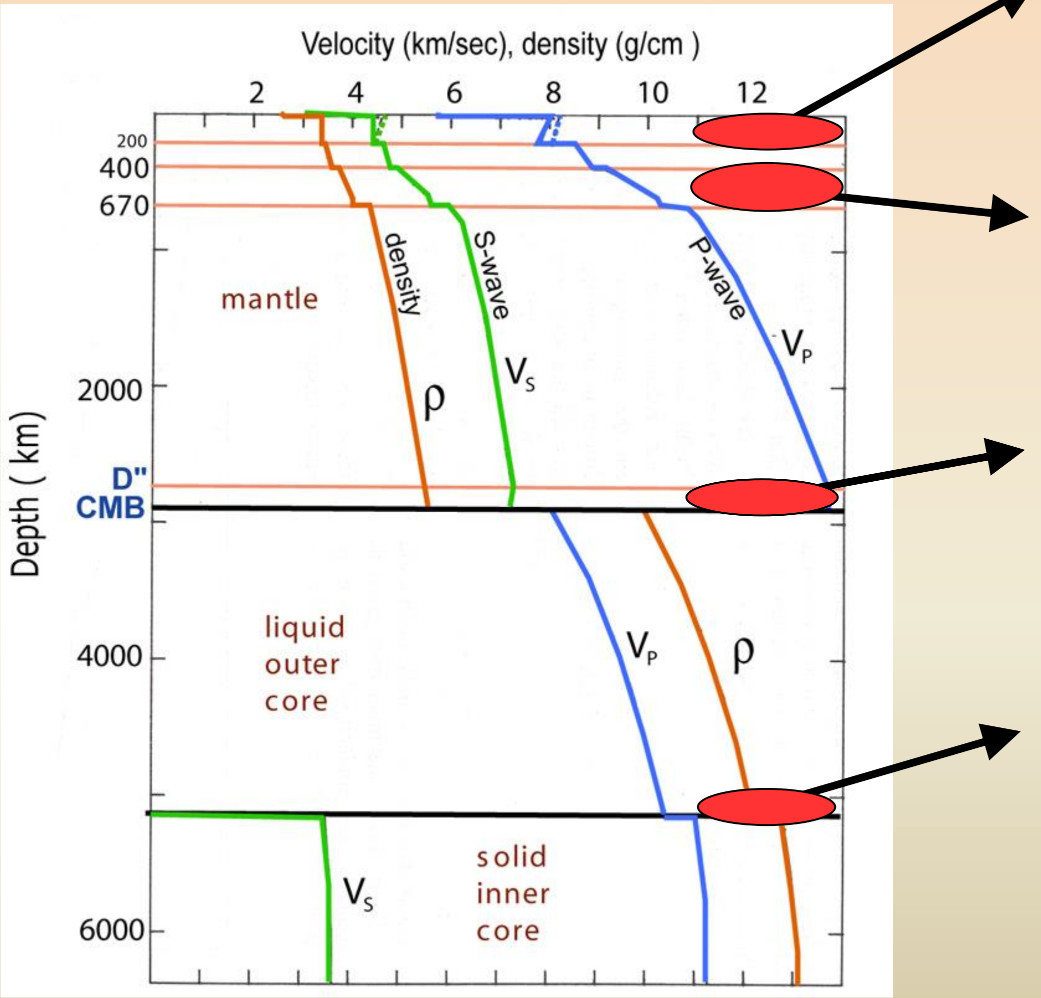






There is no shortage of those !

Studying boundary layer structure



- Lithospheric studies

  Rost and Weber, 2001
  Rost and Williams, 2003

- Transition zone structure

  Rost and Weber, 2002

- D" and CMB studies

  Rost and Revenaugh, 2001, 2003, 2004
  Rost et al., 2004

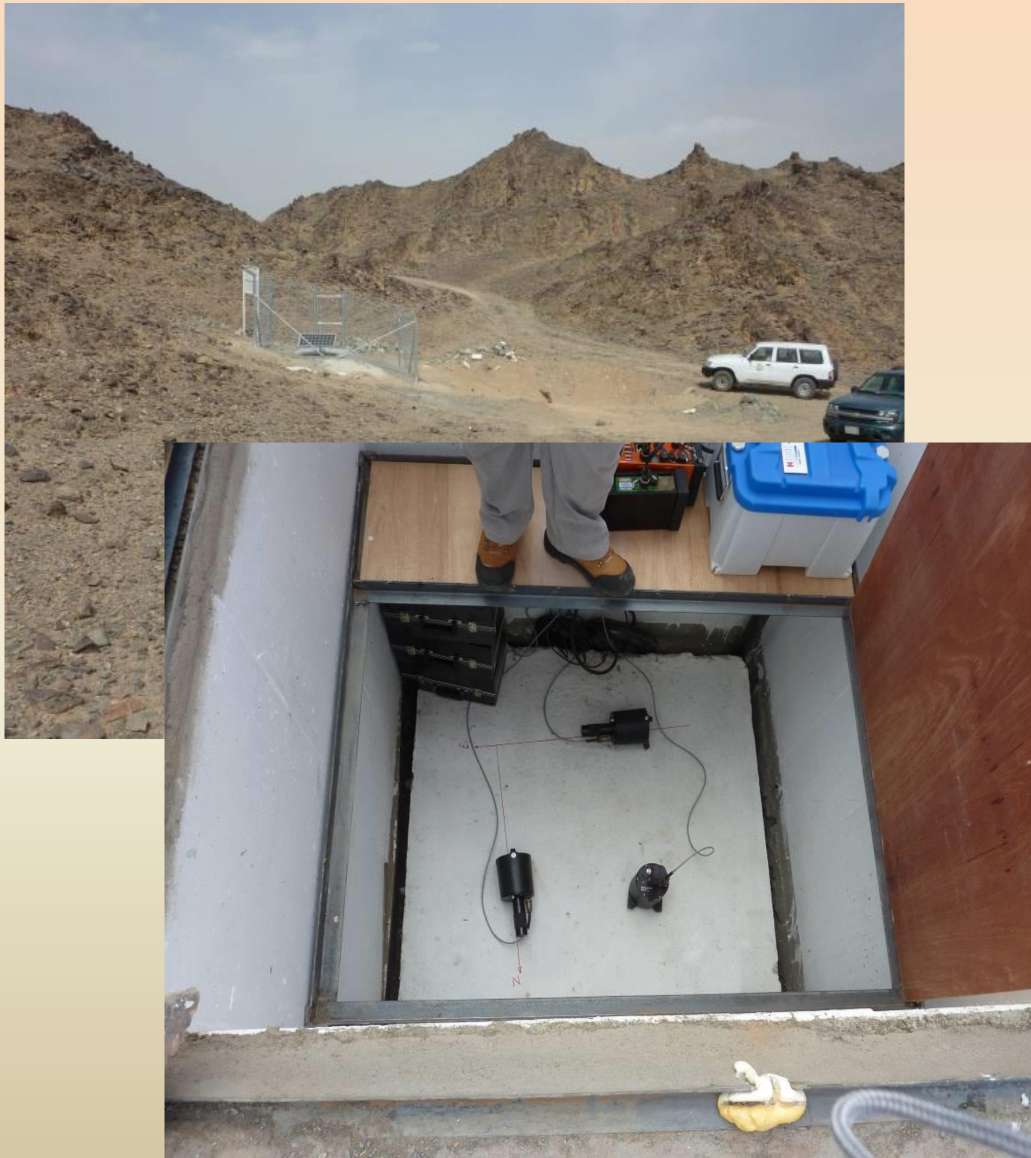
- Inner core boundary

  Rost and Garnero, 2004

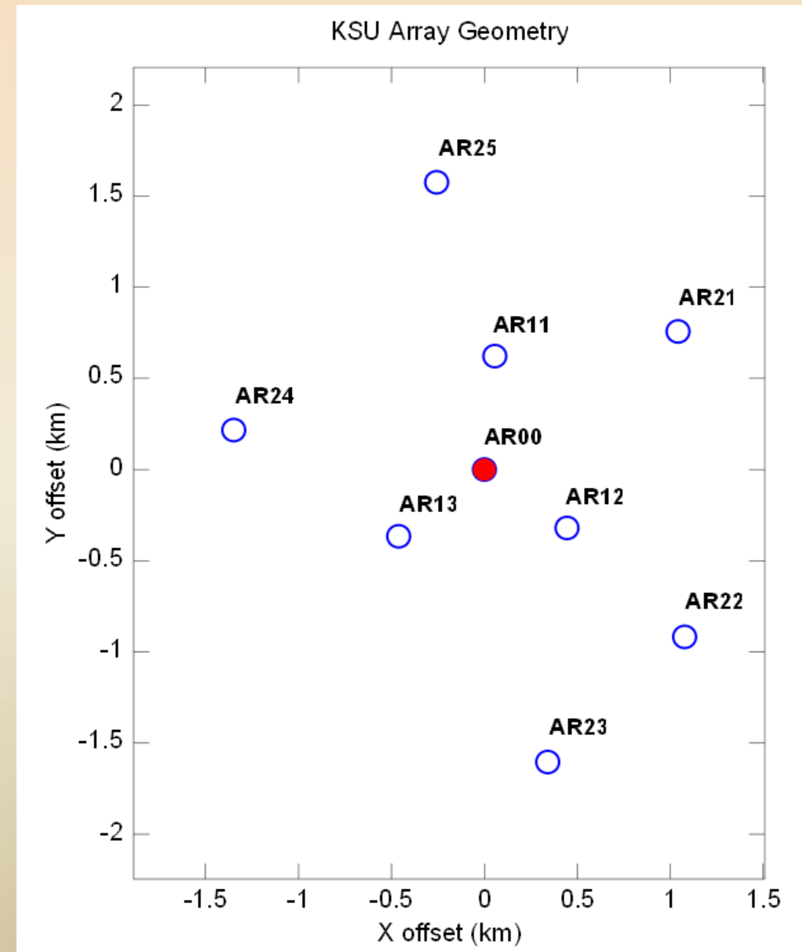
Ar Rayn Array

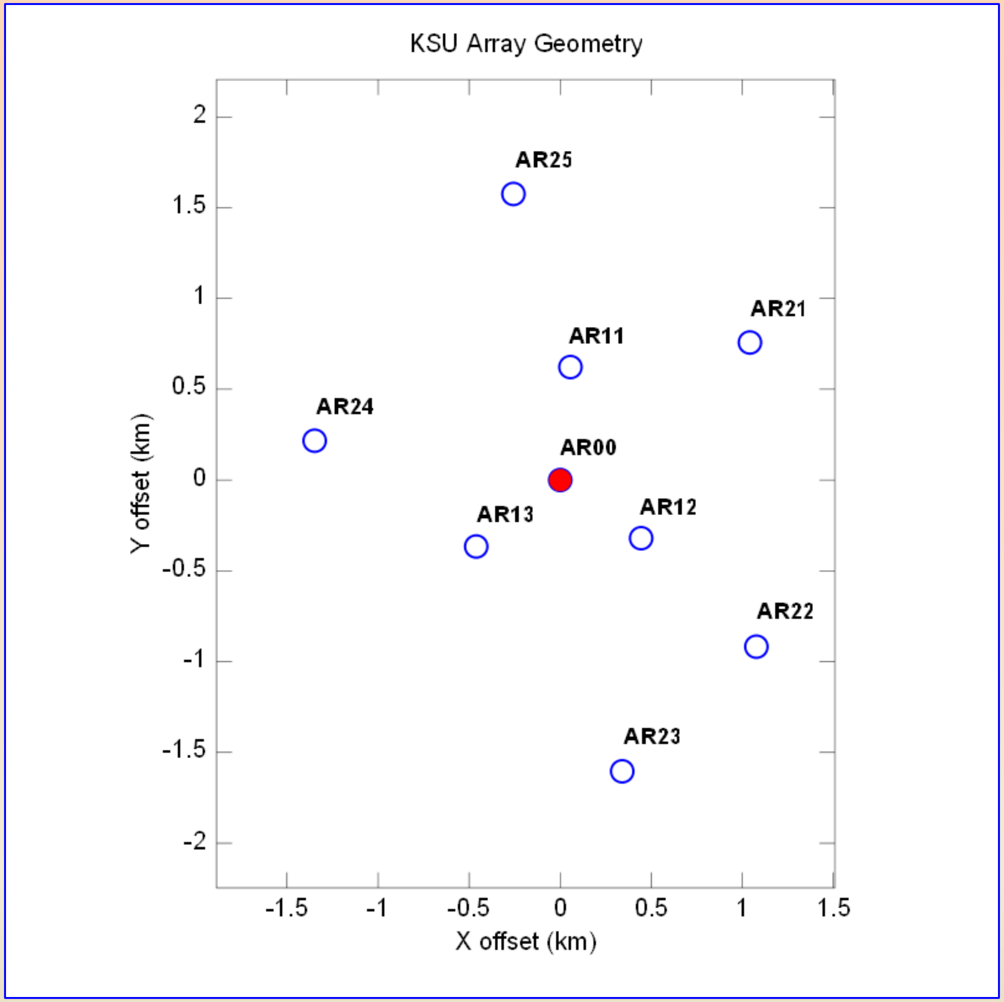
- The Ar Rayn array is a small-aperture, high-frequency regional array deployed in the Arabian shield near its eastern edge.
- It consisted of a central broadband three-component sensor (STS-2) and eight short-period three-component sensors (SS-1) spread across a 3.5 kilometer aperture.
- Data were recorded continuously at 100 samples per second on Quanterra Q330 data loggers at individual sensors of the array.
- The data were archived and processed at KSU, where basic quality control, format conversion and event extraction functions were performed.
- We applied slowness and azimuth estimation to document how seismic structure biases these measurements away from radially stratified earth models.
- Noise study showed that the site is exceptionally quiet with noise levels near the USGS low noise model for frequencies in the central band from 50 seconds to 5 Hz.
- At lower frequencies, the horizontal components showed high noise levels, possibly due to instrumental characteristics.
- The array appears to be among the best sites in the world for ground noise levels and detection.

The Ar Rayn array presents opportunities to test combined beamforming and polarization filtering



A carefully deployed array of three-component stations



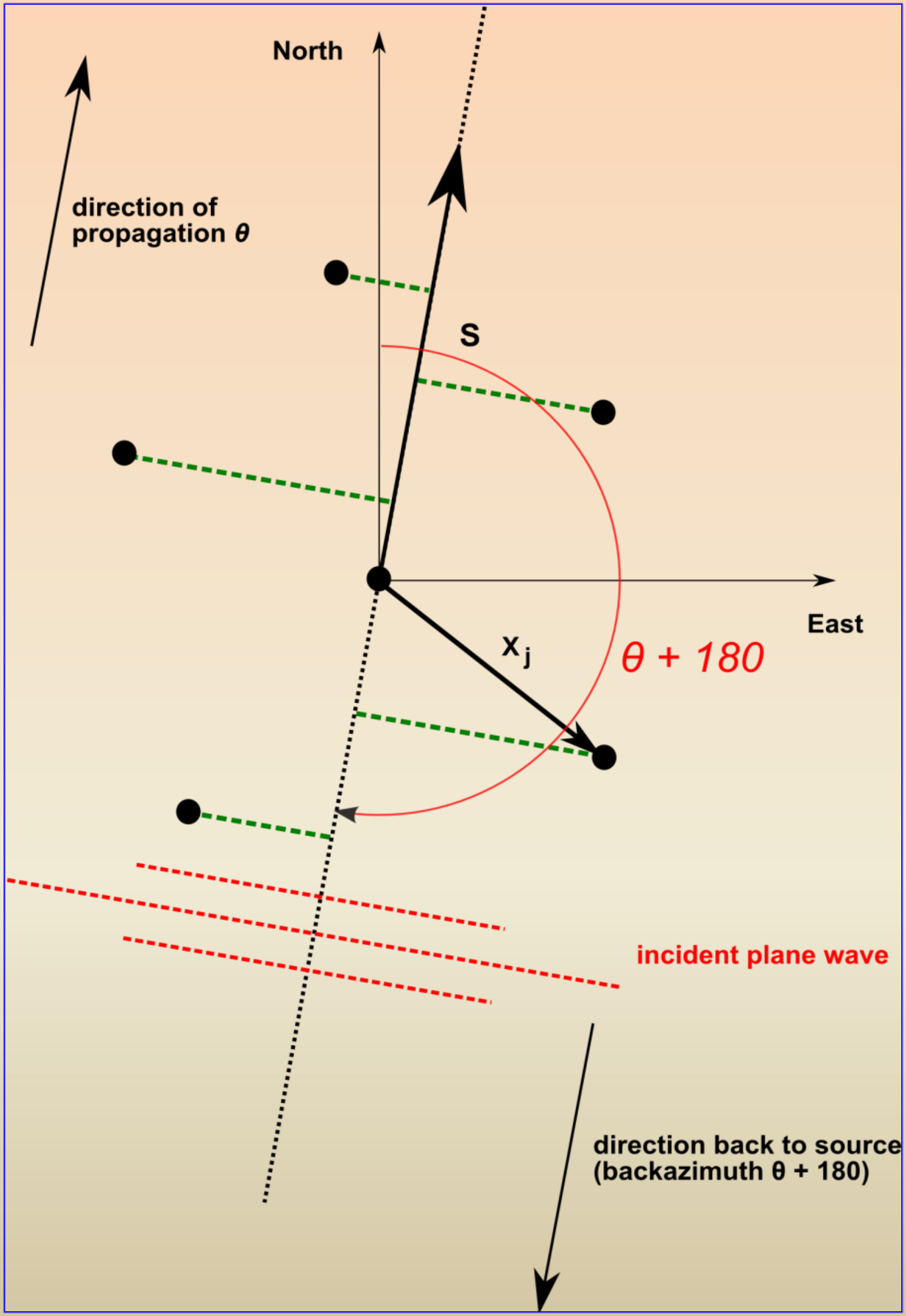


The Ar Rayn seismic array has a broadband (STS-2) three-component sensor at its central location(filled circle) surrounded by two rings of three-component short-period (SS-1 Ranger) sensors.

ARRAY PROCESSING

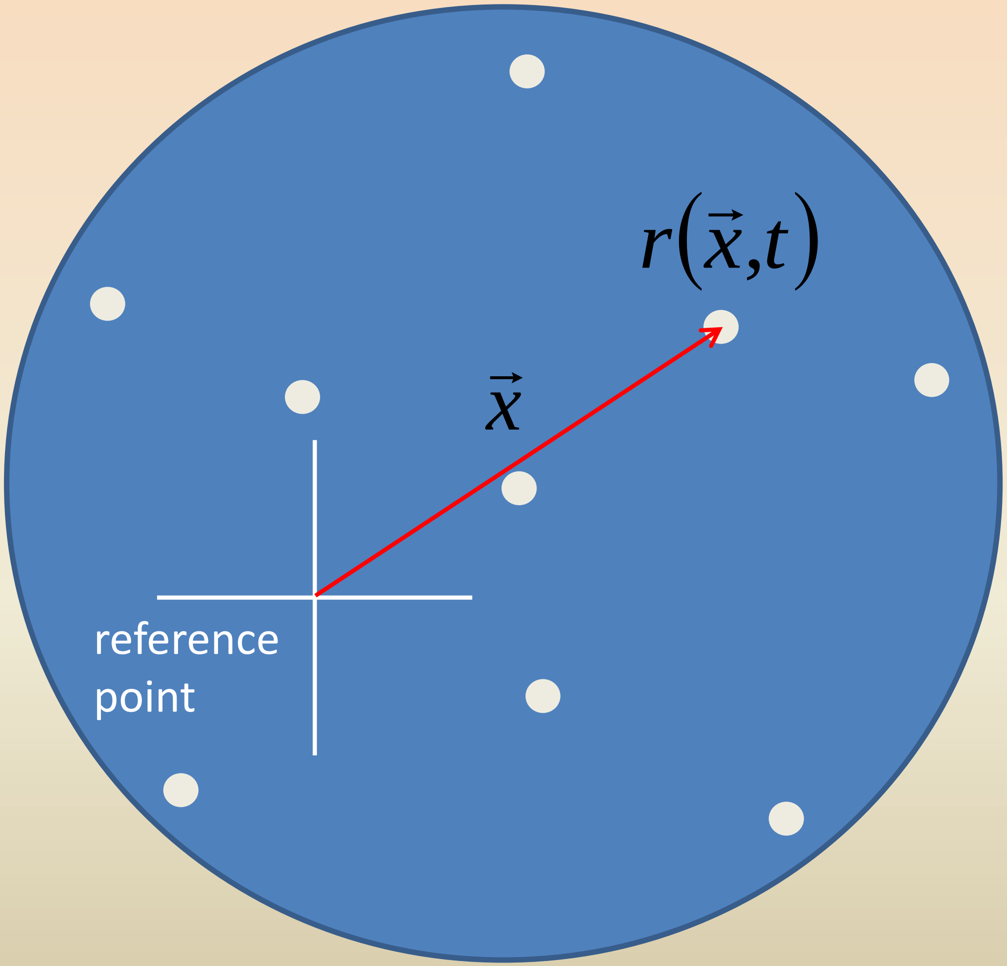
- Performing basic quality control functions .
- Inspecting waveforms and looking for consistency
- Measuring noise levels on each site-channel.
- Measuring signal coherence across the array for regional and teleseismic events
- Measuring slowness-azimuth for P-waves from large well-located (ground truth, GT) teleseismic events ($m_b \geq 5.0$ and distances 30º-90º).
- Performing slowness-azimuth analysis on regional phases (Pn, Pg, Sn and Lg) from moderate events ($m_b \geq 3.0$ and distances ≤ 20º).

