Continuous monitoring by ambient-seismic noise tomography

Sjoerd de Ridder

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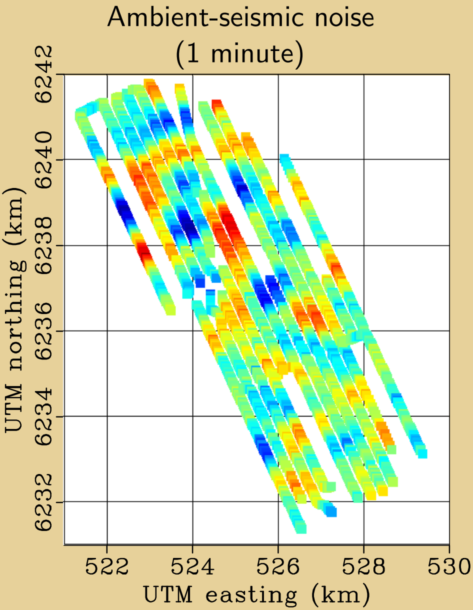
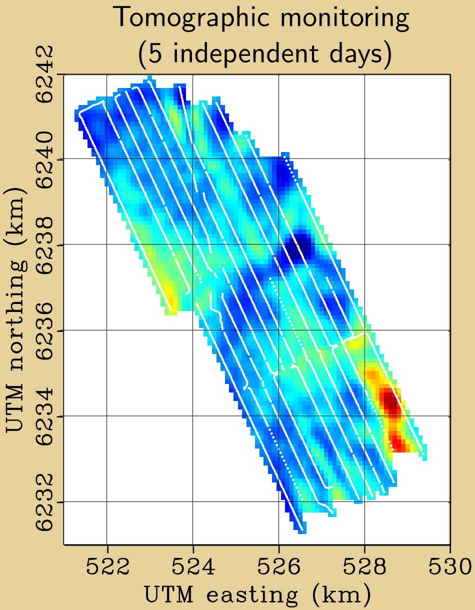
Monitoring by ambient-seismic noise tomography





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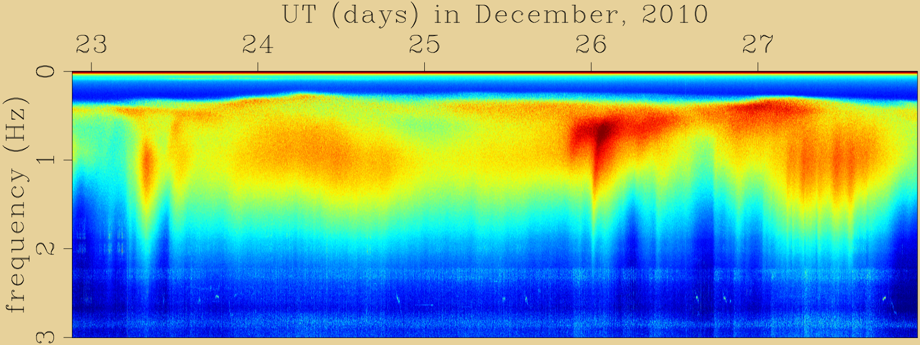
Ambient seismic noise at low frequencies

December 2010: 5 days of data without low-cut filter:
Normal operations at Valhall and active shooting at Ekofisk.



Seismic interferometry

- Seismic interferometry aims to generate virtual-sources by correlation of seismic noise recordings (Claerbout, 1986; Wapenaar, 2004).
- Correlating all noise-recordings with the recording at one station generates a virtual-source gather as if that station were acting as a source:

$$\mathbf{d}(\mathbf{x_r}, \mathrm{x_s}) = \mathbf{r}(\mathbf{x_r})\ \mathrm{r}^*(\mathrm{x_s})$$

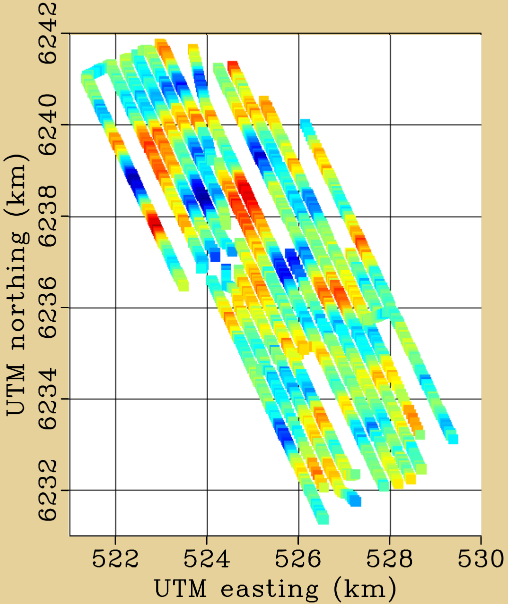
- Selecting each station as virtual-source generates a full virtual seismic survey:

$$\mathbf{D}(\mathbf{x_r}, \mathbf{x_s}) = \mathbf{r}(\mathbf{x_r})\ \mathbf{r}^\dagger(\mathbf{x_s})$$

Seismic interferometry

- Needs all wave-modes randomly and equally excited in space and time (energy equipartitioning).

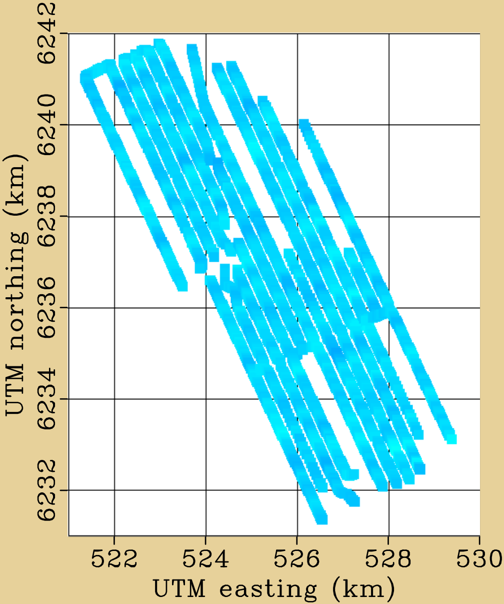
Ambient seismic noise at low frequencies