•Characterizing azimuthal and polarization properties so that noise rejection algorithms can be developed and tested.



Definition of array quantities:
slowness vector s,
station location vector x_j,
azimuth of propagation.

Array element locations are specified either by geographic coordinates or vector offsets from a reference point



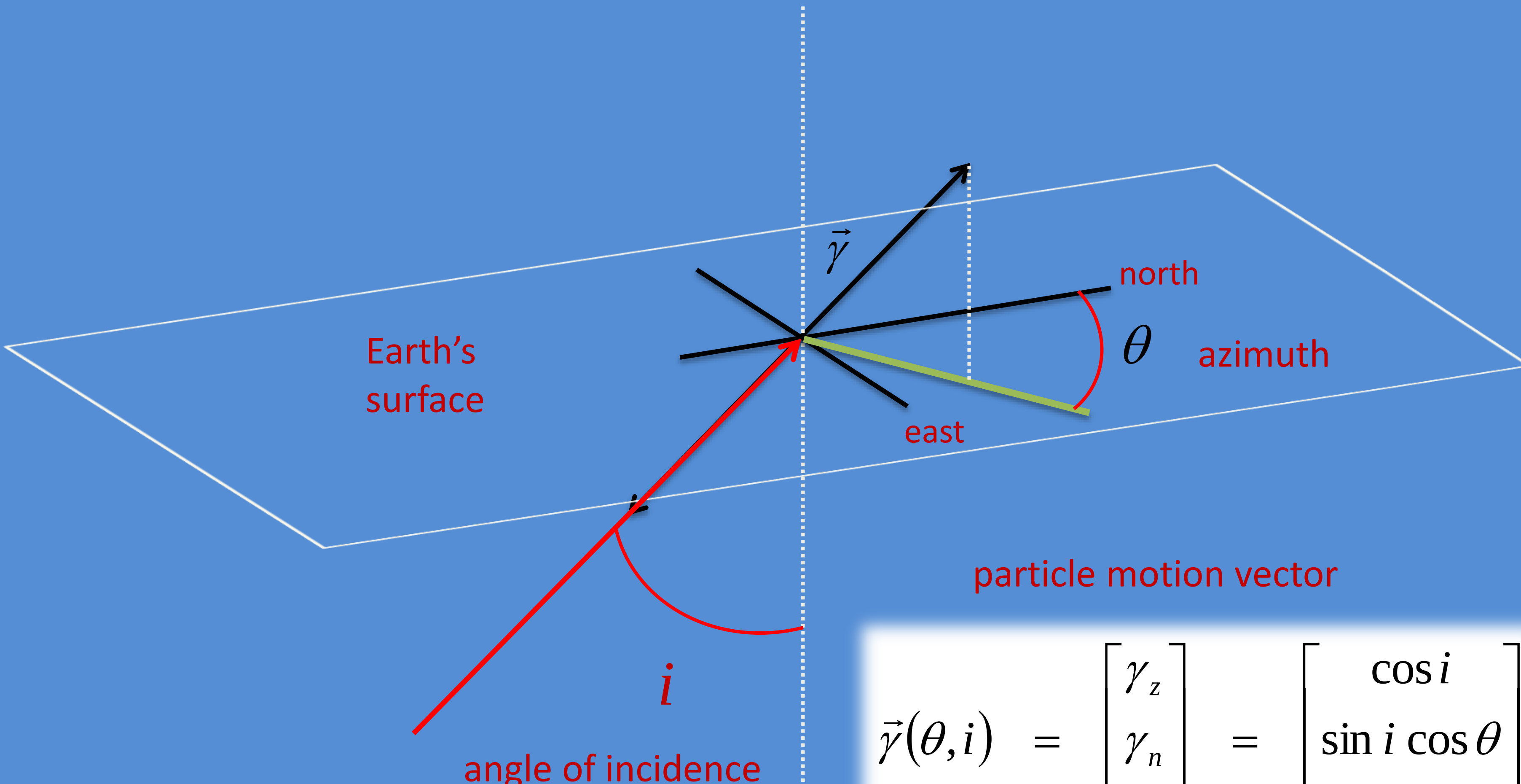
Specifications by:

- latitude, longitude, elevation

or

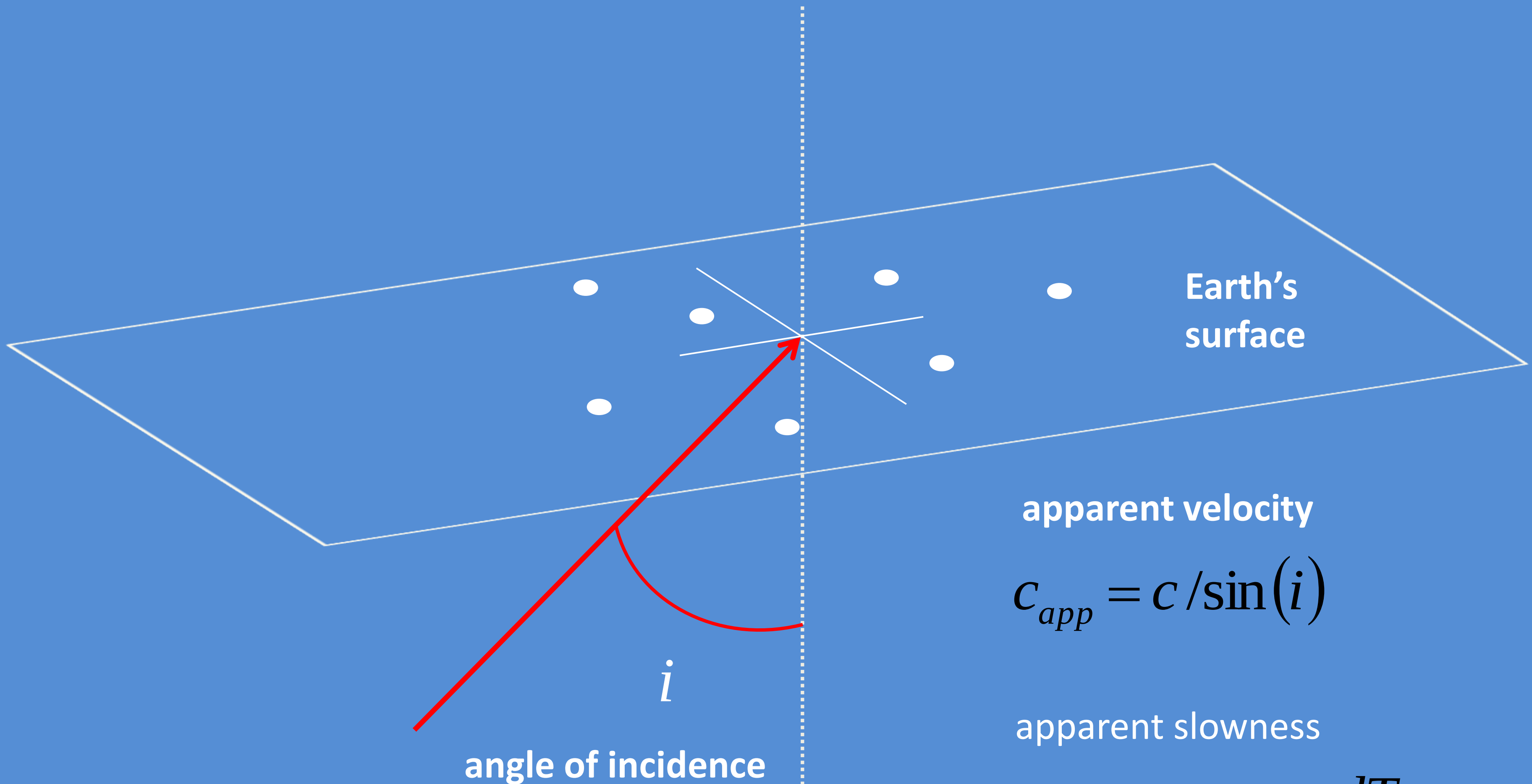
- vector offsets from a reference point. Reference is usually the geographic center of the array, but this is not required

P particle motion is characterized by a polarization vector defined by azimuth and incidence angles



$$\vec{\gamma}(\theta, i) = \begin{bmatrix} \gamma_z \\ \gamma_n \\ \gamma_e \end{bmatrix} = \begin{bmatrix} \cos i \\ \sin i \cos\theta \\ \sin i \sin\theta \end{bmatrix}$$

3D wavefields are usually observed by 2D arrays on the surface of the Earth



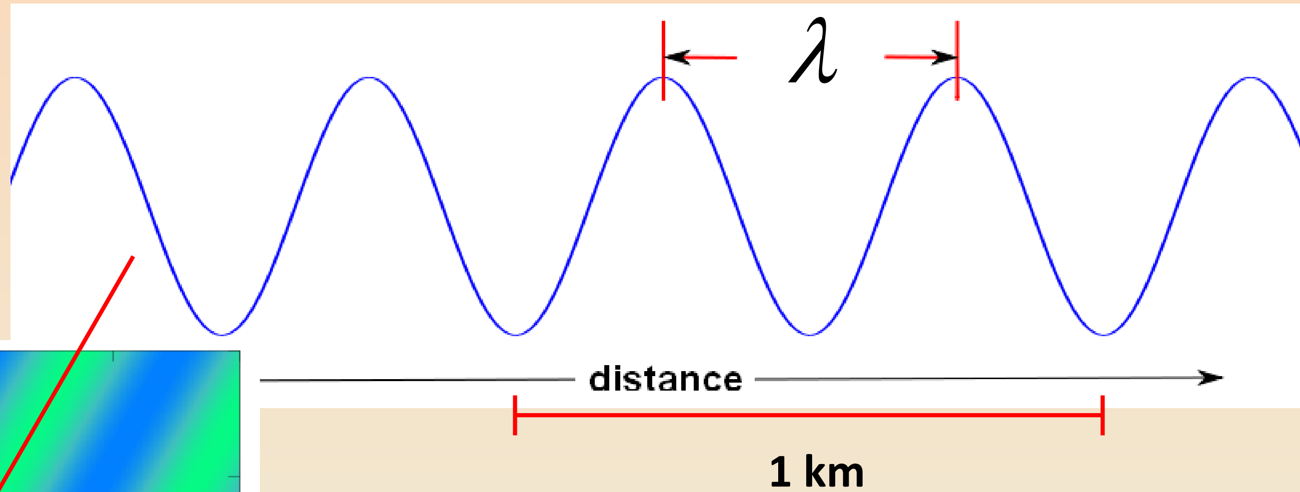
apparent velocity

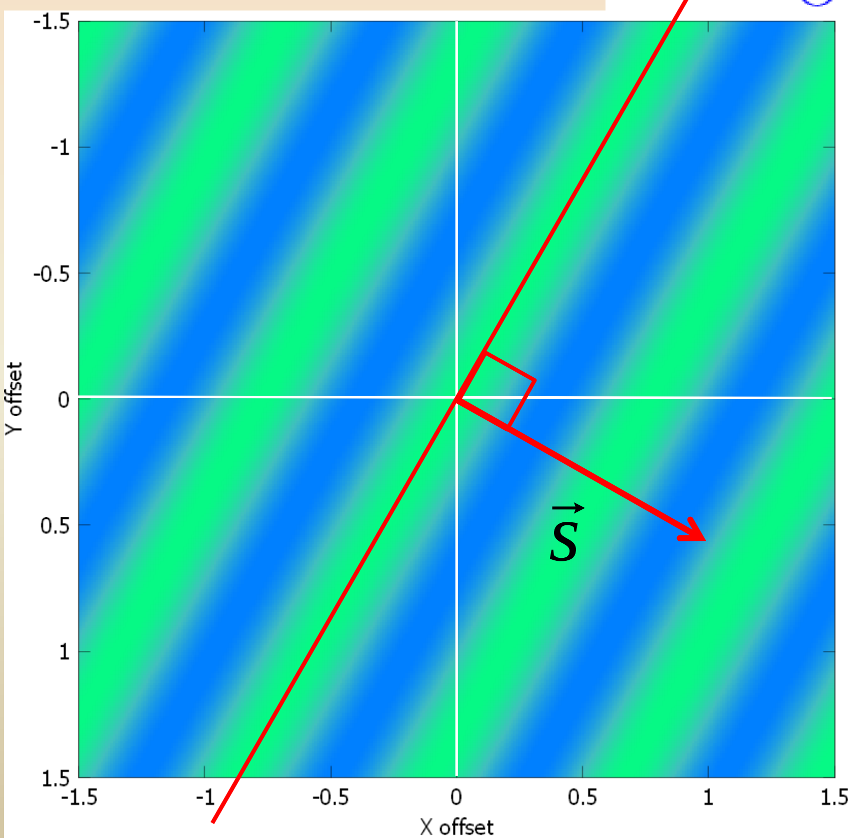
$$c_{app} = c / \sin(i)$$

apparent slowness

$$s_{app} = |\vec{s}| \sin(i) = \frac{dT}{d\Delta}$$

Wavefield definitions





wavenumber = cycles/km

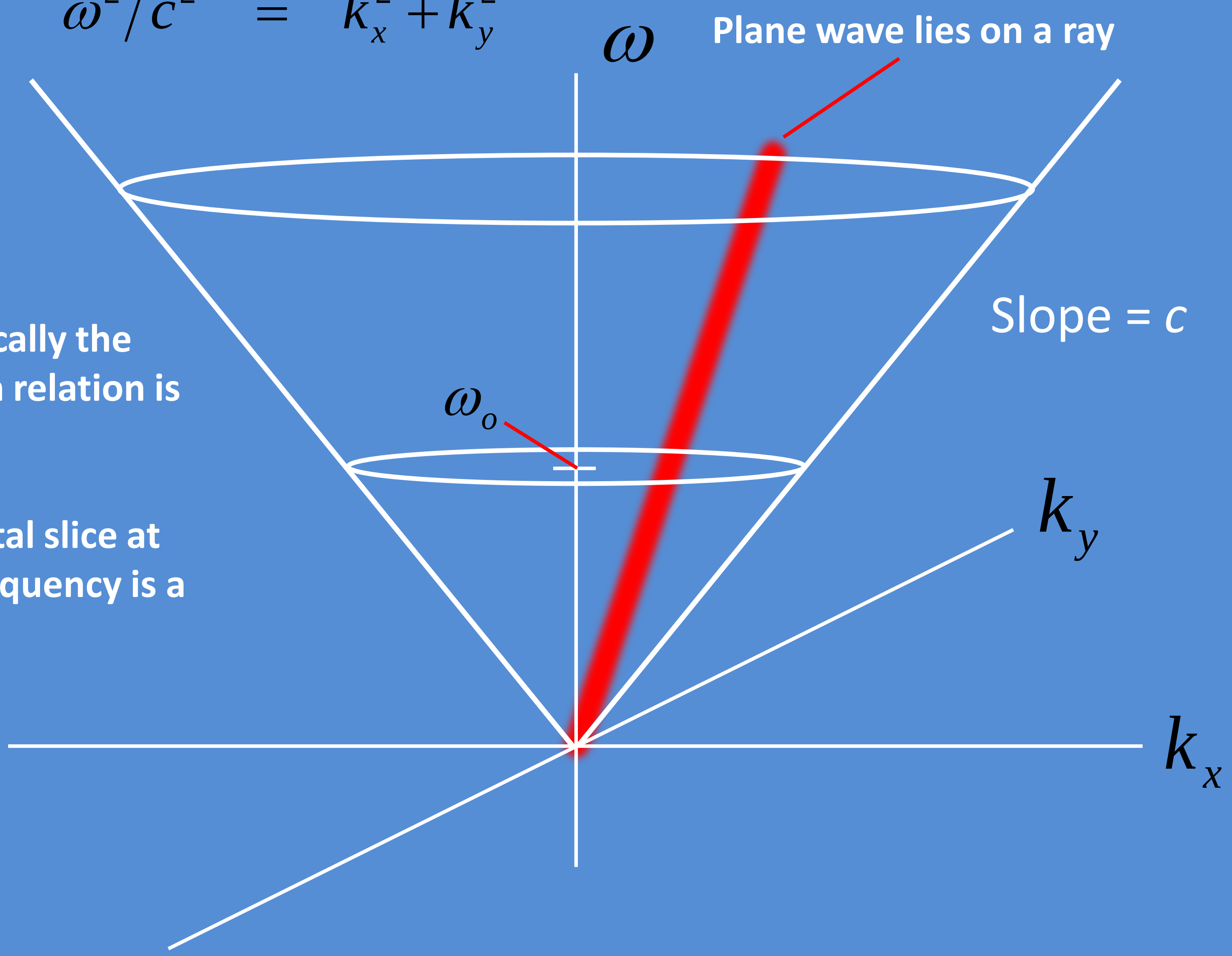
$$\upsilon = 1/\lambda$$

$$\lambda = c/f$$

$$|\vec{s}| = 1/c$$

Frequency and wavenumber are linked by the dispersion relation

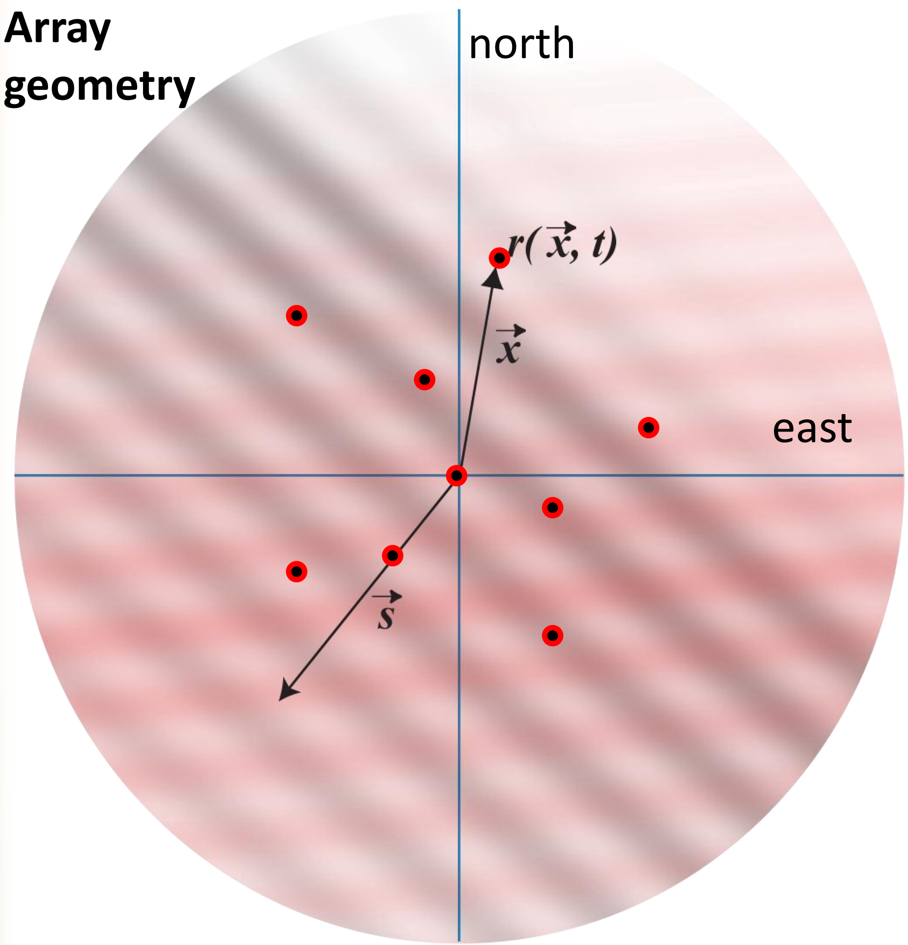
$$\omega^2 / c^2 = k_x^2 + k_y^2$$

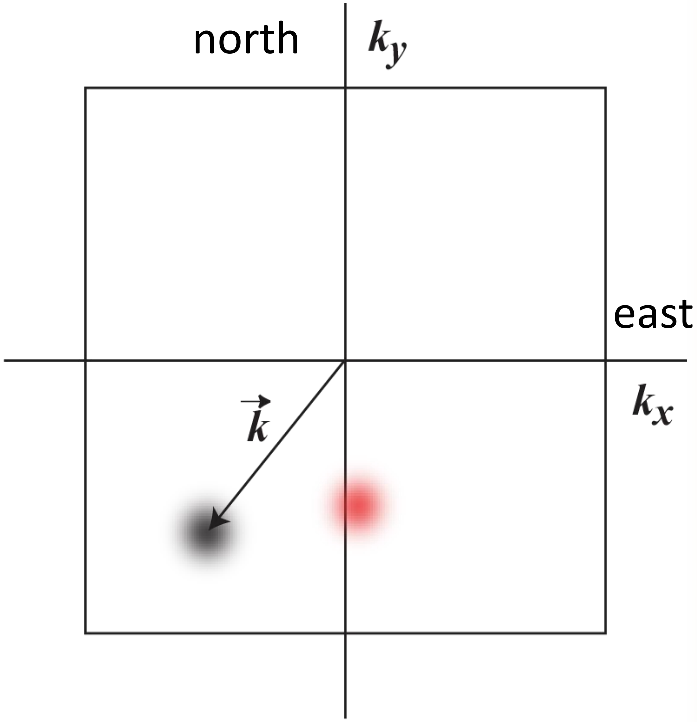


Geometrically the dispersion relation is a cone

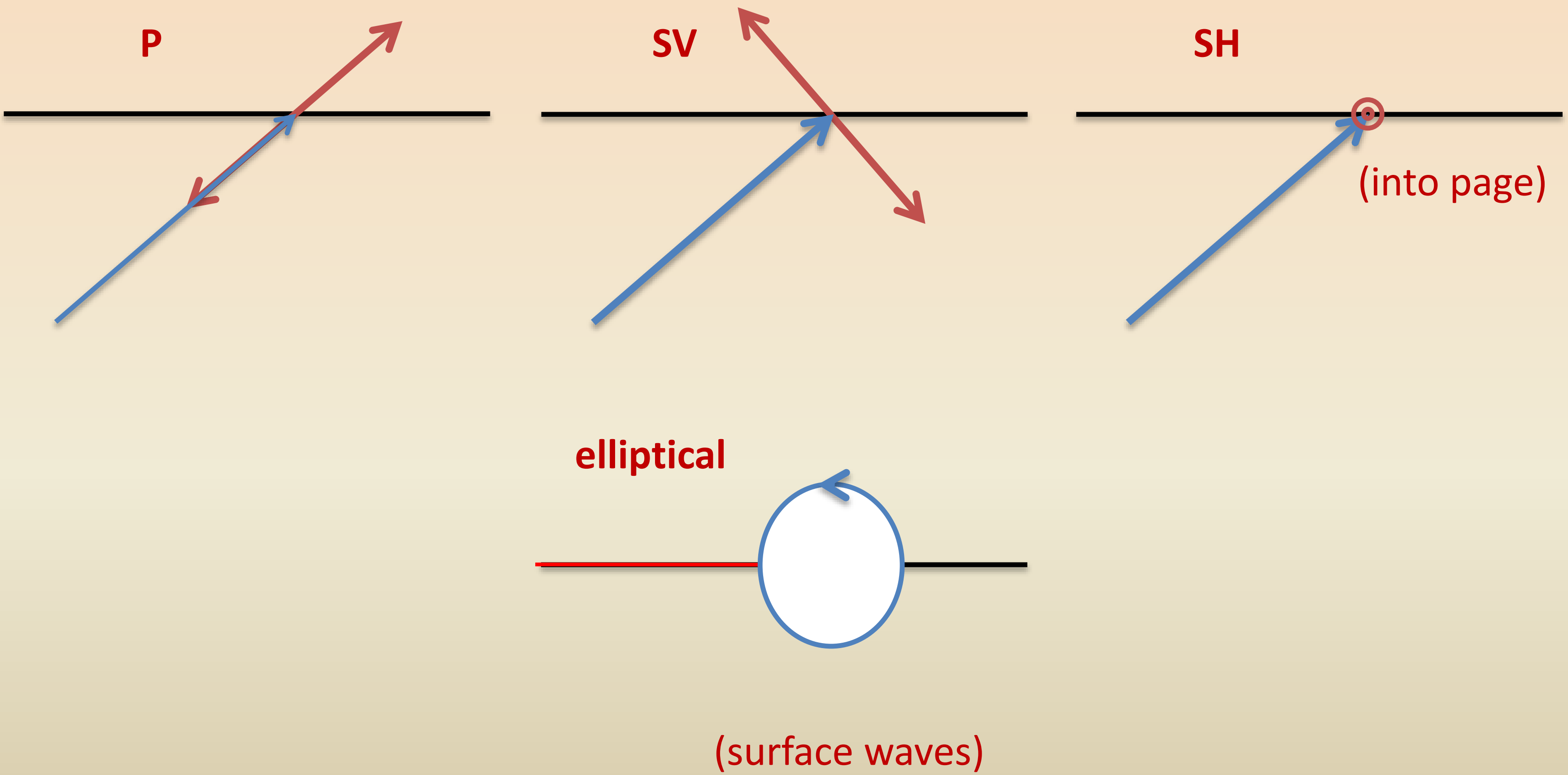
A horizontal slice at a fixed frequency is a circle

The FK spectrum is a map of energy incident on the array as a function of direction and velocity^{-1}

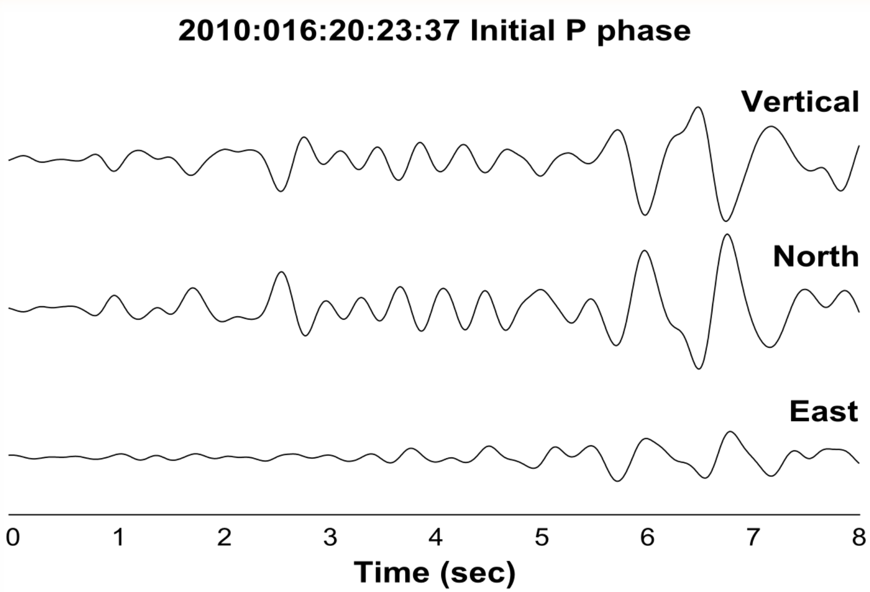


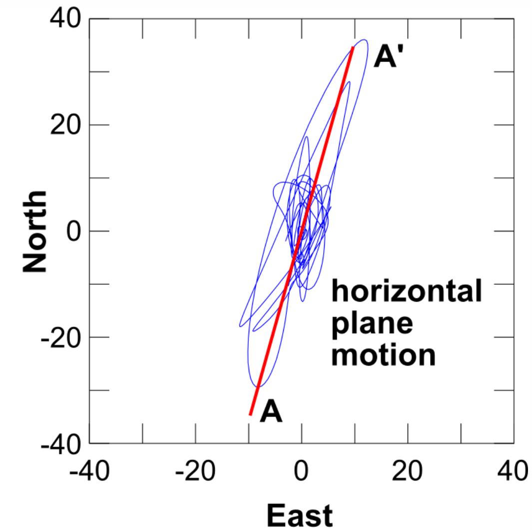


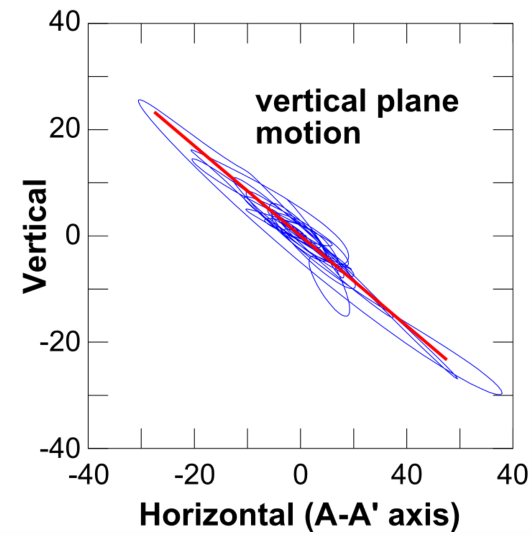
Seismic waves have at least 4 types of polarization which can be distinguished by three-component data



Pn polarization can be used to estimate direction to the source





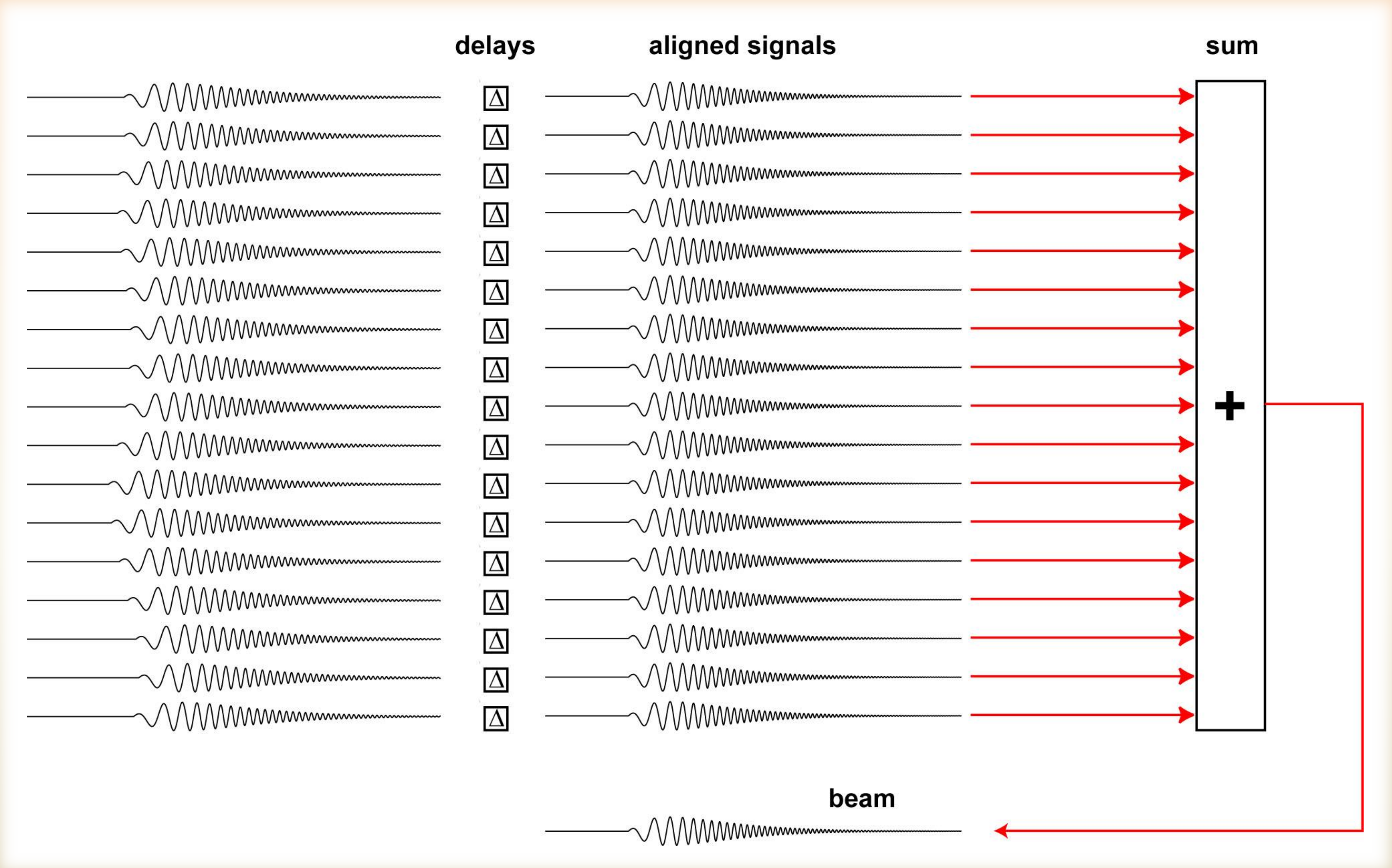


$$\vec{r}(t) = \begin{bmatrix} v(t) \\ n(t) \\ e(t) \end{bmatrix}$$

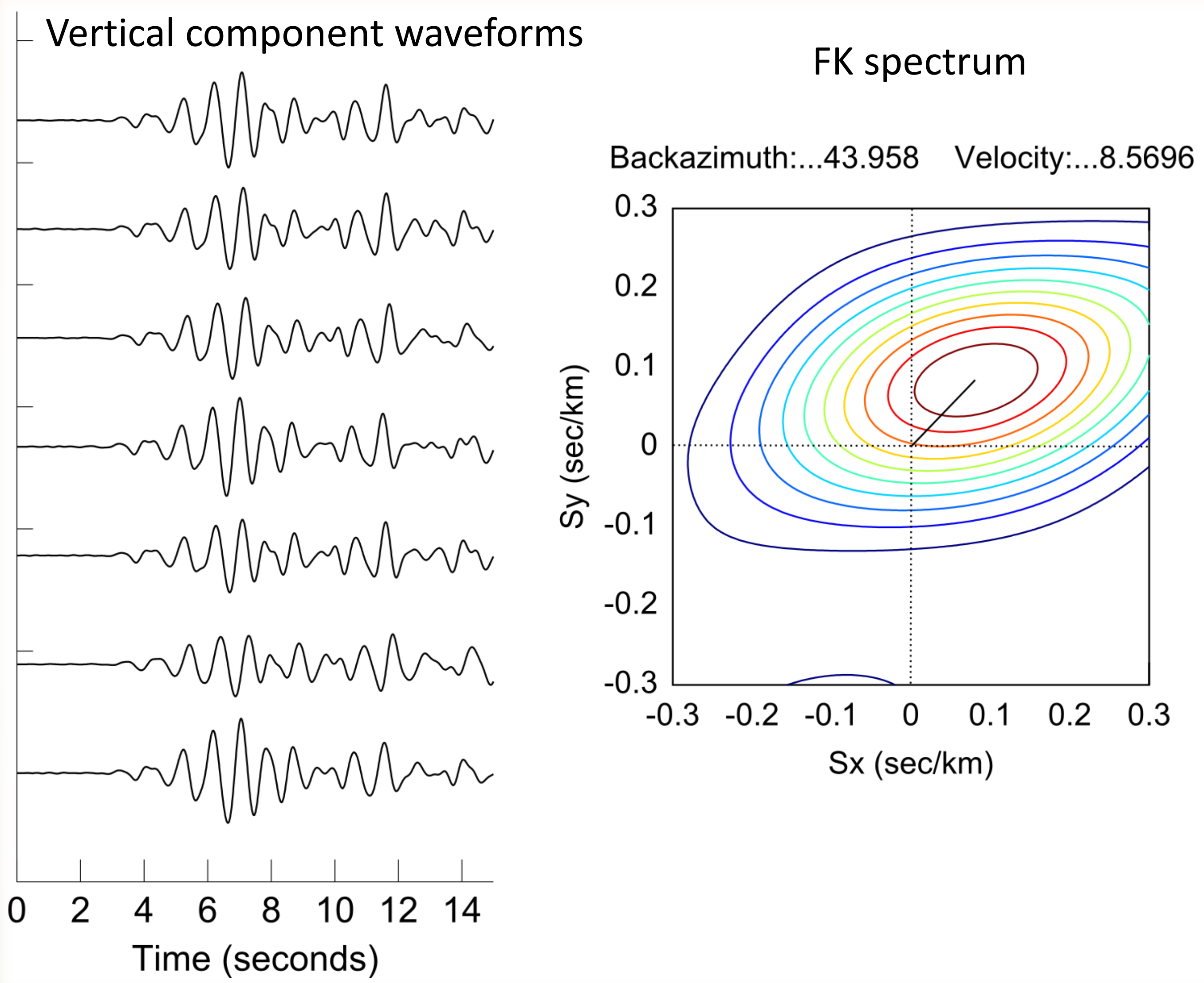
$$\vec{C} = \int \vec{r}(t)\ \vec{r}^{T}(t)\ dt$$

$$\vec{C} = E\,\Lambda\,E^{T} \qquad b(t) = \vec{e}\cdot\vec{r}(t)$$

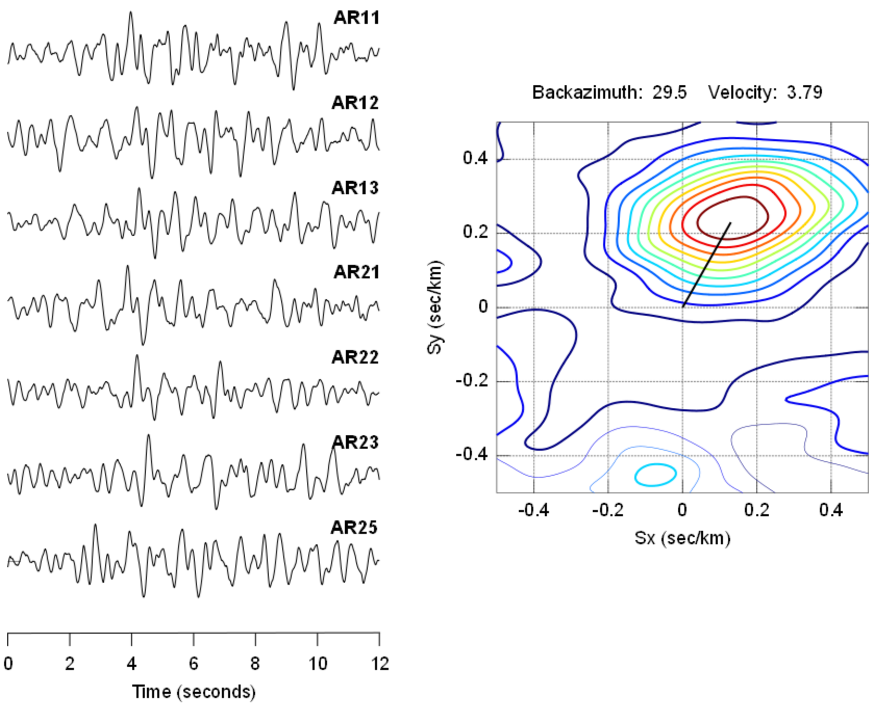
Beamforming uses the plane wave model to align waveforms, then sums them to enhance the signal



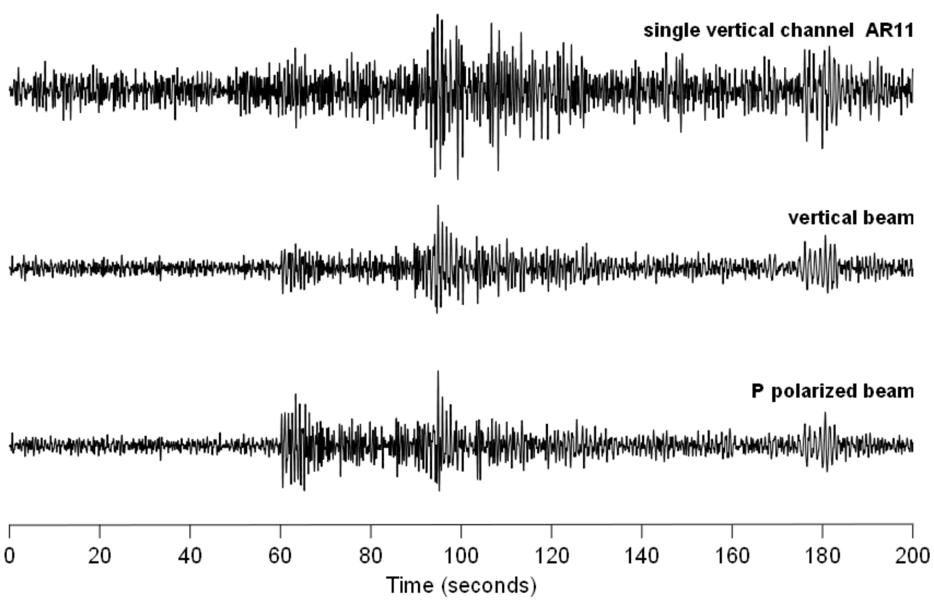
Back-azimuth estimated from the FK spectrum of the P wave – mb 5.6 event