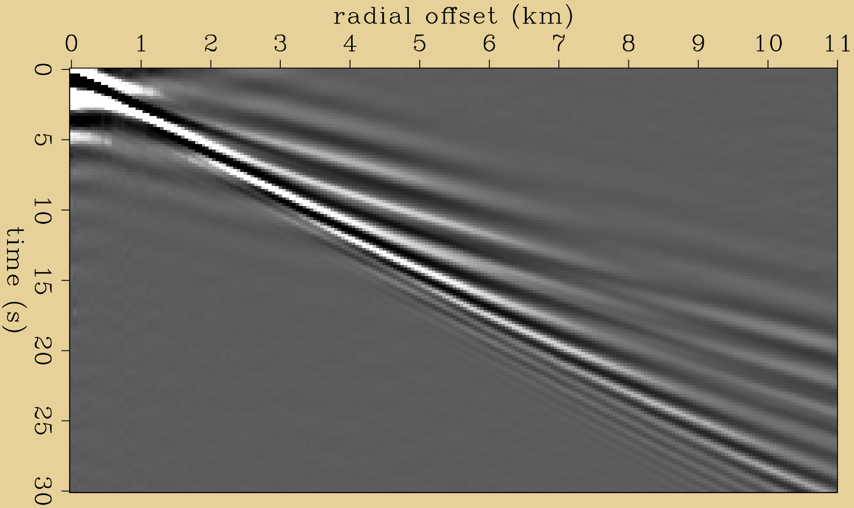
Seismic interferometry

- Needs all wave-modes randomly and equally excited in space and time (energy equipartitioning).
  $\rightarrow$ At Valhall energy between 0.15 Hz and 2.0 Hz is dominated by interface waves.

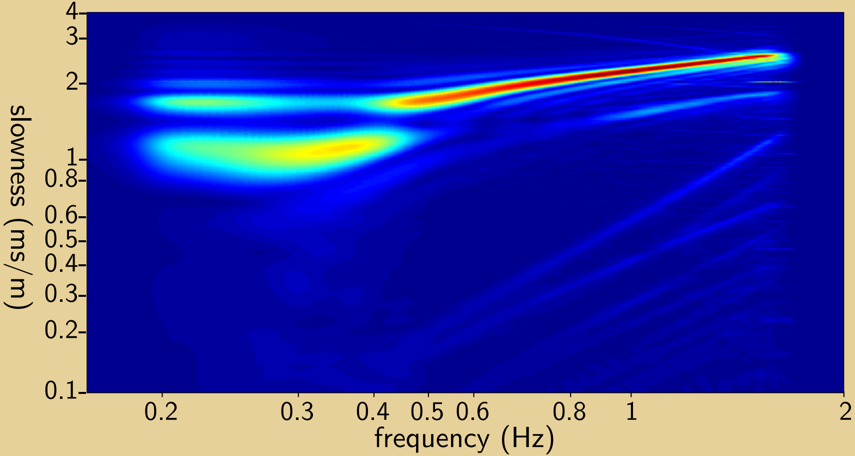
Virtual seismic source at low frequencies



Azimuthal stack in midpoint offset domain



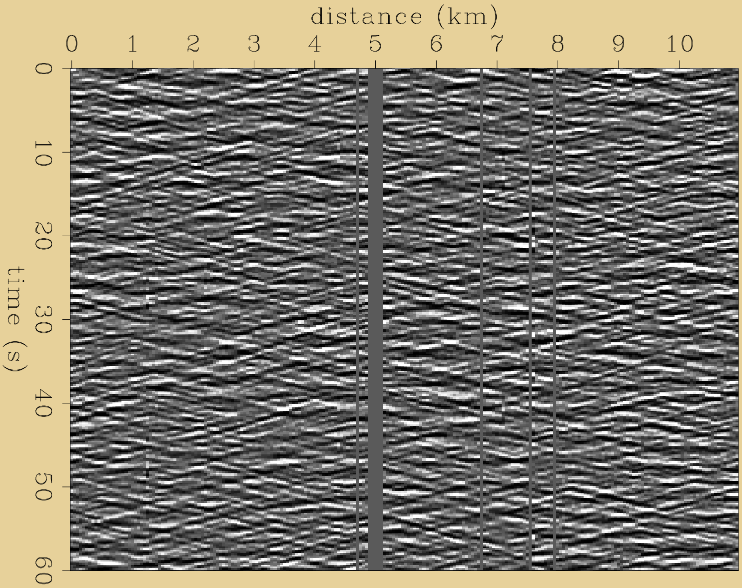
Azimuthal stack in midpoint offset domain: $\omega - \mathrm{p}$ image



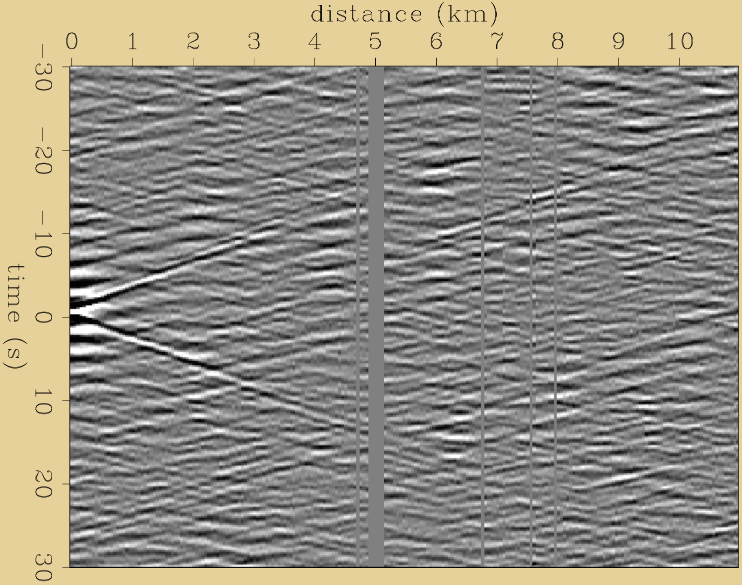
Seismic interferometry

- Needs all wave-modes randomly and equally excited in space and time (energy equipartitioning).
  $\rightarrow$ At Valhall energy between 0.15 Hz and 2.0 Hz is dominated by interface waves; so the virtual sources only emit those waves.
- When we correlate more data, the quality of the virtual seismic sources improves.