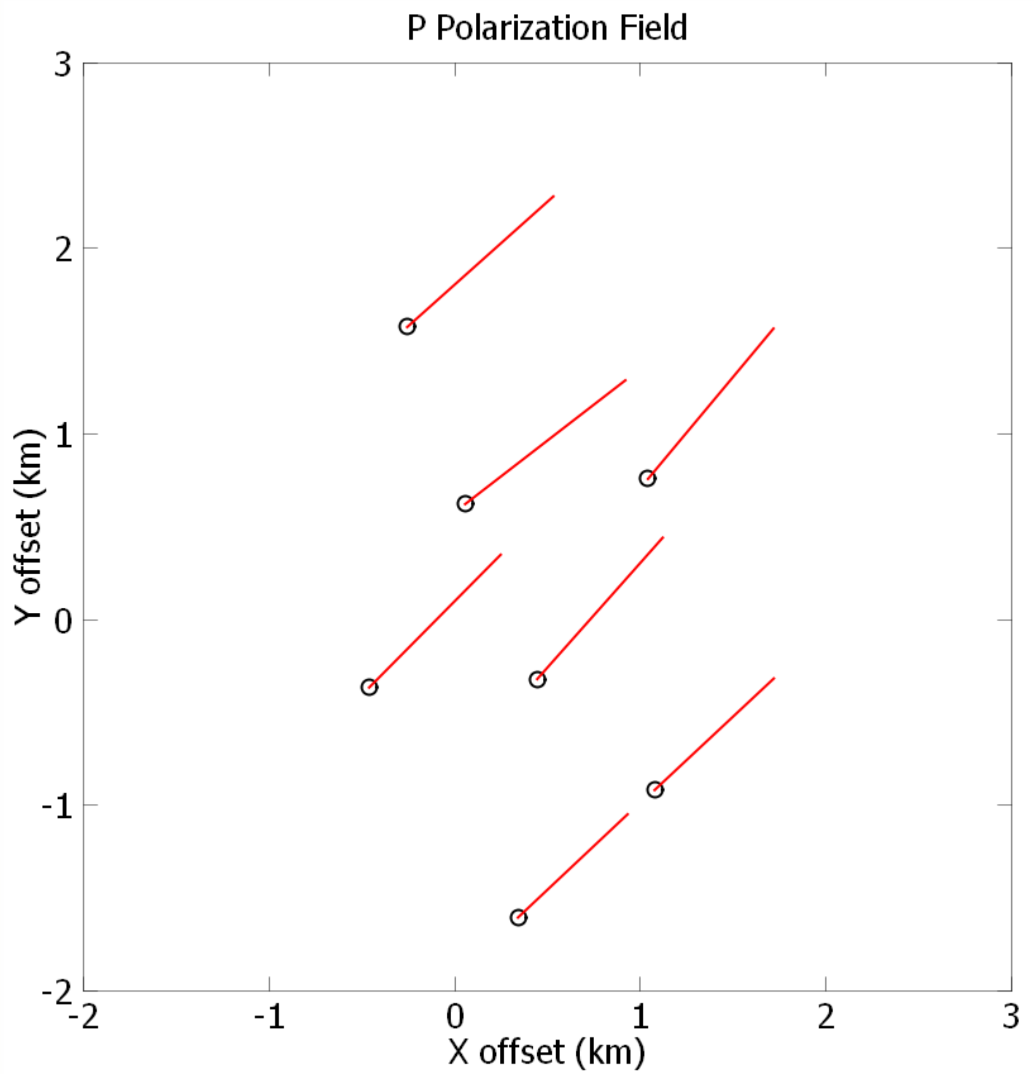
Local event example with back-azimuth determined from Lg



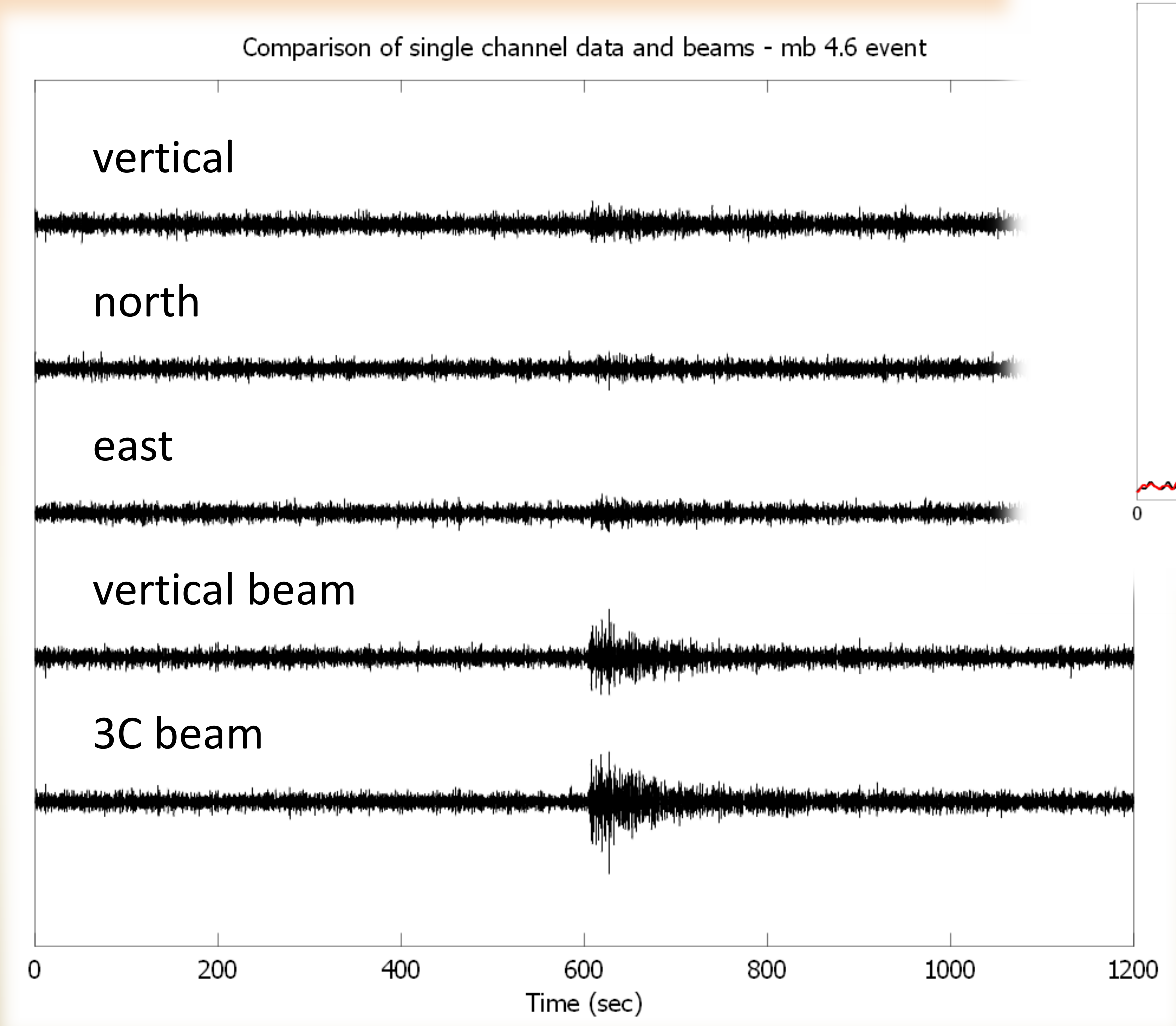
Three-component beamforming may perform better with local events, due to larger P projections onto the horizontal array elements

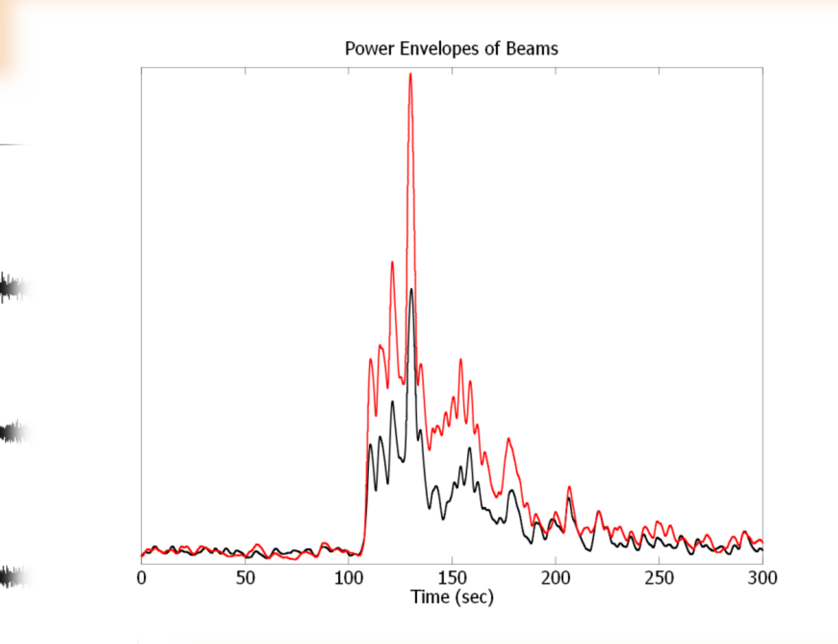


P polarization for the mb 5.6 event is consistent over the array aperture



Beamforming brings up the P wave in this event

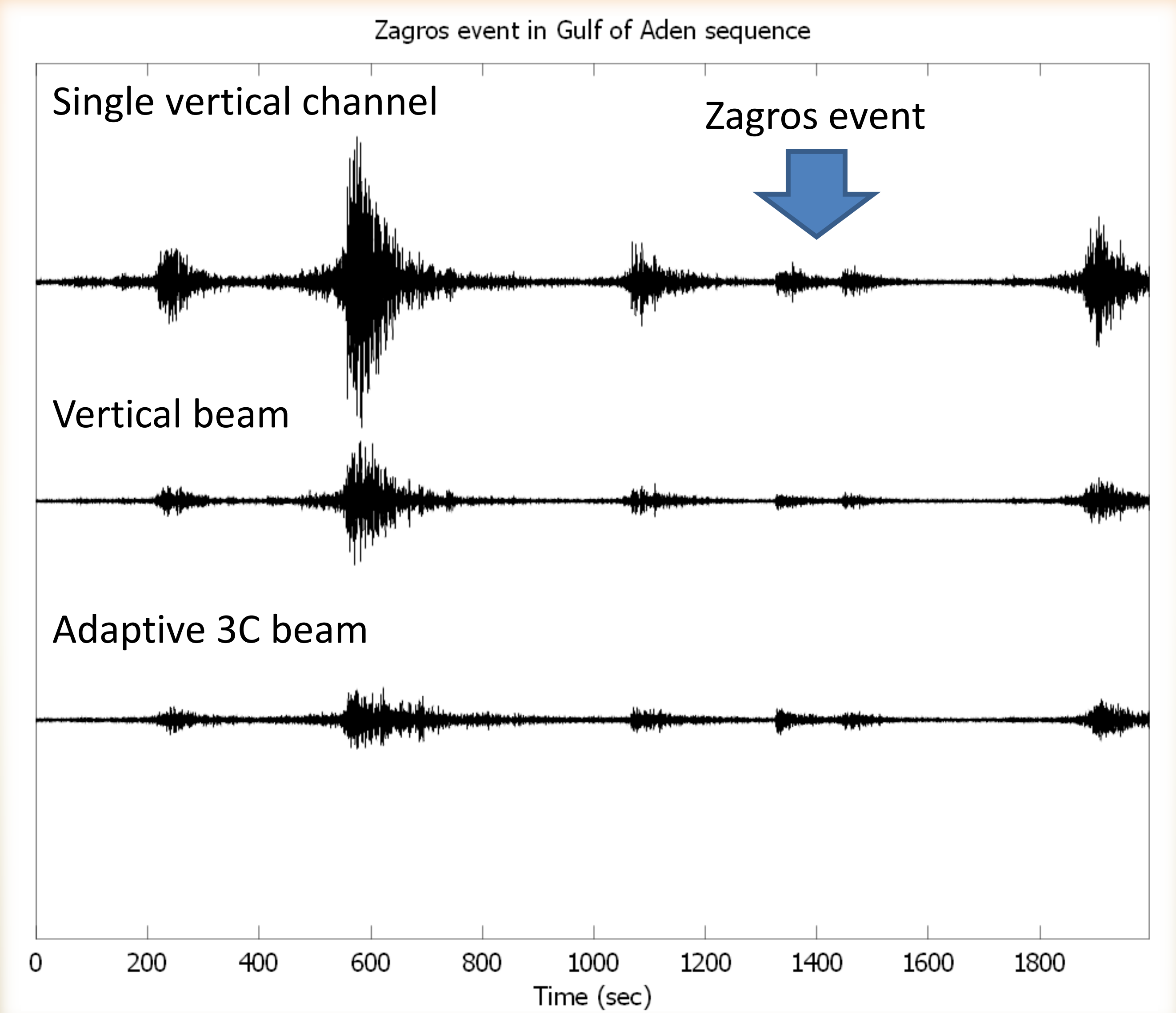




Backazimuth, velocity and polarization parameters estimated from the mb 5.6 event

Three-component beamforming doubles the power SNR

Adaptive beamforming effectively suppresses the Gulf of Aden signals while passing the Makran P wave



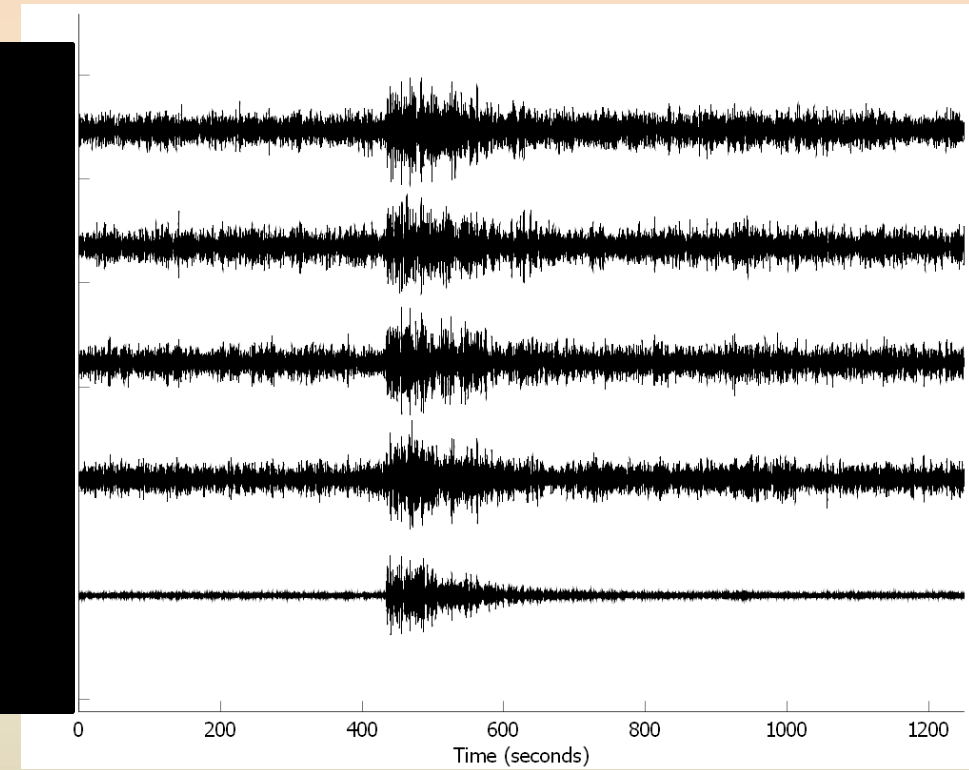
Only 13 of 21 channels were available for this example

Vertical beam shown in the middle is not adaptive

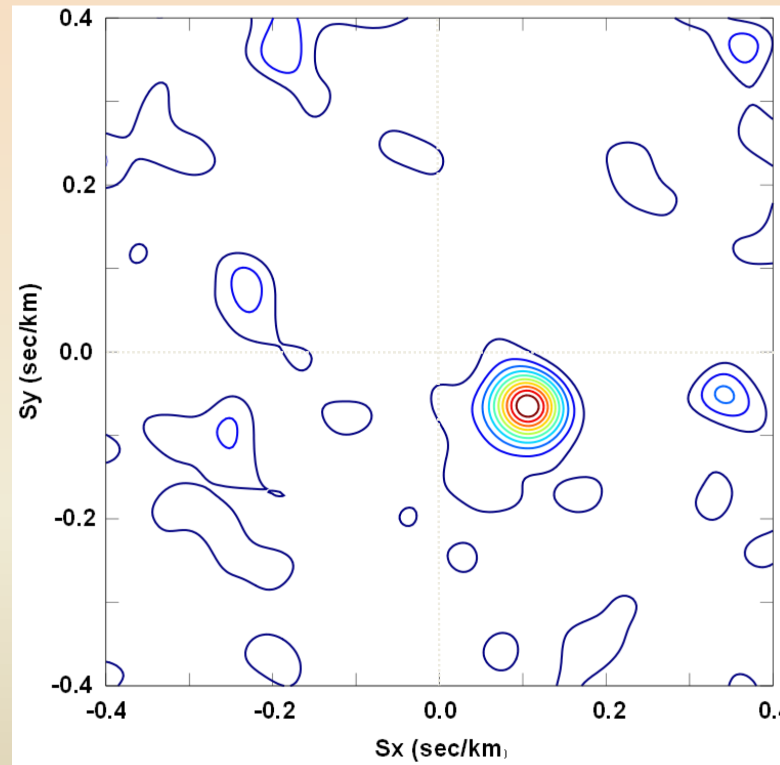
Adaptive beam combined polarization filtering, beamforming and calibration

Arrays permit us to see weaker signals and measure wave field properties

Beamforming

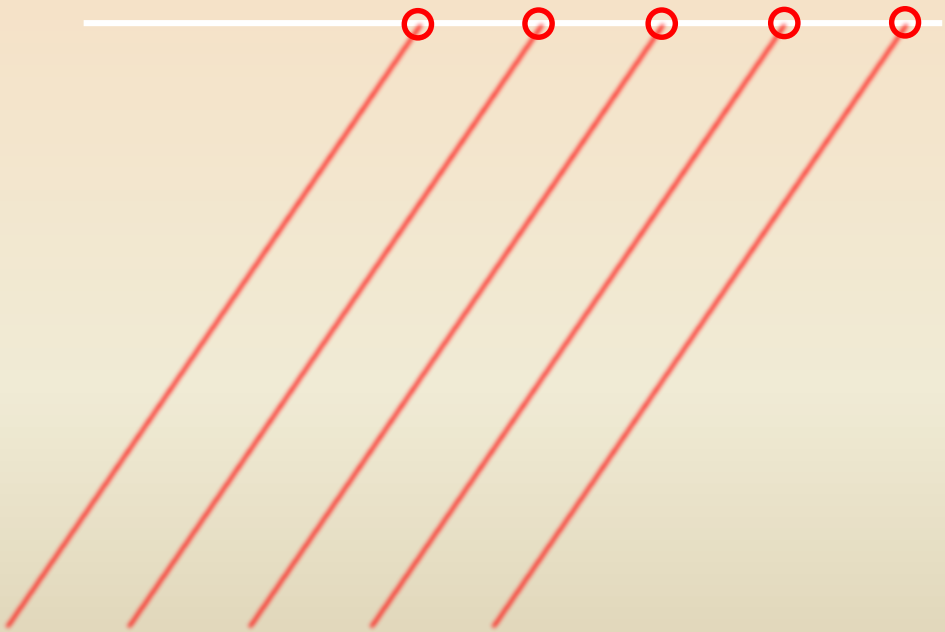


FK Analysis

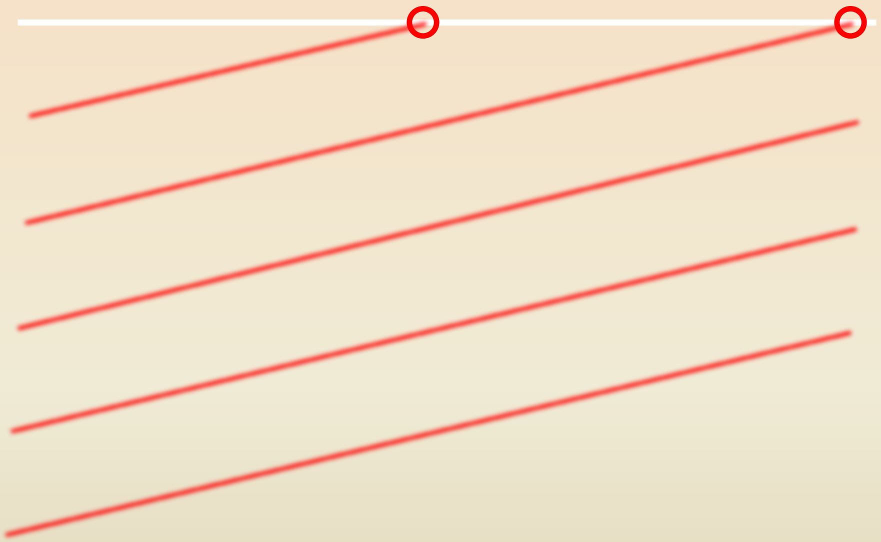


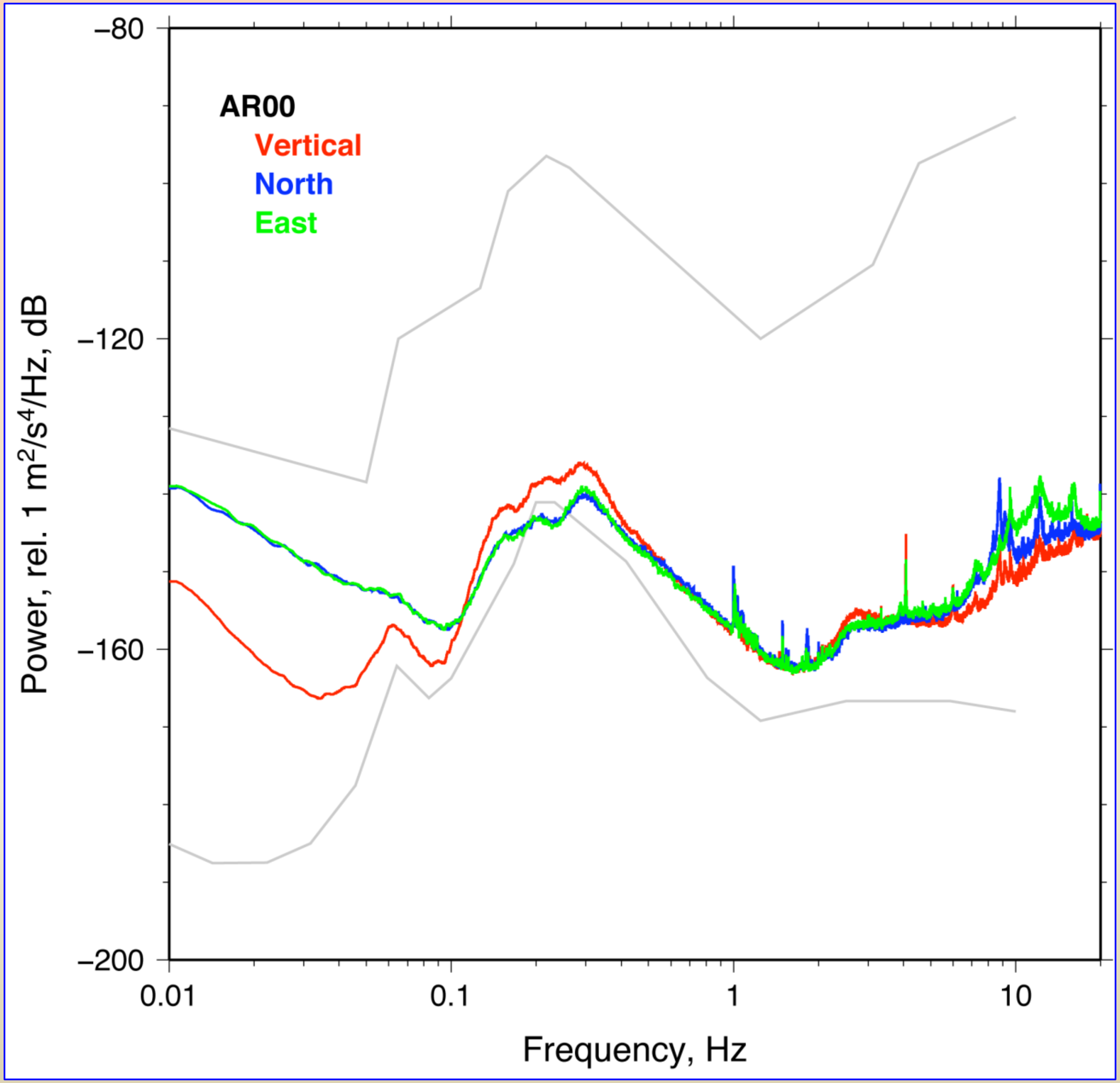
The angle of incidence controls apparent surface velocities and wavelengths

Near horizontal propagation produces short wavelengths – typical of regional waves, e.g. Pn



Near vertical propagation produces long wavelengths – typical of teleseismic waves





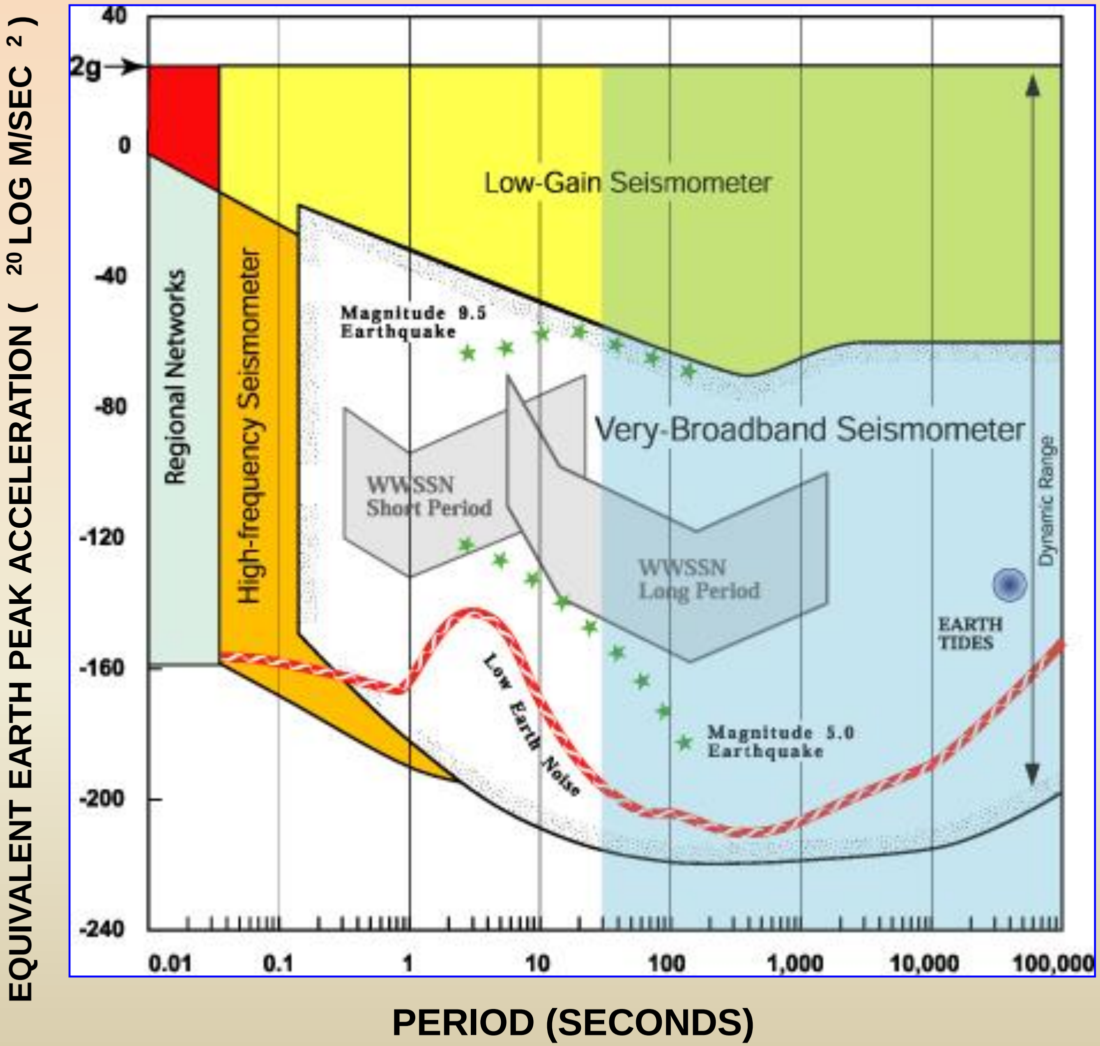
Average ambient noise levels for the three components of the central broadband element AR00

Reported low and high noise models from Peterson (1993) are shown as gray curves.

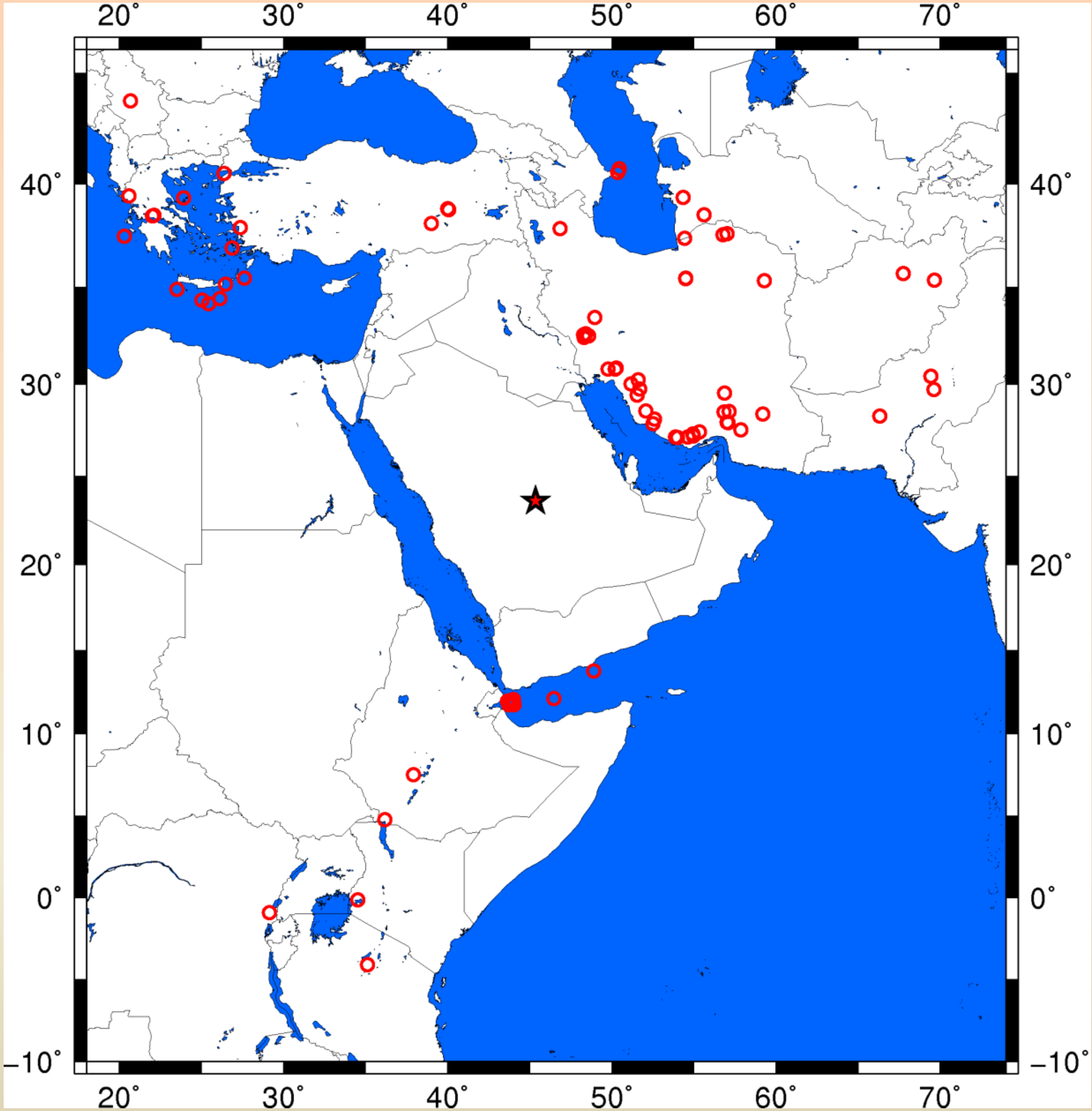
The noise levels are quite low, near the USGS low noise model for the central band of 0.05 – 10 Hz. Noise levels increase from the low noise model away from the central frequencies.

Sharp noise spikes are apparent at 1.0 and 4.0 Hz in all channels. These could be instrumentation noise or cultural noise from the nearby town of Ar Rayn, which is 15 kilometers distant.

IRIS GSN SYSTEM

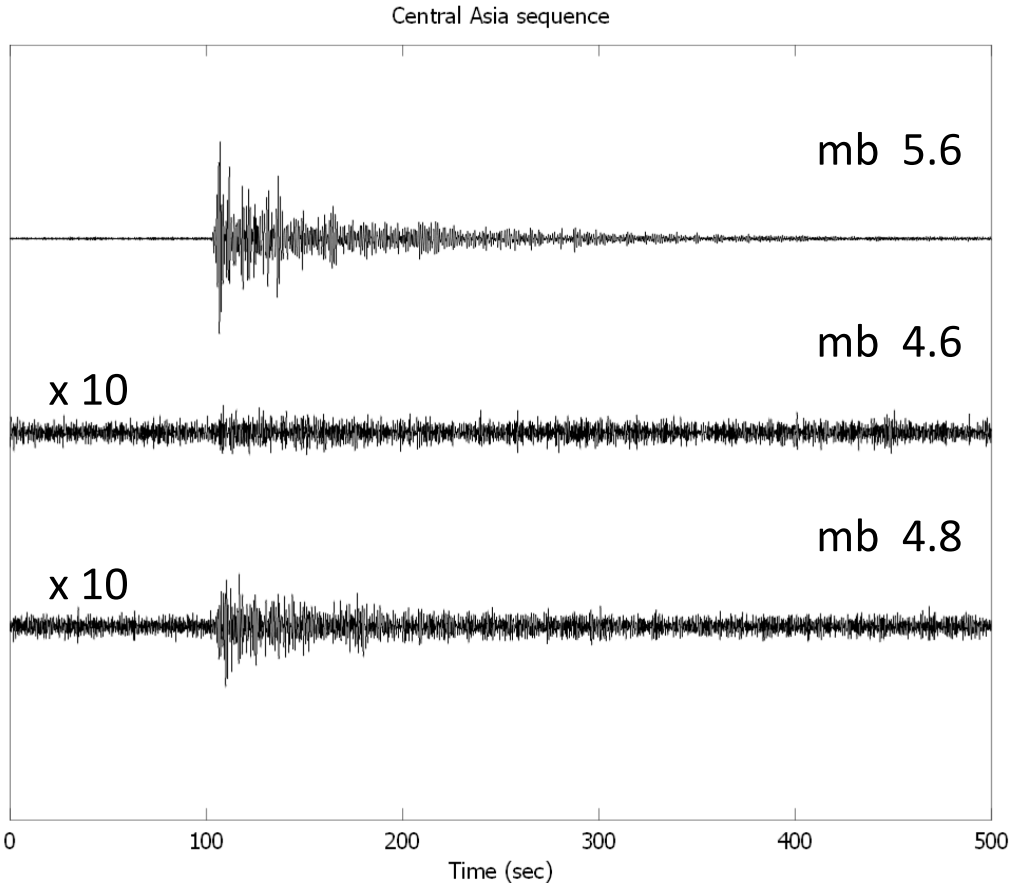


Global networks choose instruments capable of recording long period waves. Local arrays may use short period sensors to record local earthquakes.

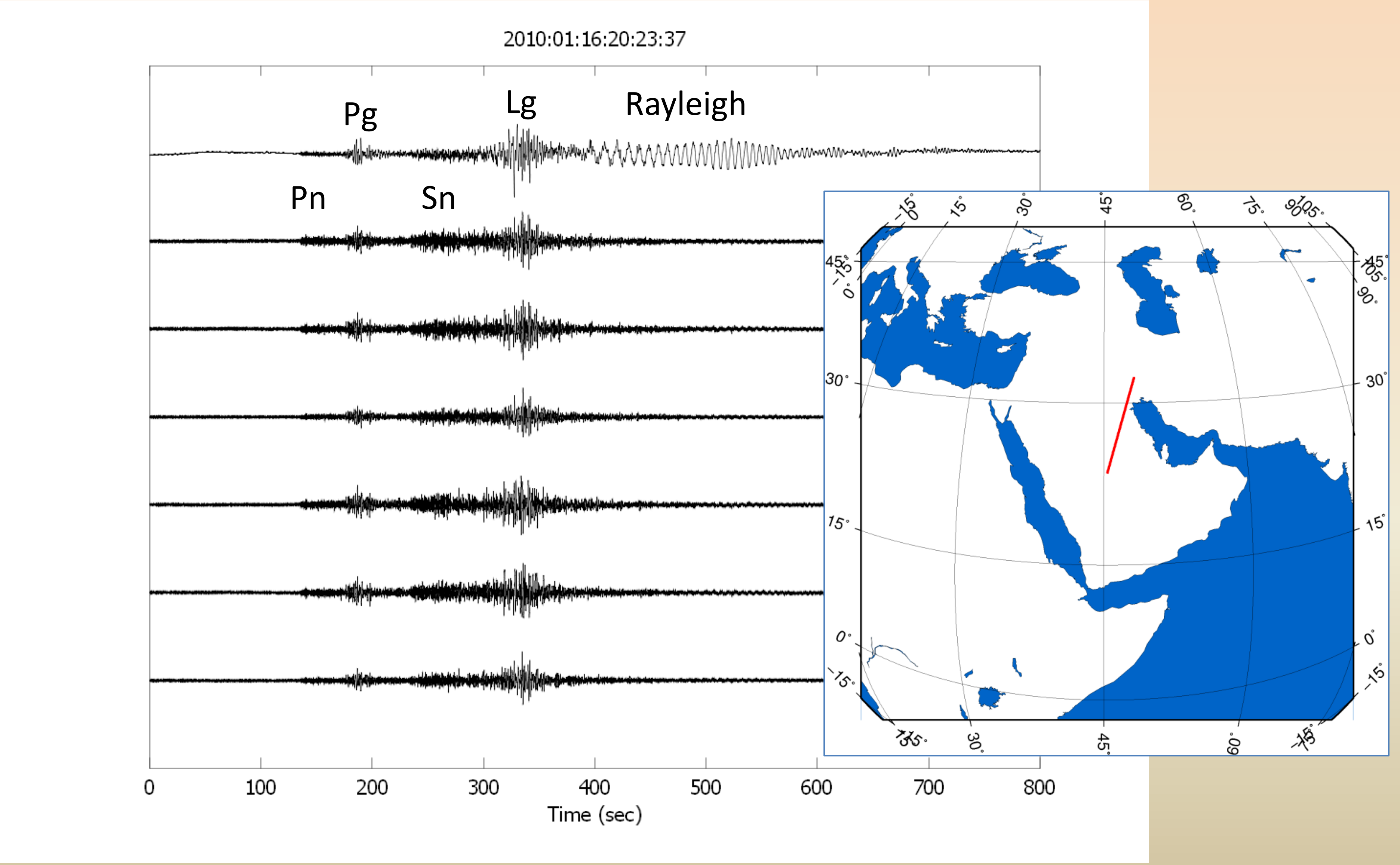


Distribution of events used in back-azimuth and slowness study. The array location is denoted by a star. Earthquake locations are denoted by open circles.