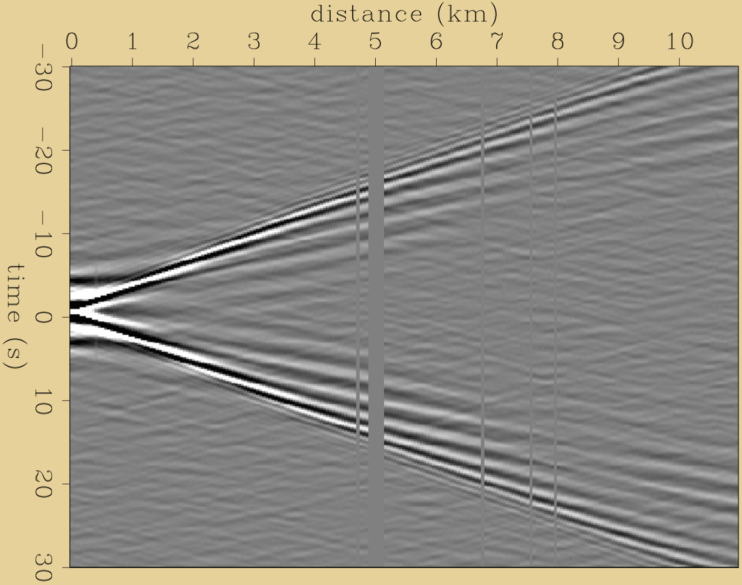
Ambient seismic noise at low frequencies



Correlations of ambient seismic noise



Virtual seismic source at low frequencies



Seismic interferometry

- Needs all wave-modes randomly and equally excited in space and time (energy equipartitioning).
  $\rightarrow$ At Valhall energy between 0.15 Hz and 2.0 Hz is dominated by interface waves; so the virtual sources only emit those waves.
- When we correlate more data, the quality of the virtual seismic sources improves. $\rightarrow$ How much data do we need to correlate to establish a permanent monitoring system based on ambient seismic noise tomography?

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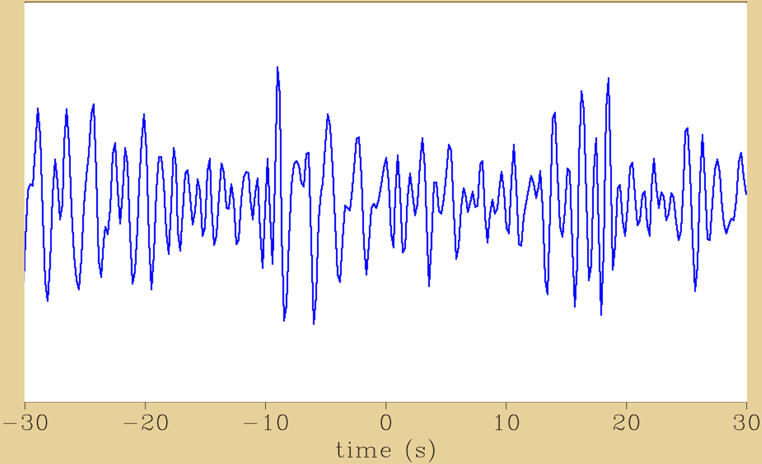
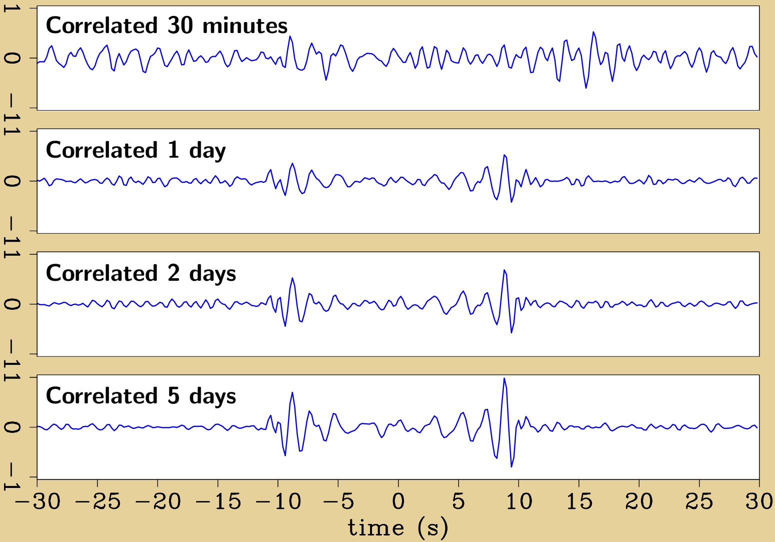
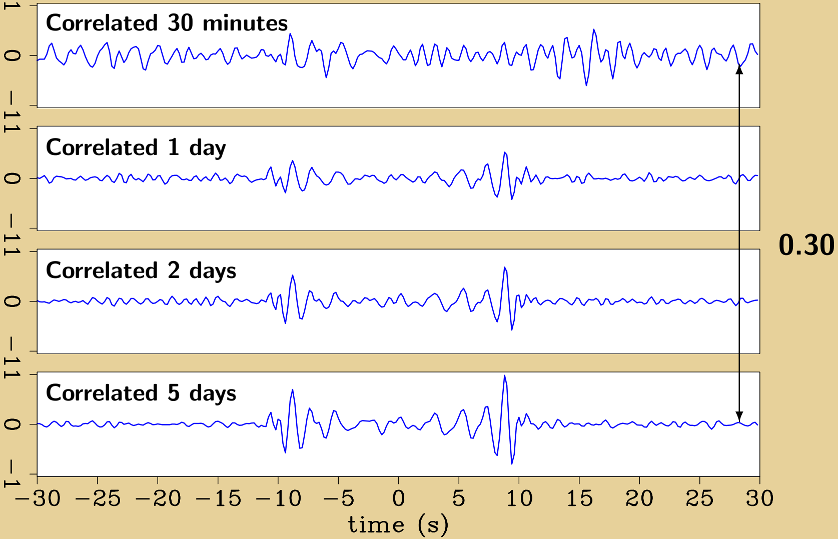
Convergence of correlations between two stations



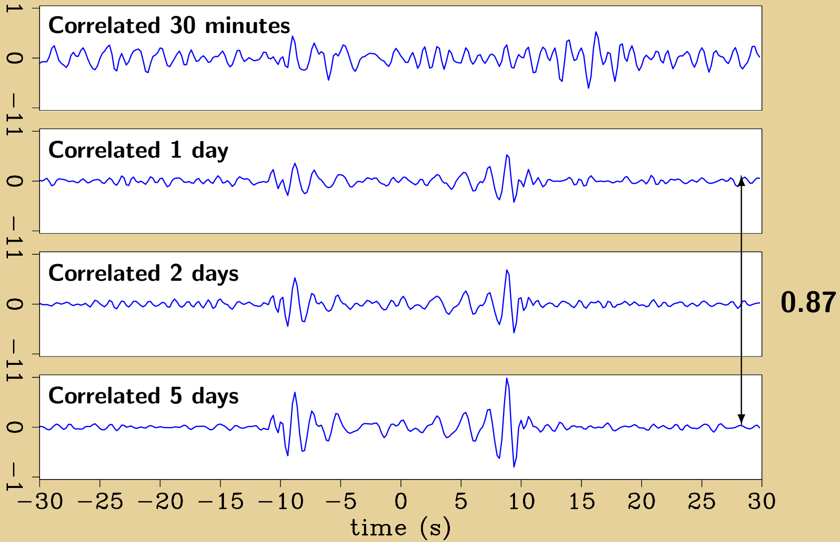
Correlation coefficient between 4 cross-correlation lengths