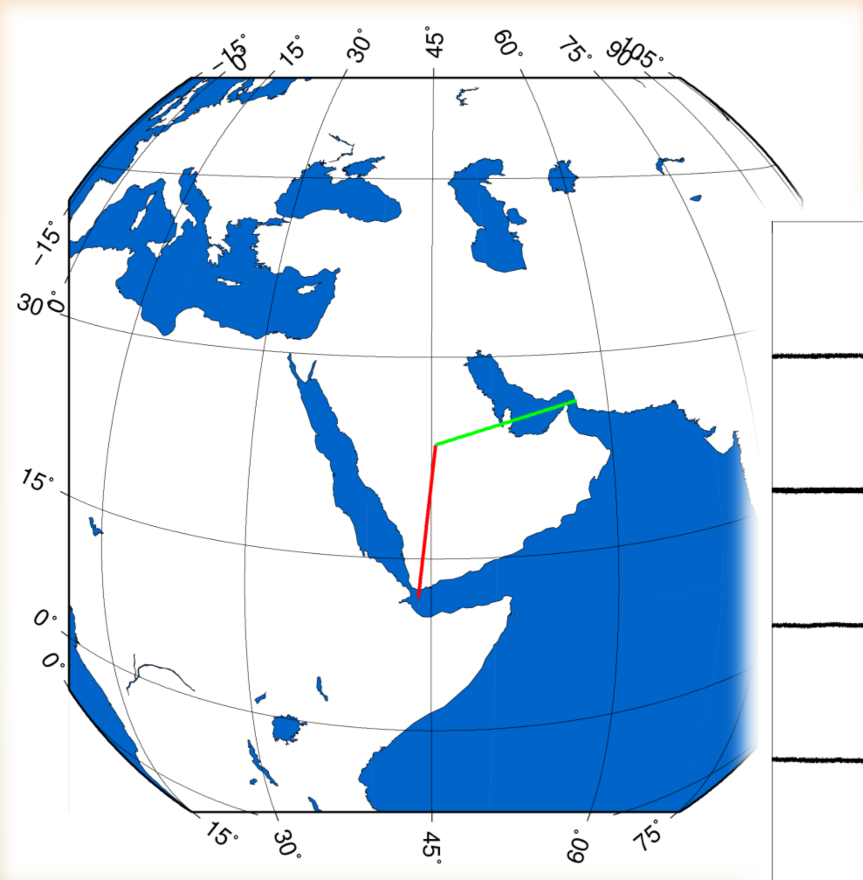
Beamforming example: Central Asian sequence
distance: 2537 km

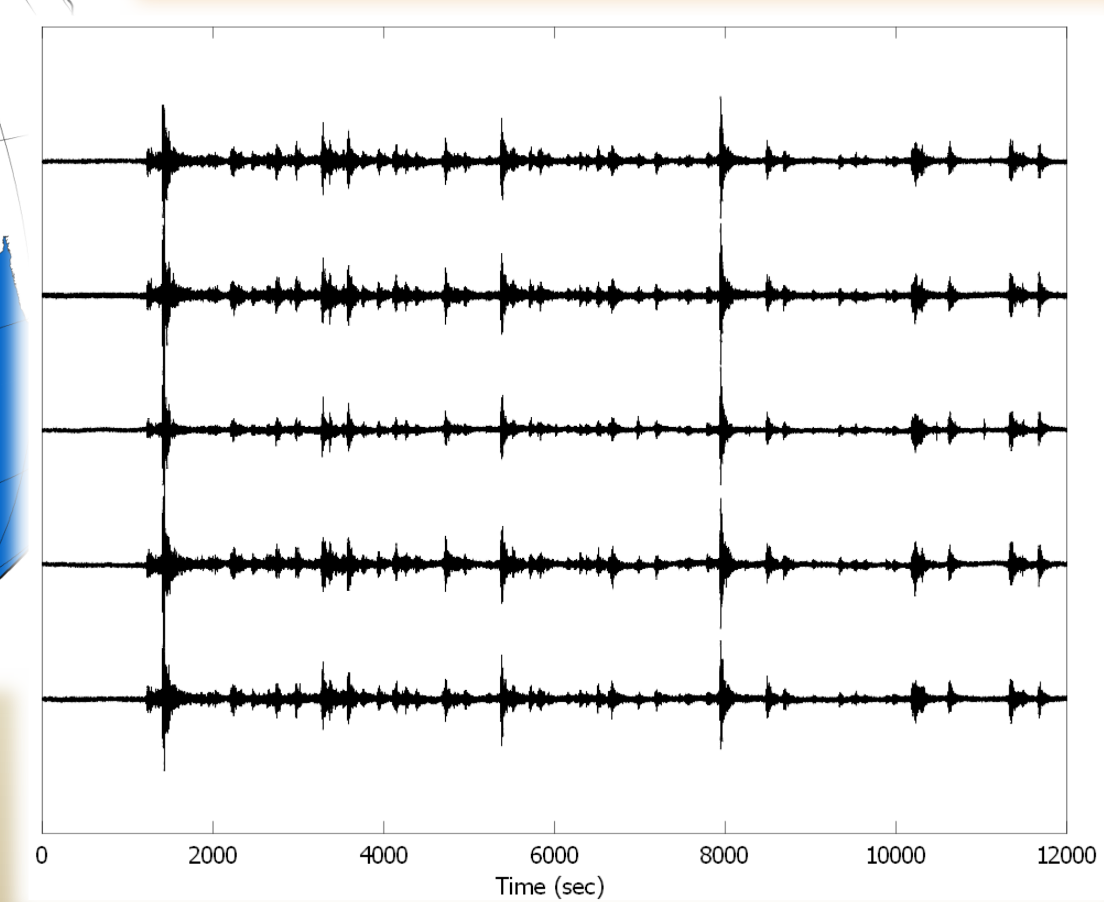


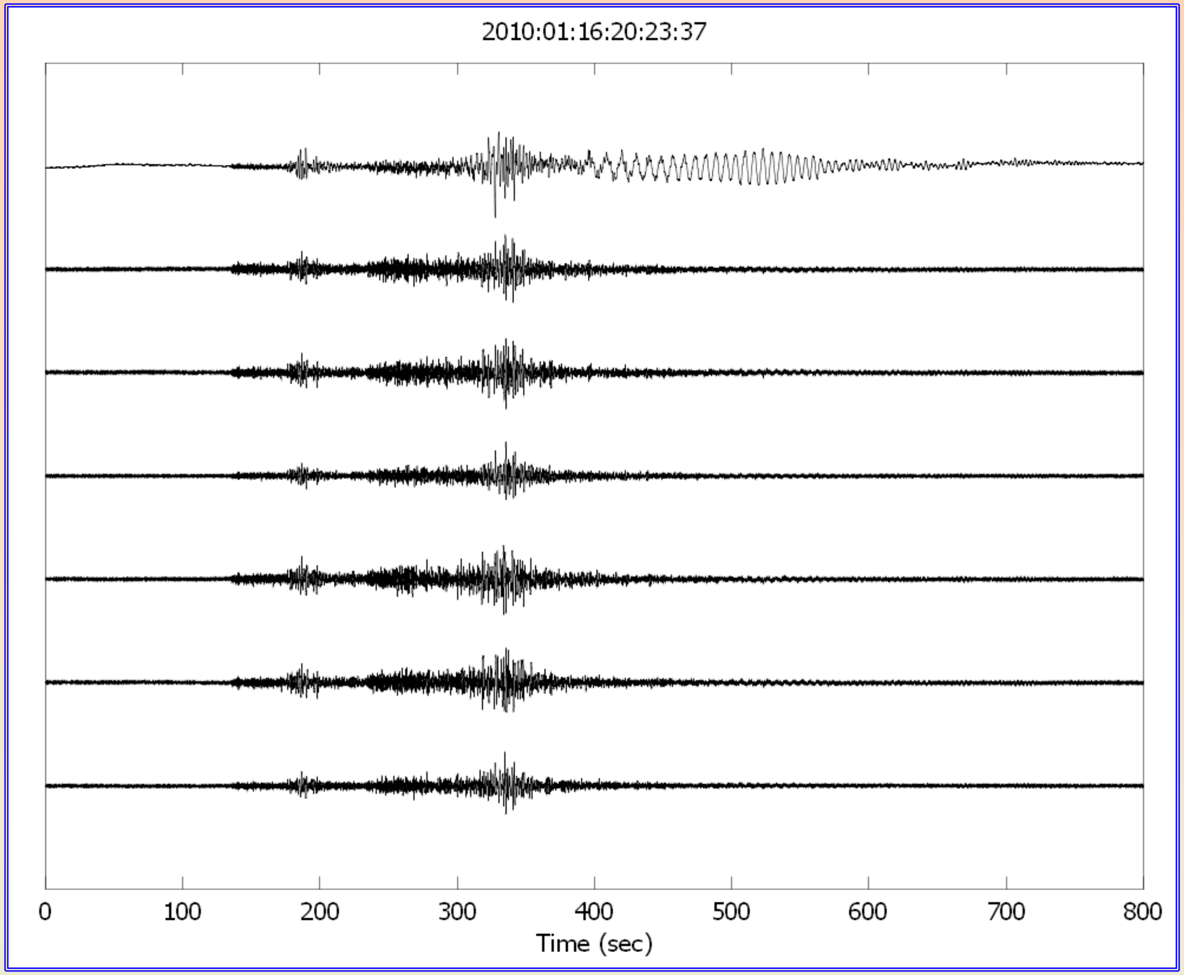
P polarization example, event 2010 01/16 20:23:37
distance: 1036 km



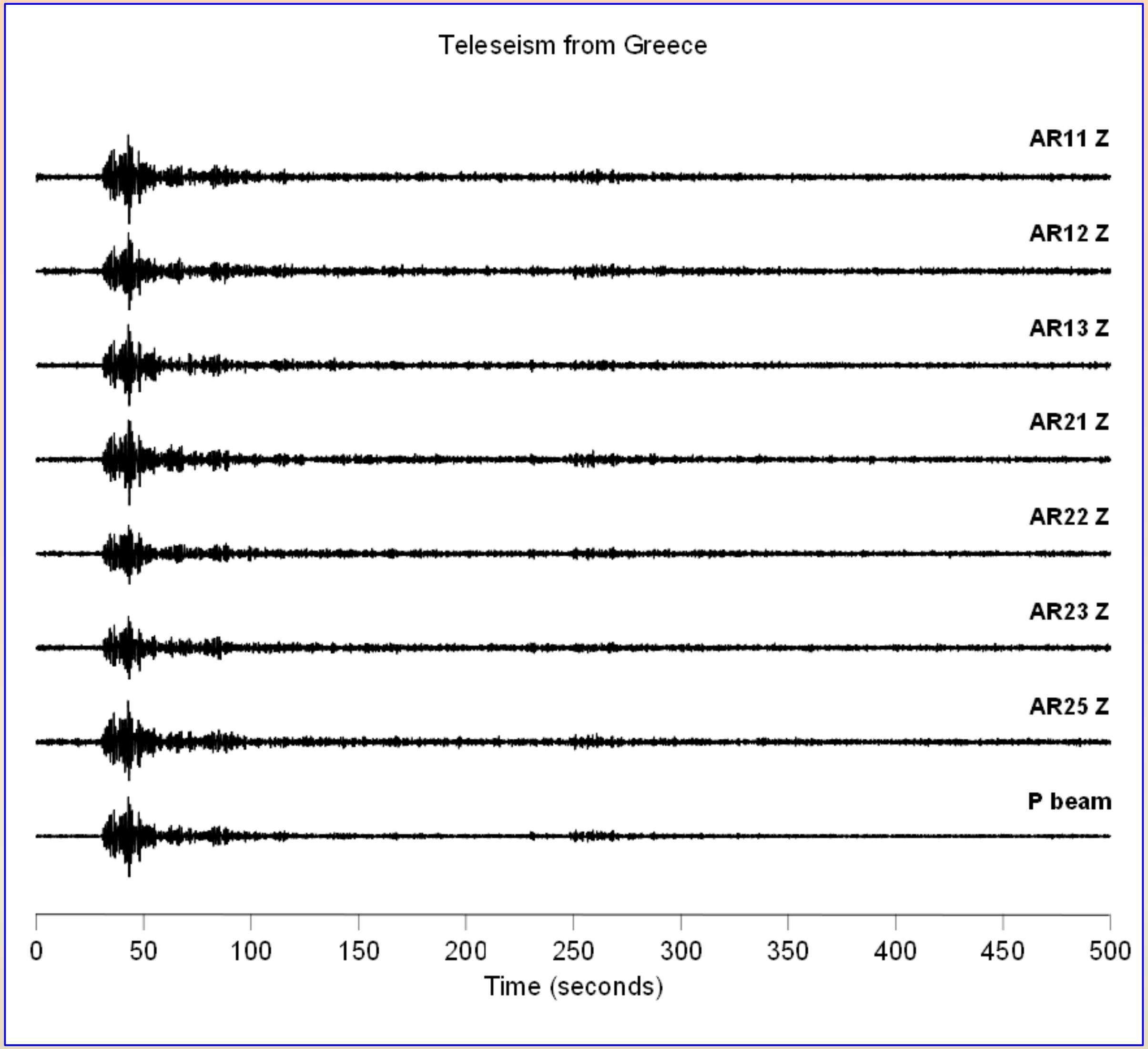
Adaptive beamforming example – attempt to extract a Makran event in the midst of a Gulf of Aden swarm



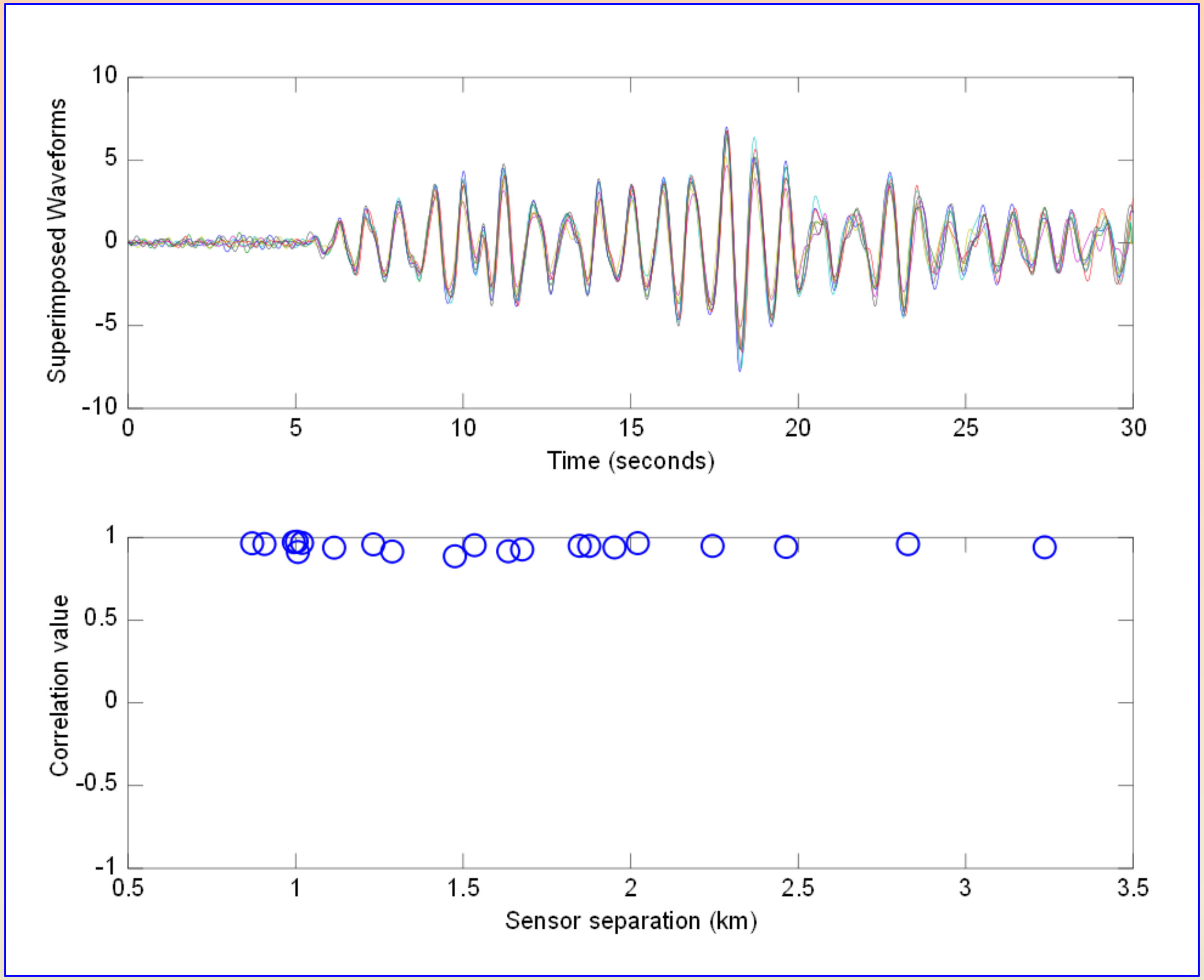




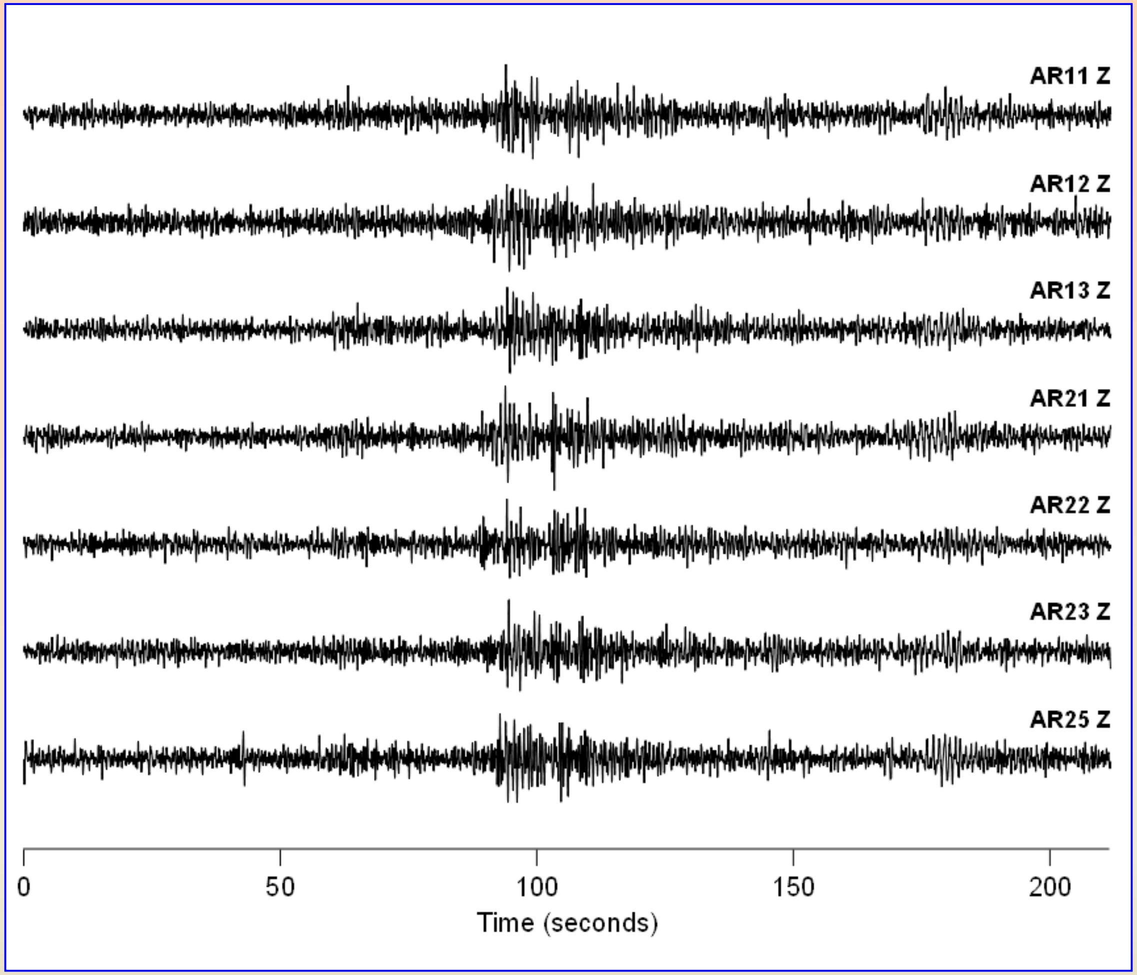
Ground motion recorded by the vertical-component seismographs of the Ar Rayn array for the magnitude 5 event. The top trace is from the broadband station at the center of the array. Note the surface (Rayleigh) wave well-dispersed by the deep sediments of the Arabian Gulf. The other six traces are from the short-period stations that were operating at the time. These show (in order of arrival) Pn, Pg, Sn and Lg phases. The Pg and Lg phases are slower in this region than in other parts of the world due to propagation through the deep sediments of the eastern Arabian peninsula.



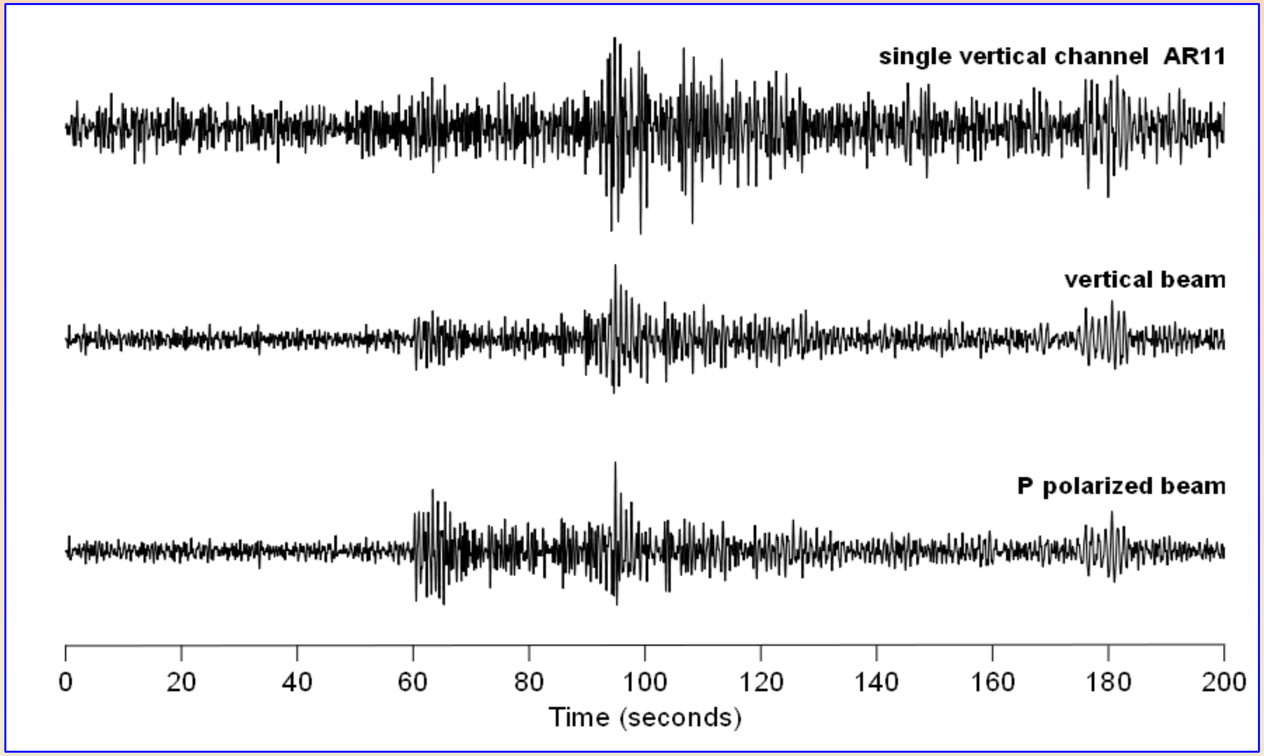
Teleseismic P wave from an event near Greece recorded on 7 sensors of the array. The beam at the bottom of the plot is steered to the direction and velocity of the initial P wave, and indicates a weak P arrival (PcP?) about 250 seconds into the plot.



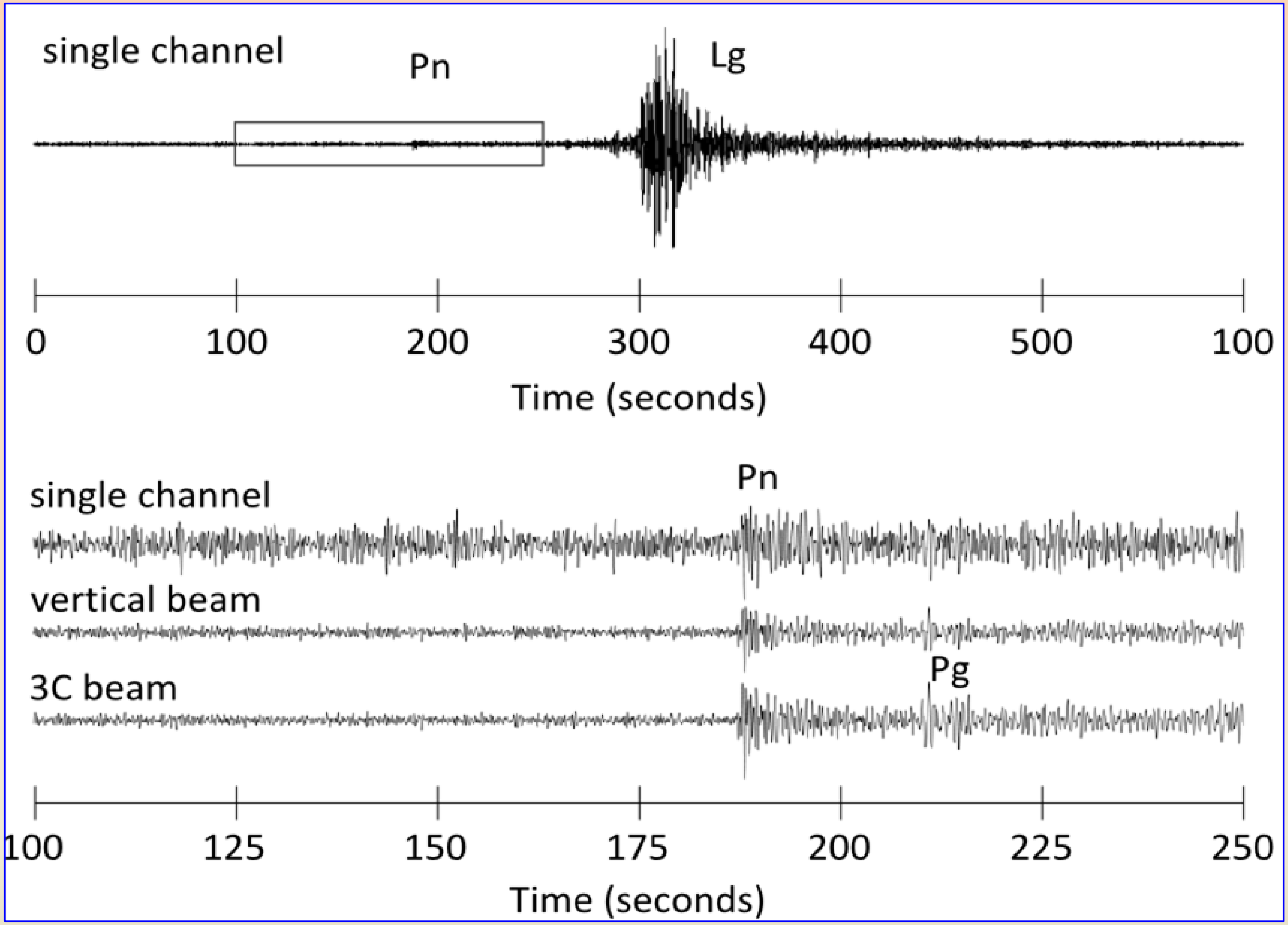
Coherence of the teleseismic P phase at the array is high, demonstrating uniformity of installation and instrumentation. At top, the first 25 seconds of the P wave of the teleseism from Greece are superimposed after being shifted to align them to the back-azimuth and velocity obtained with FK analysis. At the bottom, the 21 correlation coefficients between unique pairs of sensors are shown plotted as a function of sensor separation. The P phase is relatively narrowband, with most of its energy just above 1 Hz.



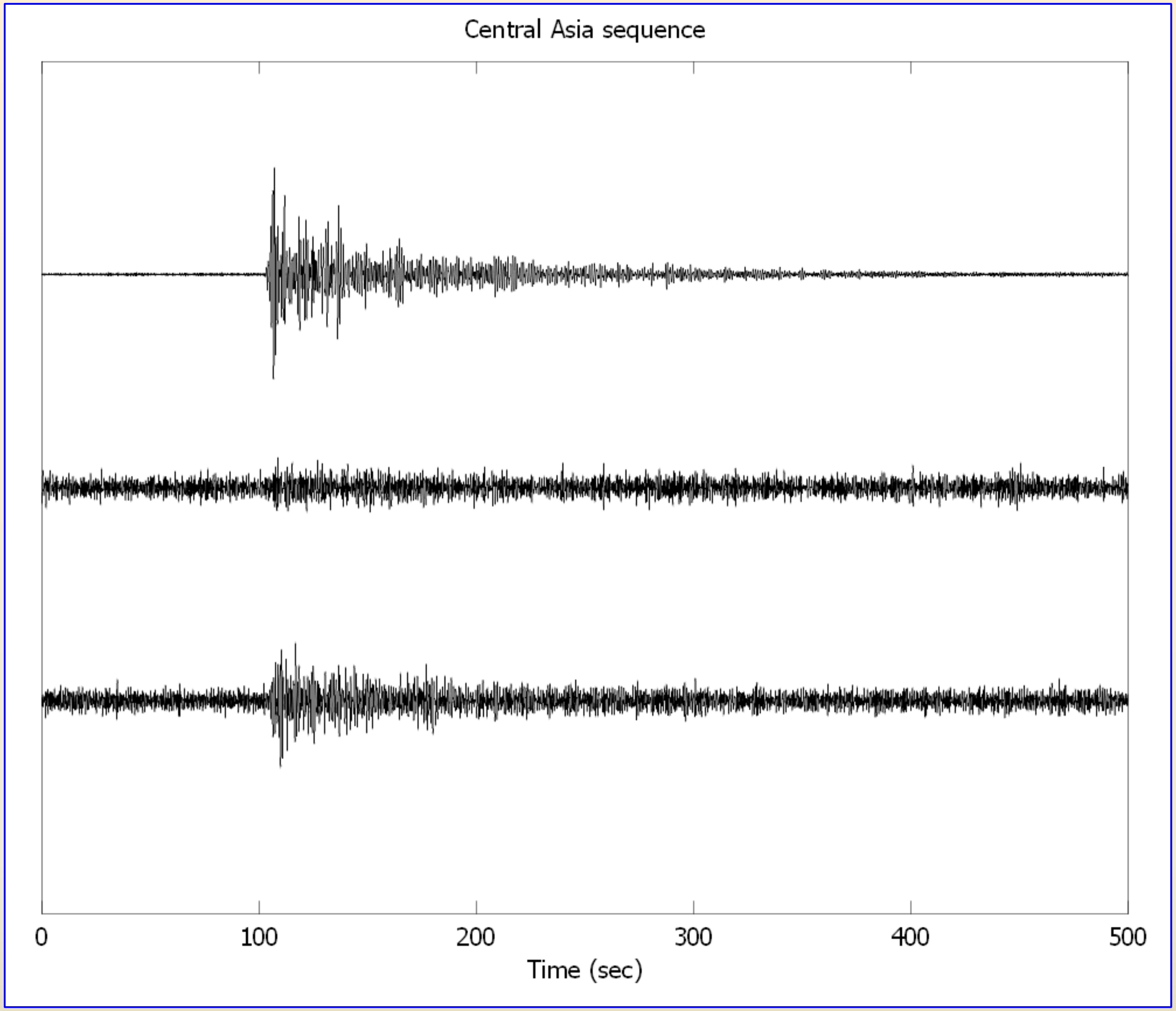
This small central Arabian event about 260 kilometers from the array has a low SNR that makes observation of the P phases difficult. A window around the Lg phase from 90 to 100 seconds allows backazimuth estimation with an FK spectrum.



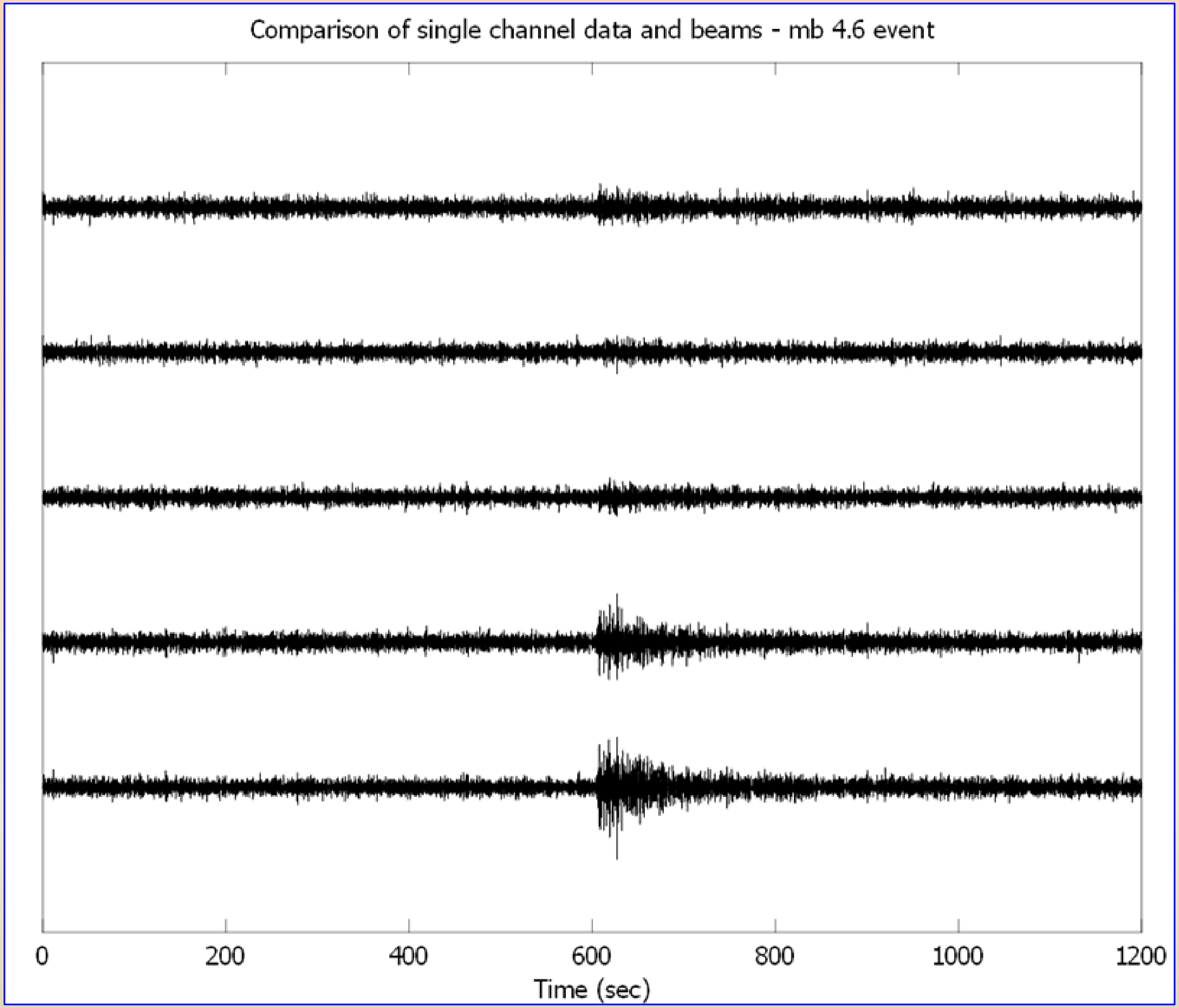
Single vertical channel (top trace), vertical beam (middle trace) and three-component beam (bottom trace) directed at the Pn phase for the central Arabian event.



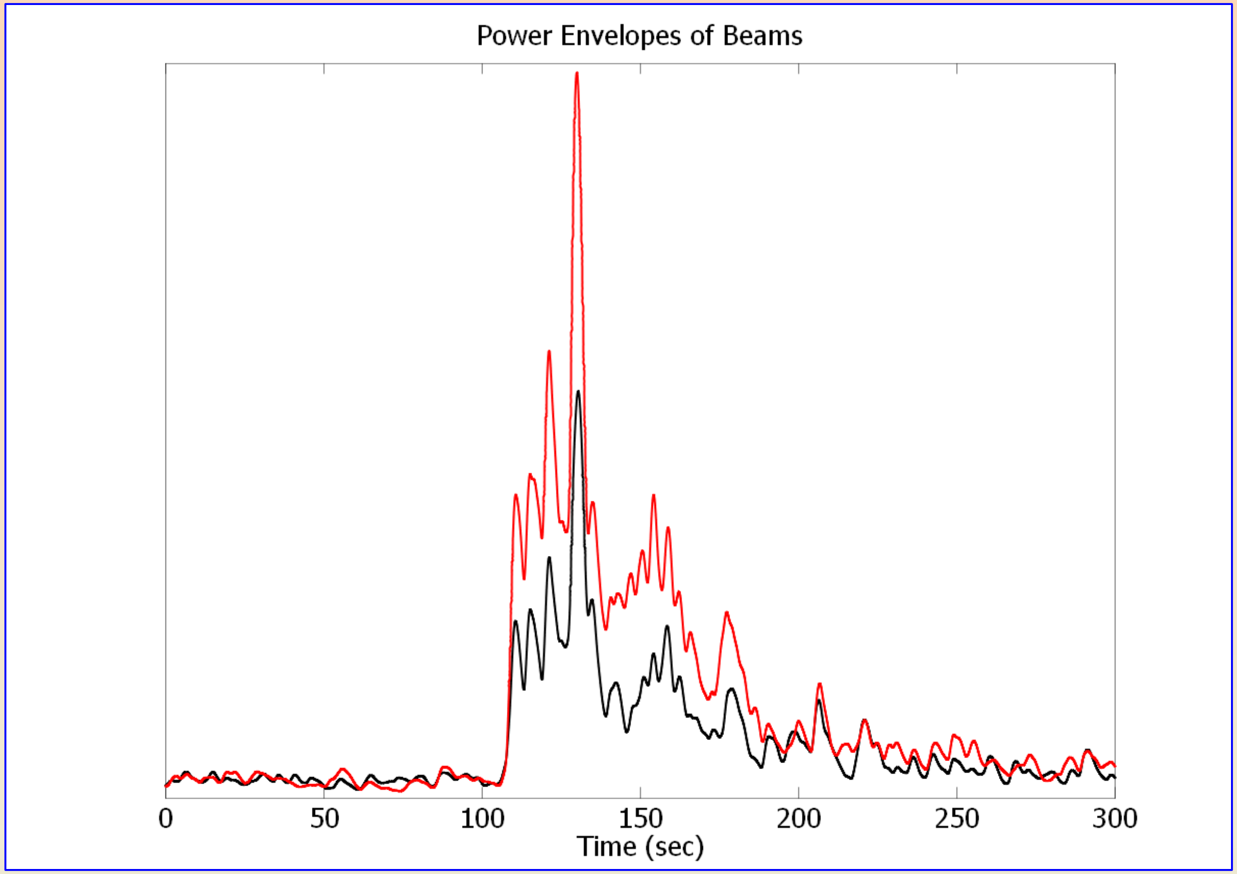
Example of beamforming for an event at Harrat Lunnayir. The top trace shows a single channel of the array filtered into the 1-3 Hz band. The bottom three traces show a smaller time interval around the initial P arrivals. Pn is just visible in the single channel trace. A beam of vertical channels only shows the onset of the Pn phase much more clearly. The three-component beam (bottom trace) roughly doubles the SNR of the Pn phase and also clearly displays Pg.