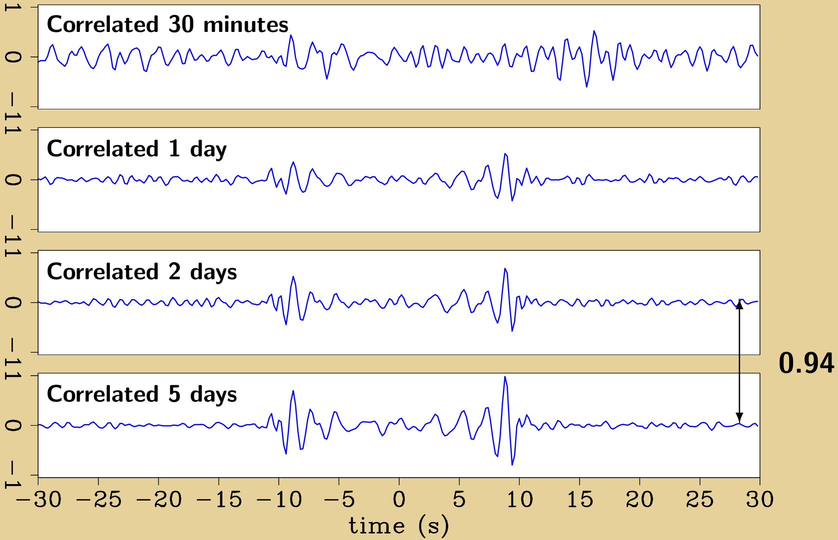
Correlation coefficient between 4 cross-correlation lengths



Correlation coefficient between 4 cross-correlation lengths



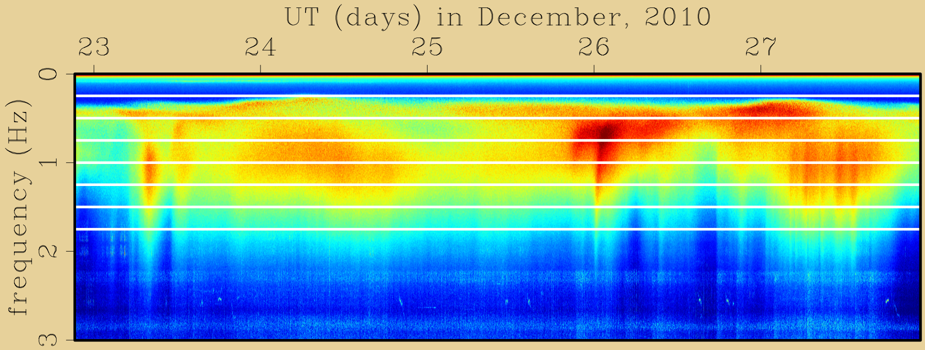
Correlation coefficient between 4 cross-correlation lengths



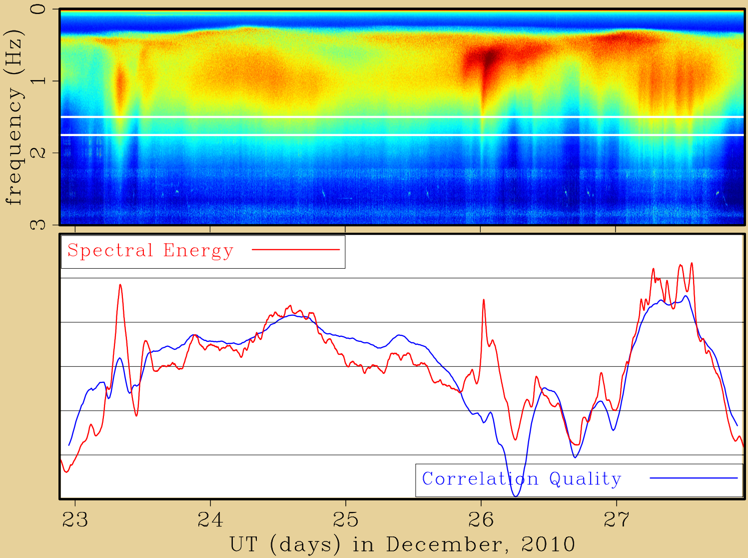
Correlation quality varies over time

- Cross correlate noise twice, for two different recording lengths (1.5 hrs and 5 days), between a station couple.
- Calculate the correlation coefficient between both cross correlation results.
- Repeat (1) and (2) while varying the starting time of the shorter recording. Keep the correlation coefficients as a function of the central time of the shorter recording.
- Average these correlation coefficients over all receiver stations for 250 randomly picked virtual sources.

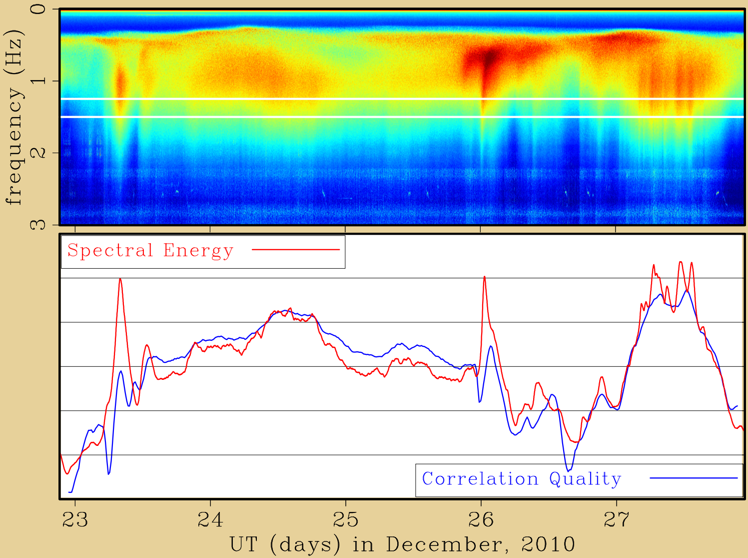
Ambient seismic noise at low frequencies