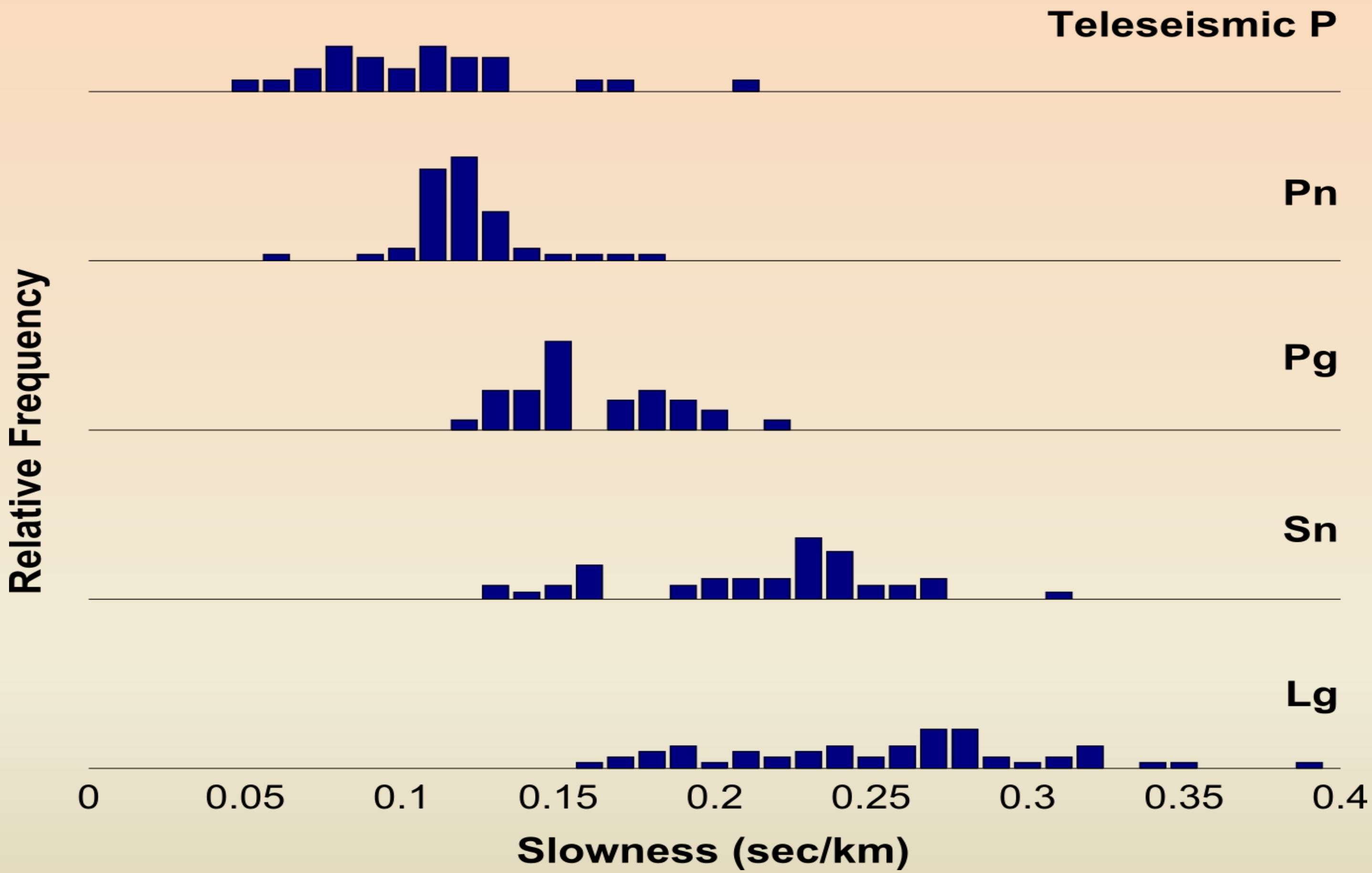
Representative P phases (0.8 - 3 Hz) for three Central Asian events. At top is an mb 5.6 event, followed by mb 4.6 (middle) and mb 4.8 (bottom) aftershocks. The two bottom traces have been multiplied by a factor of 10.



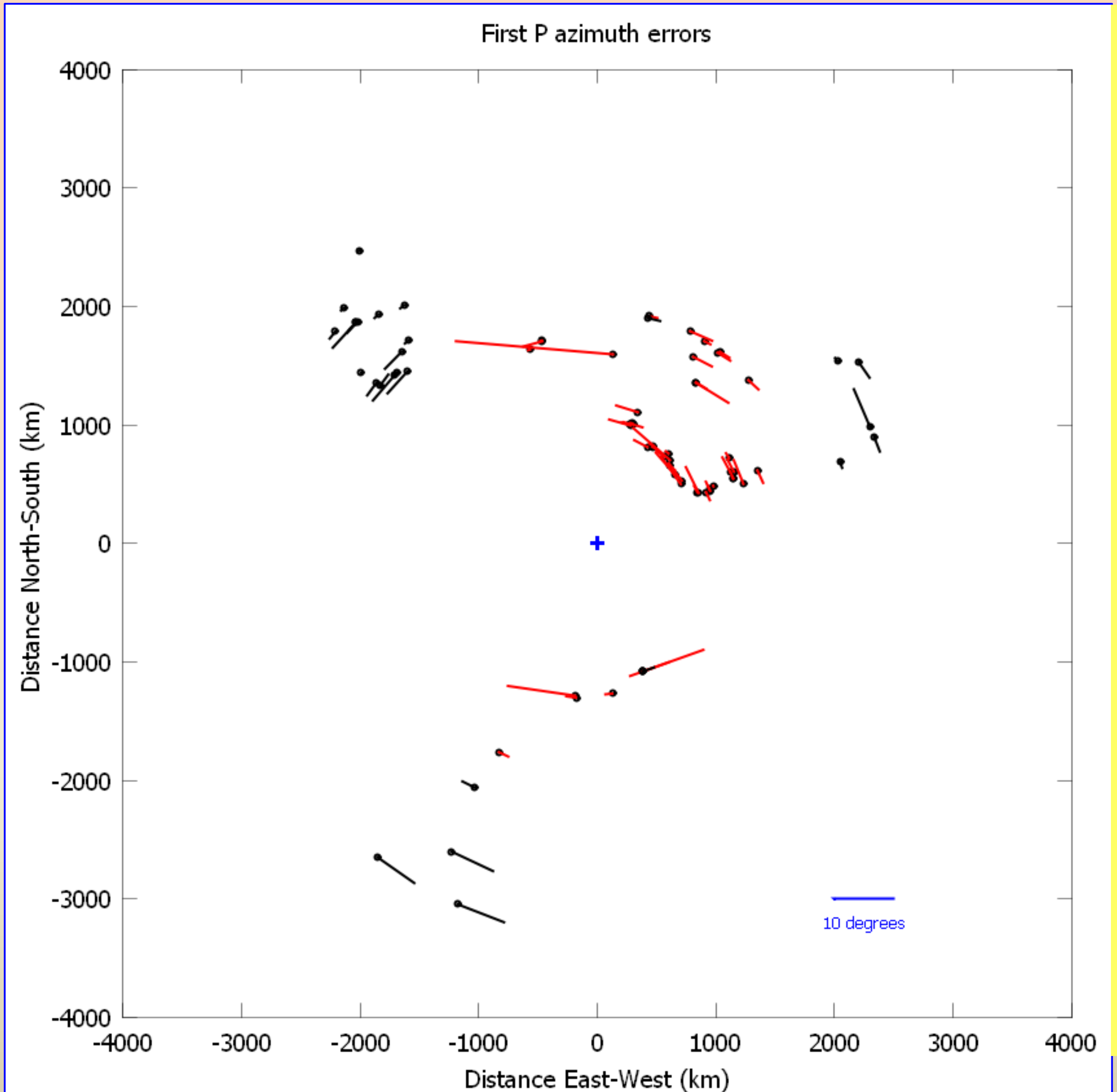
Comparison of individual channels (top 3 traces) and array beams (bottom 2 traces) for the magnitude 4.6 central Asia aftershock.



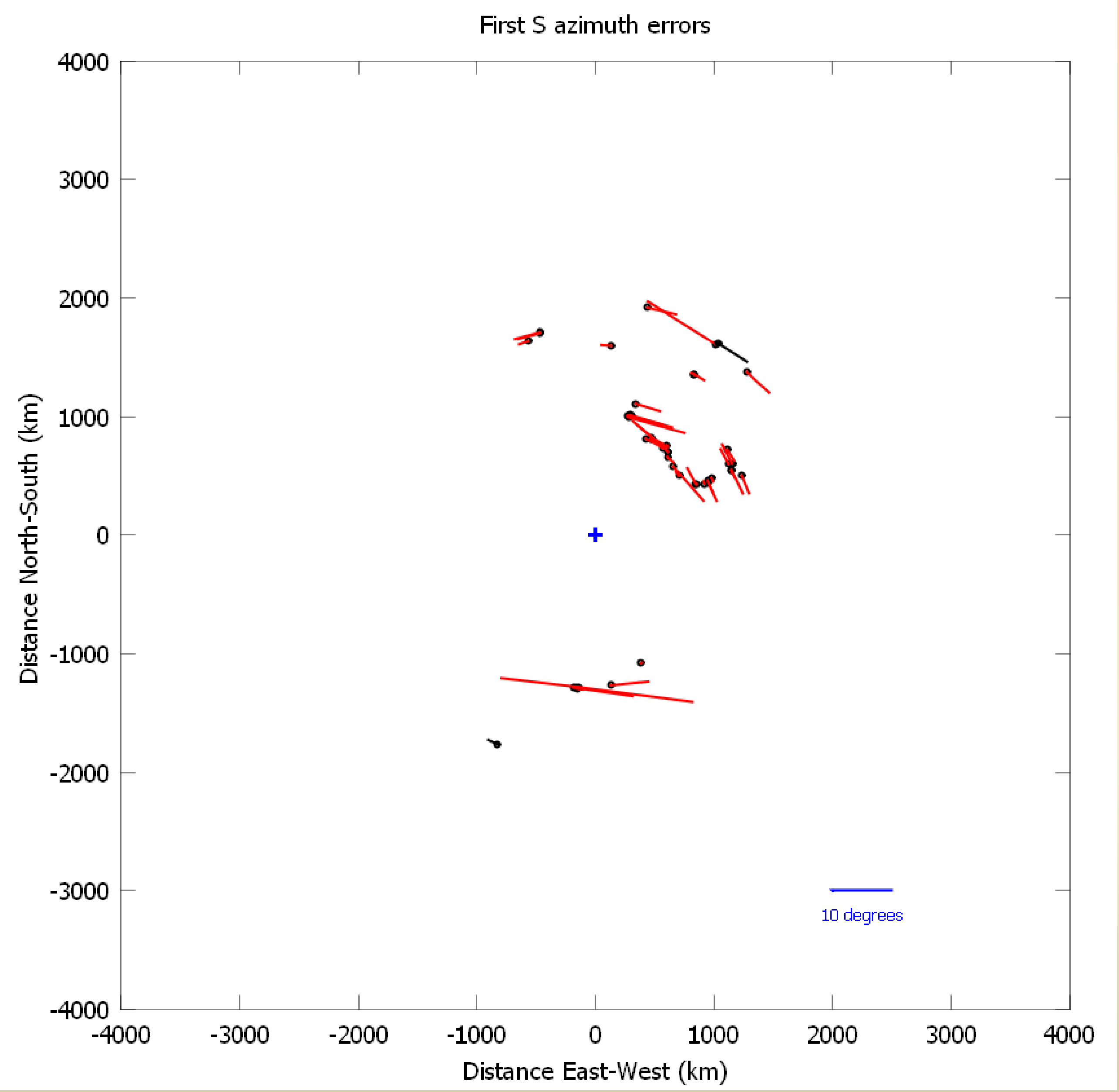
Approximate power envelopes for the vertical-component beam (black) and the three-component beam (red). The power signal to noise ratio of the three-component beam is about twice that of the vertical-only beam.



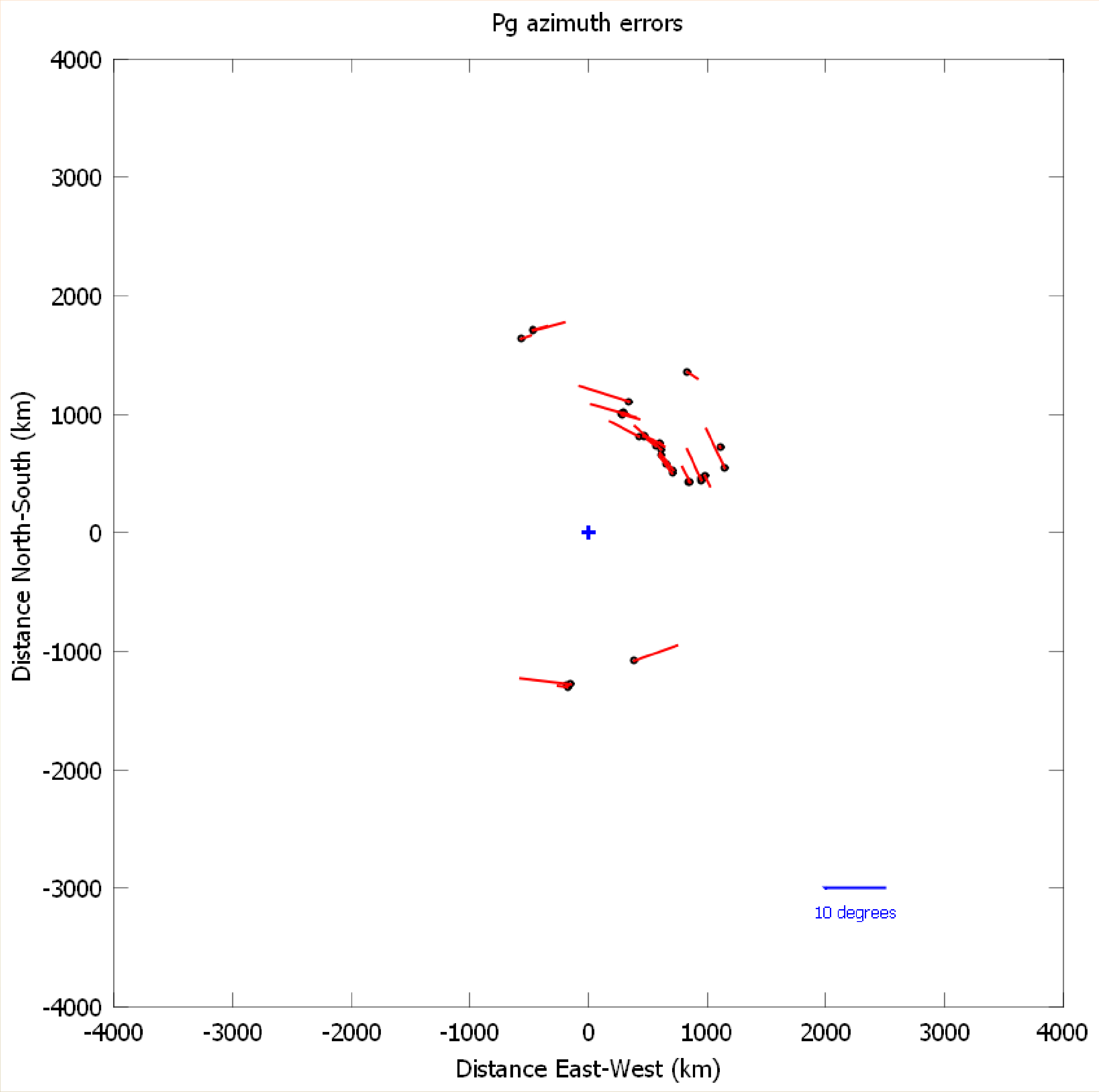
Slowness histograms for teleseismic P and the four regional phases Pn, Pg, Sn, and Lg. Note the increasing slowness values, but significant overlap among the phases.



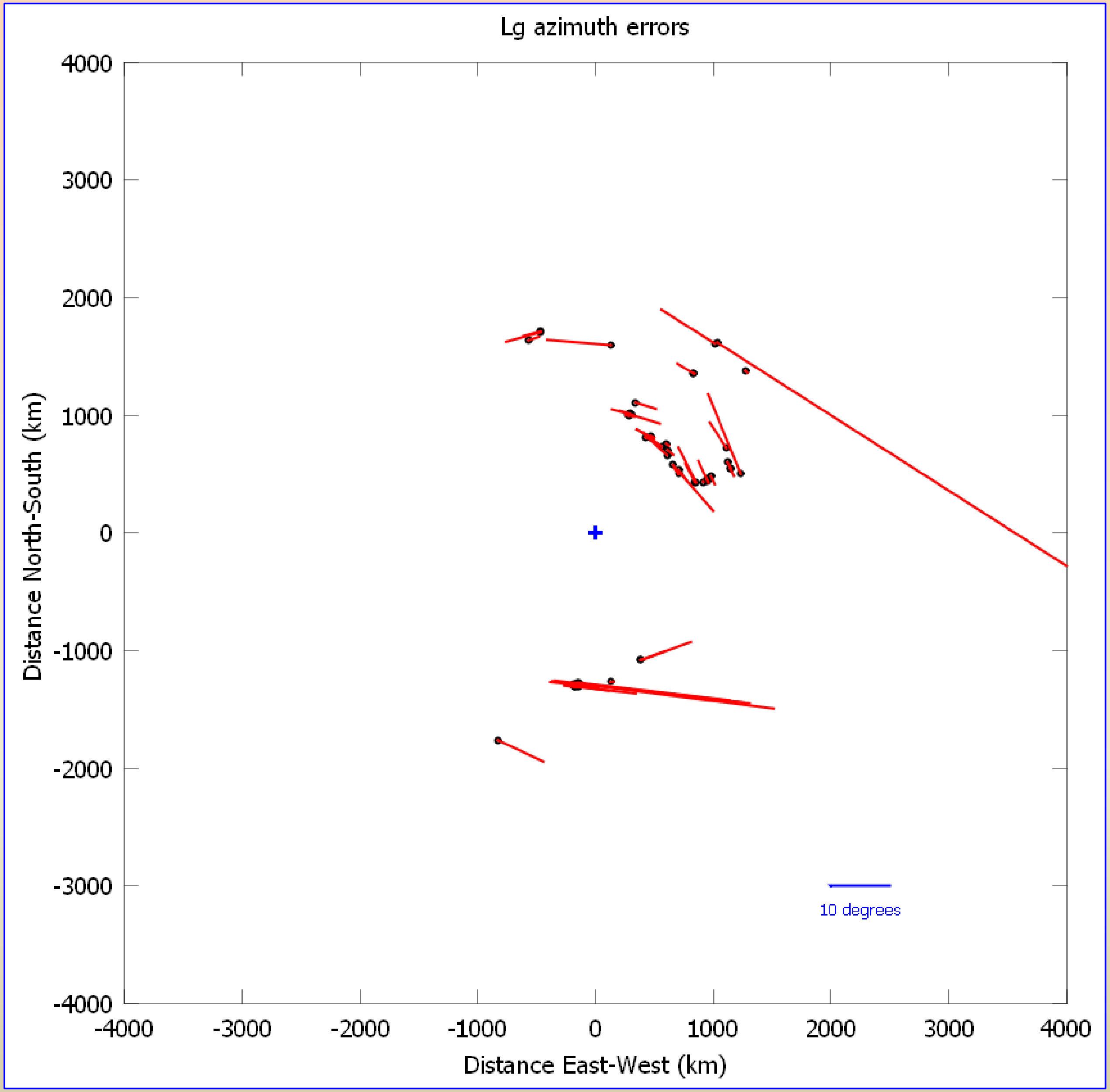
Spatial distribution of first P azimuth error determined from FK analysis. The location of the array is at the origin (blue cross). The points indicate event locations and the lengths of the line segments emanating from the points indicate the size of the azimuth error. Counterclockwise pointing lines indicate negative azimuth error and clockwise pointing lines indicate positive error. Pn measurements are indicated in red and teleseismic P in black. Most errors are below 10 degrees.



Spatial distribution of first S azimuth error determined from FK analysis.
Sn measurements are indicated in red and teleseismic S in black.



Spatial distribution of Pg azimuth error determined from FK analysis.



Spatial distribution of Lg azimuth error determined from FK analysis.

Summary

- **There are no seismic arrays in the Arabian Peninsula. This array will provide new data and unduplicated research results for studying signal propagation behavior in the region.**

- A large archive of continuous waveform data has been assembled.
- The array of three-component stations (one of a very few) allows comparison of many processing strategies.

- The noise level at the Ar Rayn site approaches the Peterson low noise model in the central frequency band 0.2 – 5.0 Hz.
- The most obvious discrepancy between the noise levels at the central element of the array and the Low Noise Model is in the horizontal long periods.
- Horizontal components are significantly noisier than the vertical component at frequencies below 0.1 Hz.
- At frequencies greater than 0.1 Hz, vertical and horizontal noise levels are similar. The source of the long-period noise is not clear and may be due to small tilts which affect the horizontal components more than the verticals.

- Proper installation of the array has been validated with coherence and polarization checks performed on teleseismic P phases. Coherence at 1-3 Hz is quite good for regional and teleseismic P, less good for S.
- This observation suggests that it would be possible to add a larger third ring to the array to enhance resolution of regional P phases and markedly improve teleseismic P processing.
- Standard beamforming and three-component beamforming have been performed and demonstrate the marked superiority of arrays for examine low-magnitude seismicity in the region.
- Three-component beamforming may perform better with local events, due to larger P projections onto the horizontal array elements.
- Conventional and adaptive beamforming give the analyst an ability to suppress swarm events and aftershocks, allowing studies of higher-priority local seismicity during such events.
- An initial study of backazimuth and slowness estimation with FK processing indicates good slowness measurement capability for Pn, but relatively poor capabilities for the other regional phases and teleseismic P. A third ring would substantialy improve this performance.
- Backazimuth measurements for teleseismic P, Pn, Pg and Sn phases have error levels consistent with other regional arrays around the world.

Beamforming and polarization filtering functions have been validated with the Ar Rayn array data

- Polarization and beamforming results are consistent with expectations
  - The installation is high quality
- The array offers the opportunity to study low-level seismicity and earth structure in the Arabian peninsula
- The three-component nature of the array also supports studies of more sophisticated array signal processing

Array Processing in Antelope

A new Antelope program, **orbwfproc**, has been developed that will provide real-time array processing capability. This program will

❖ Import raw waveform data from real-time ORBs from one or more seismic arrays

❖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

❖Compute azimuth and scalar slowness corresponding to maximum semblance