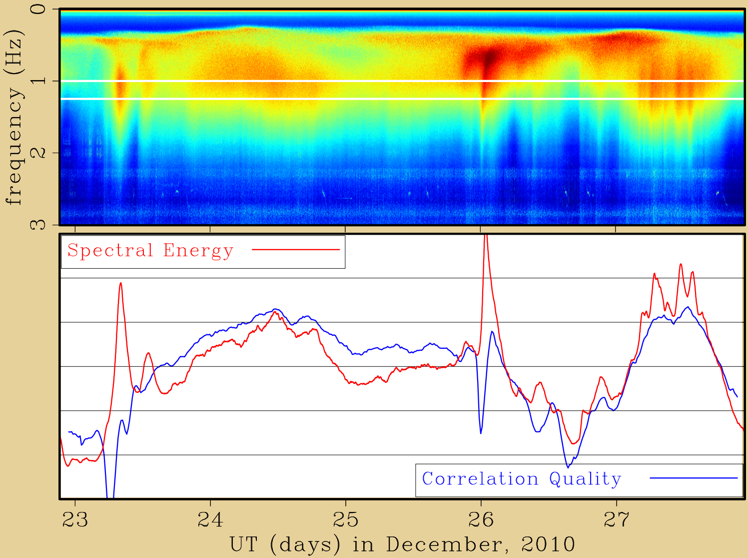
Correlation coefficient for 1.50 – 1.75 Hz



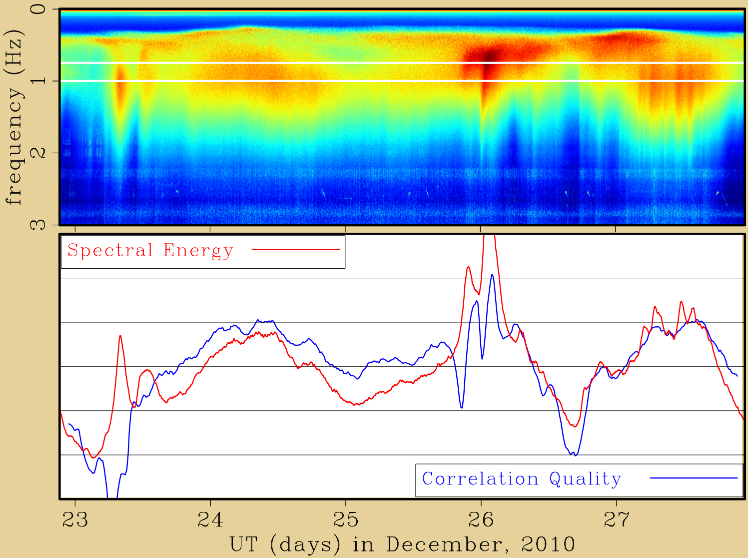
Correlation coefficient for 1.25 – 1.50 Hz



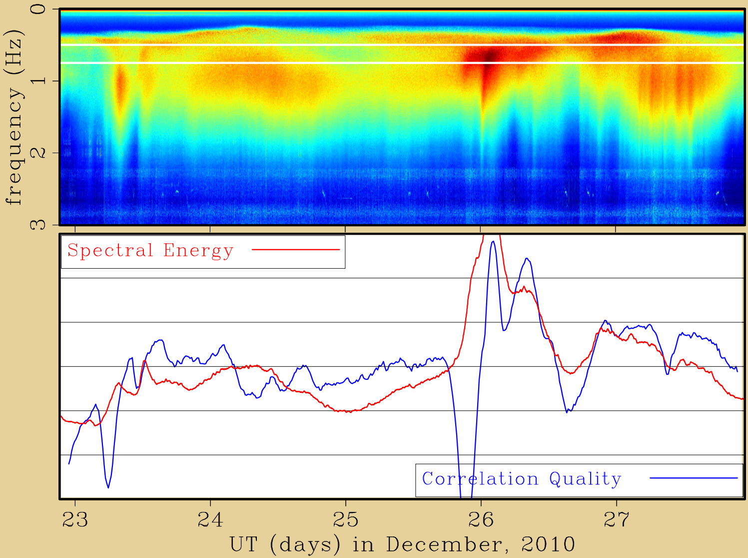
Correlation coefficient for 1.00 – 1.25 Hz



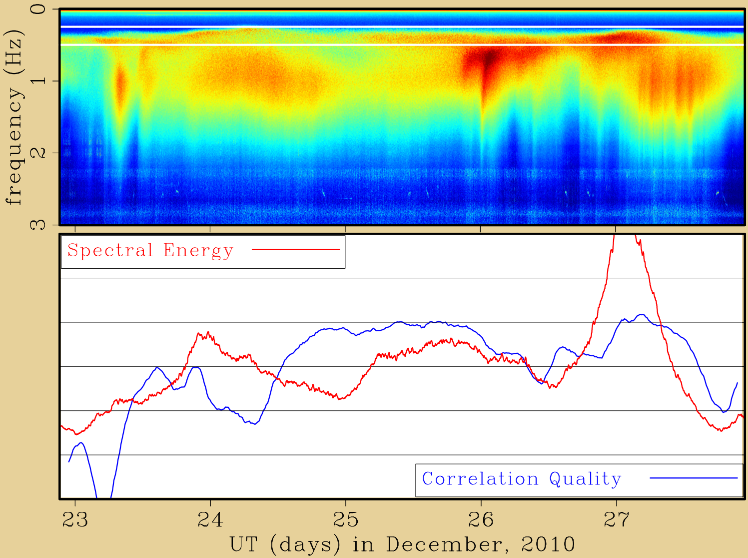
Correlation coefficient for 0.75 – 1.00 Hz



Correlation coefficient for 0.50 – 0.75 Hz



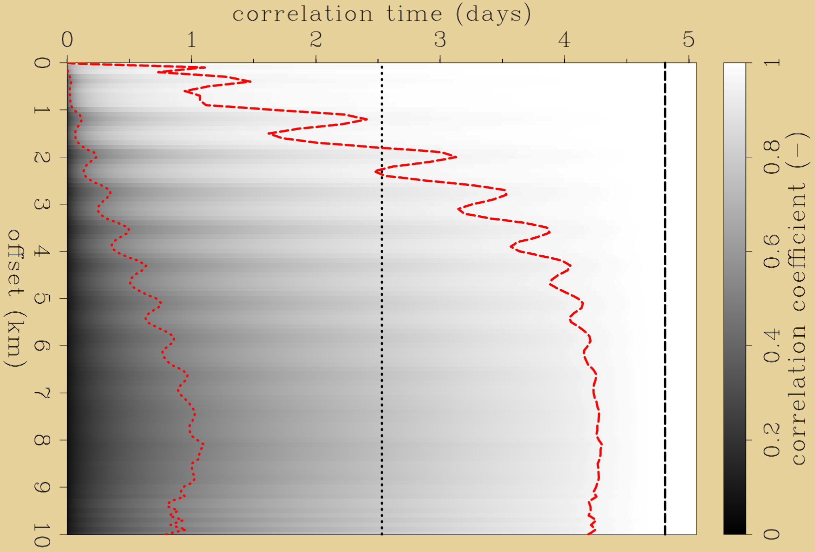
Correlation coefficient for 0.25 – 0.50 Hz



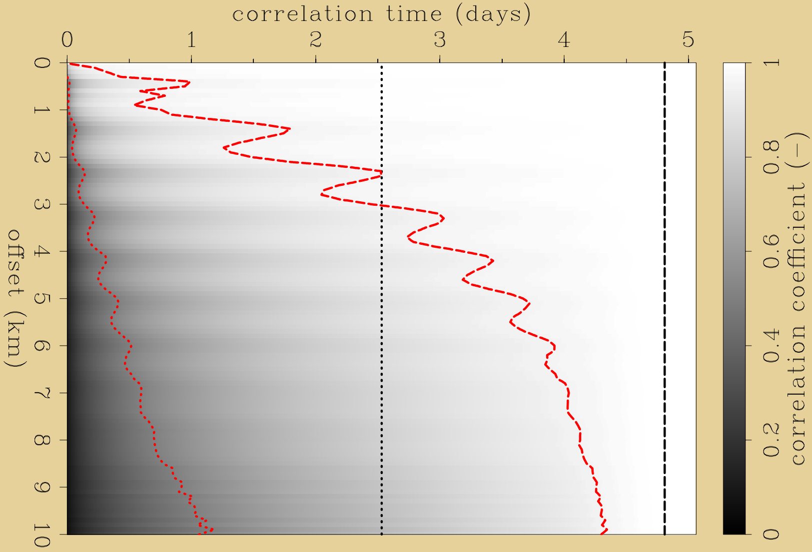
Correlation quality varies with offset and correlated time

- Cross correlate noise twice, for two different recording lengths (1.5 hrs and 5 days), between a station couple.
- Calculate the correlation coefficient between both cross correlation results.
- Repeat (1) and (2) while varying the recording length of the shorter recording recording. Keep the correlation coefficients as a function of the recording length of the shorter recording and as a function of station-distance.
- Average these correlation coefficients over all receiver stations for 250 randomly picked virtual sources.
- Average for 250 randomly picked virtual sources.

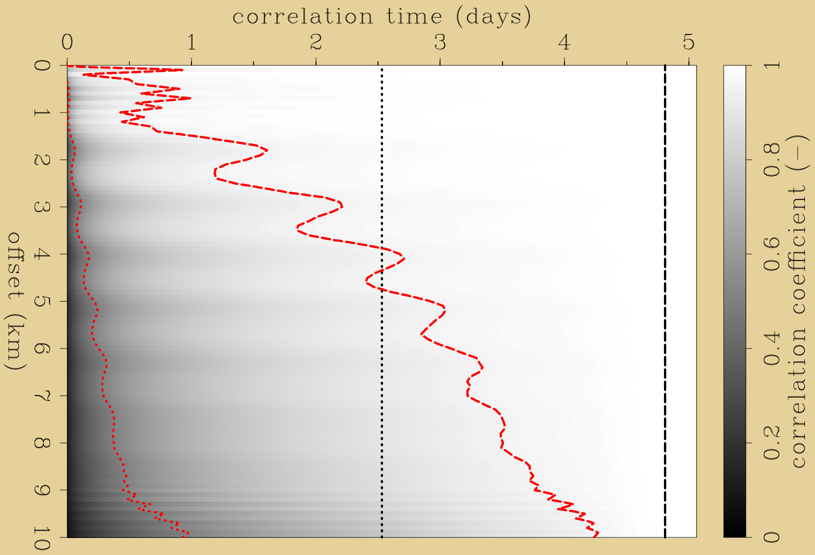
Correlation coefficient for 1.50 – 1.75 Hz



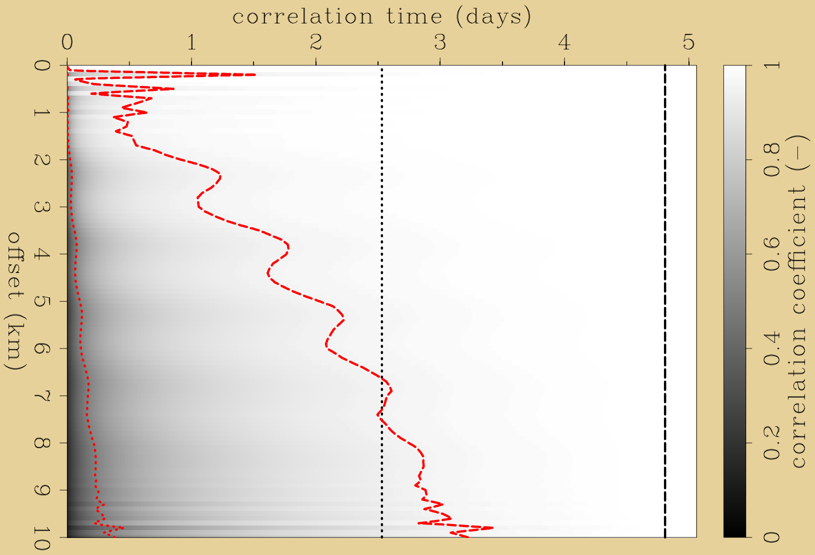
Correlation coefficient for 1.25 – 1.50 Hz



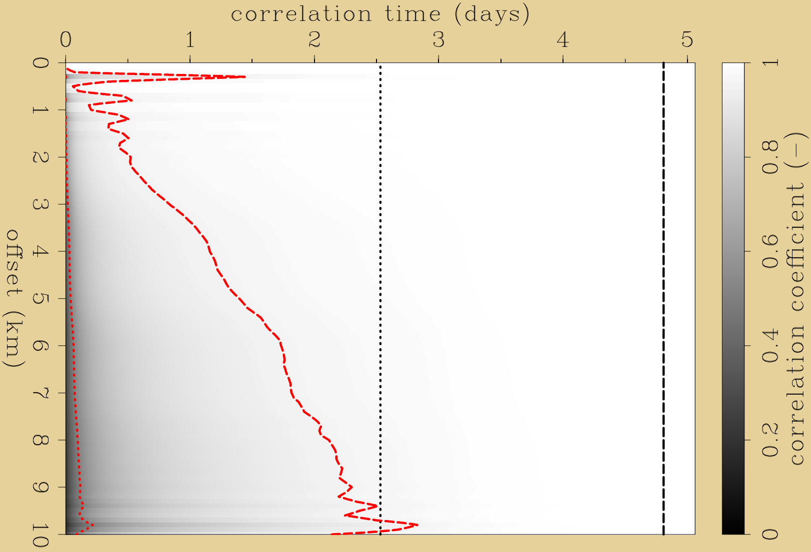
Correlation coefficient for 1.00 – 1.25 Hz



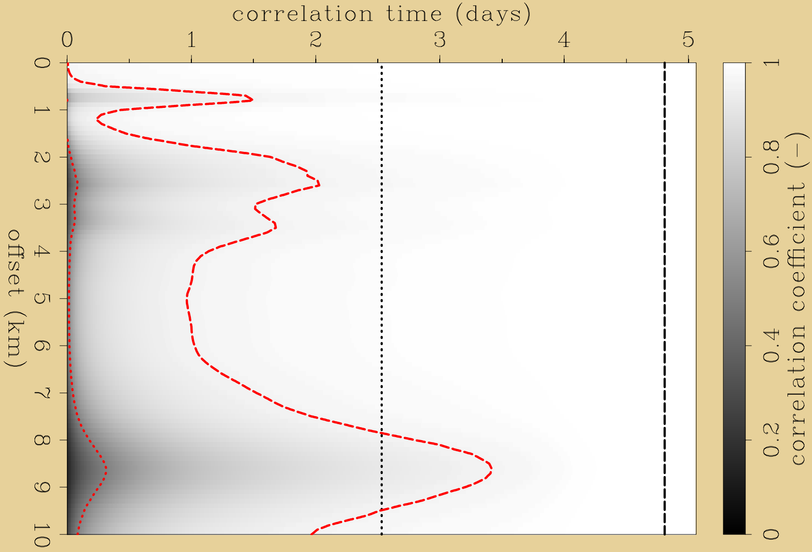
Correlation coefficient for 0.75 – 1.00 Hz



Correlation coefficient for 0.50 – 0.75 Hz



Correlation coefficient for 0.25 – 0.50 Hz



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Ambient-Seismic Noise Tomography (ASNT)

- Most basic tomography kernel, linearized on homogeneous average slowness.
- Sensitivity strictly along straight lines.
- Takes about 2 minutes for 150 iterations to fit 500000 picks (single core).

$$\mathbf{F}\Delta\mathbf{m} - \Delta\mathbf{t} = \mathbf{0} \qquad (1)$$

$$\epsilon\nabla^2\Delta\mathbf{m} = \mathbf{0} \qquad (2)$$

$\mathbf{F}$: Integration kernel
$\Delta\mathbf{m}$: slowness pertubation
$\Delta\mathbf{t}$: travel time pertubation

Ambient-Seismic Noise Tomography (ASNT)

- Most basic tomography kernel, linearized on homogeneous average slowness.
- Sensitivity strictly along straight lines.
- Takes about 2 minutes for 150 iterations to fit 500000 picks (single core).

Travel time picking:

- Define linear moveout window, 350 m/s.
- Pick maximum of envelope function within moveout window.
- Define SNR as the ratio of the maximum of the envelope within moveout window to the average of the envelope outside the moveout window.

Straight-ray tomography

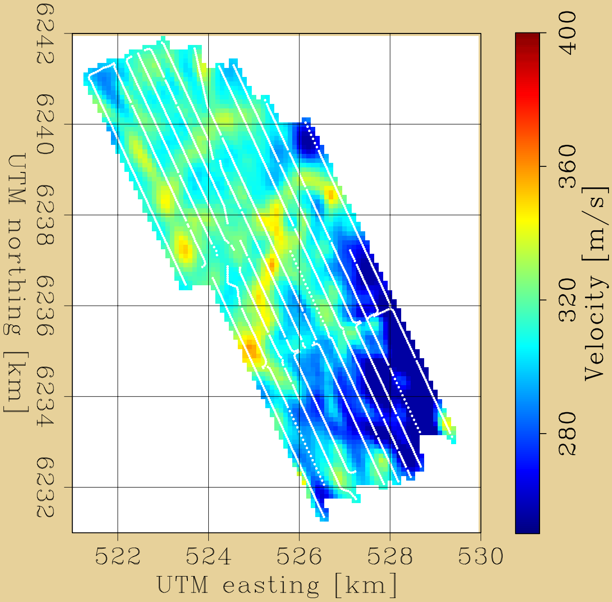
- Most basic tomography kernel, linearized on homogeneous average slowness.
- Sensitivity strictly along straight lines.
- Takes about 2 minutes for 150 iterations to fit 500000 picks (single core).

$$\begin{aligned} \mathbf{F}\Delta\mathbf{m} - \Delta\mathbf{t} &= \mathbf{0}, && (3) \\ \epsilon\nabla^2\Delta\mathbf{m} &= \mathbf{0}. && (4) \end{aligned}$$

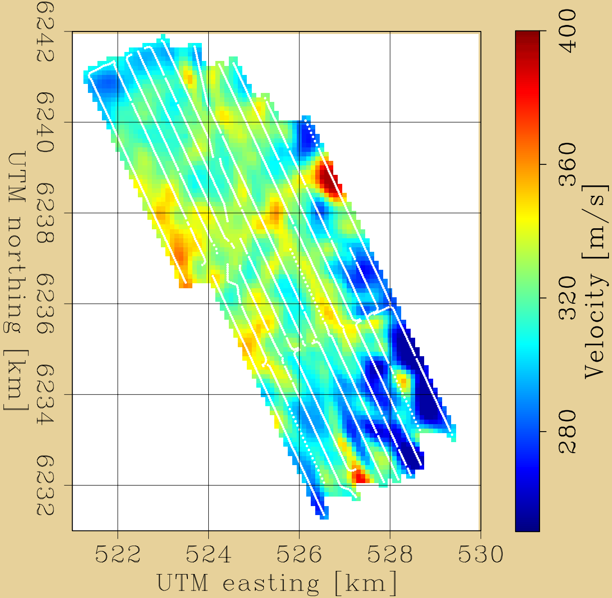
Pick selection

- Offsets $>$ 2000 m.
- SNR $>$ 10 for $(0.25 - 0.50)$.
- SNR $>$ 5 for $(0.50 - 1.50)$.
- SNR $>$ 2 for $(1.50 - 1.75)$.

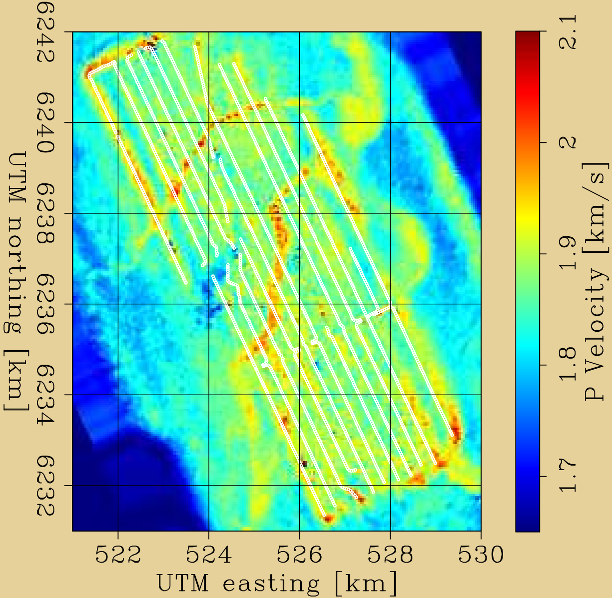
ASNT 1.50 – 1.75 Hz



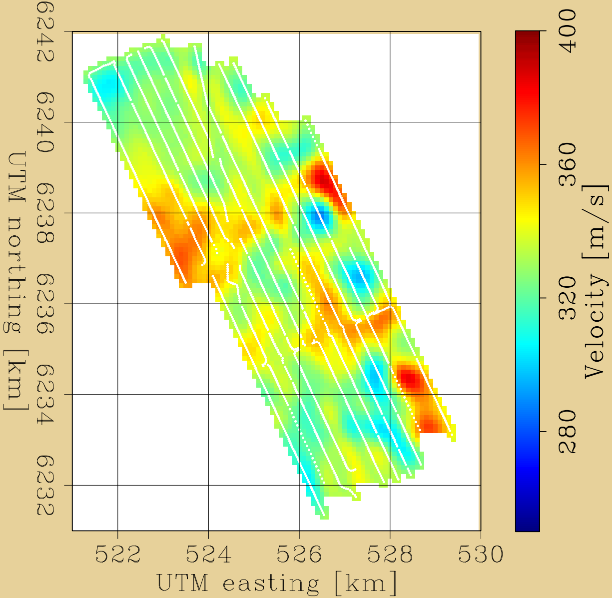
ASNT 1.25 – 1.50 Hz



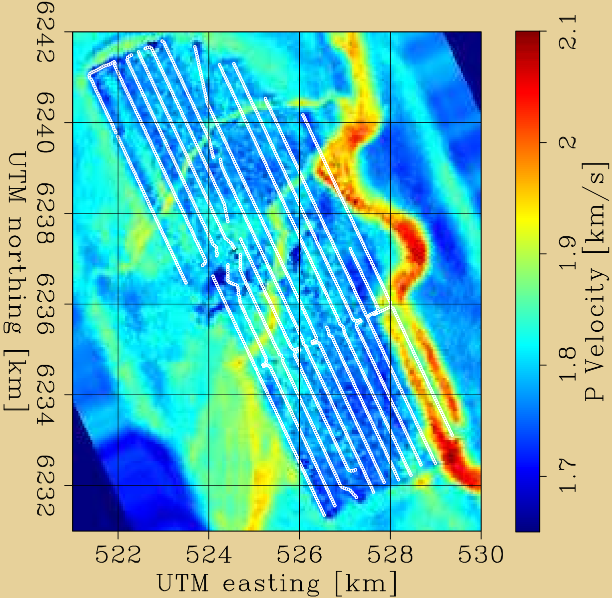
Full Waveform Inversion (FWI) 60 – 105 m



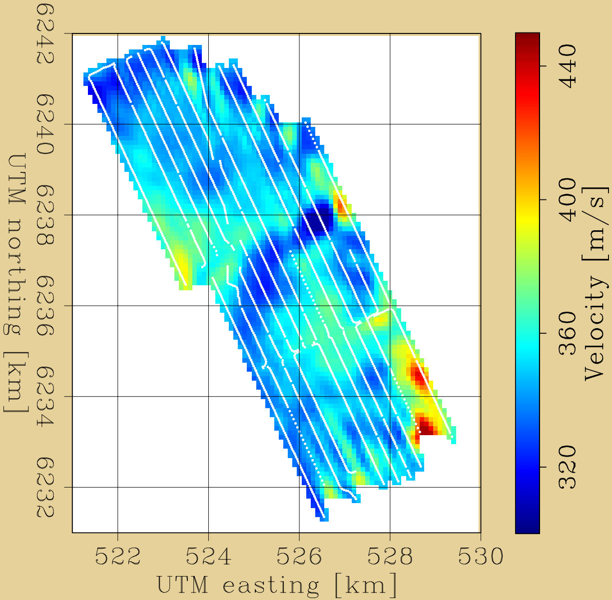
ASNT 1.00 – 1.25 Hz



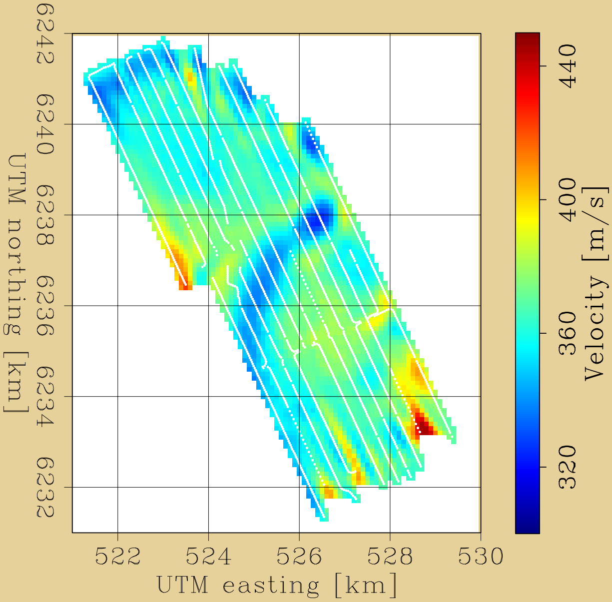
FWI 105 – 150 m


6242
6240
6238
6236
6234
6232
UTM northing [km]
522
524
526
528
530
UTM easting [km]
2.1
2
1.9
1.8
1.7
P Velocity [km/s]

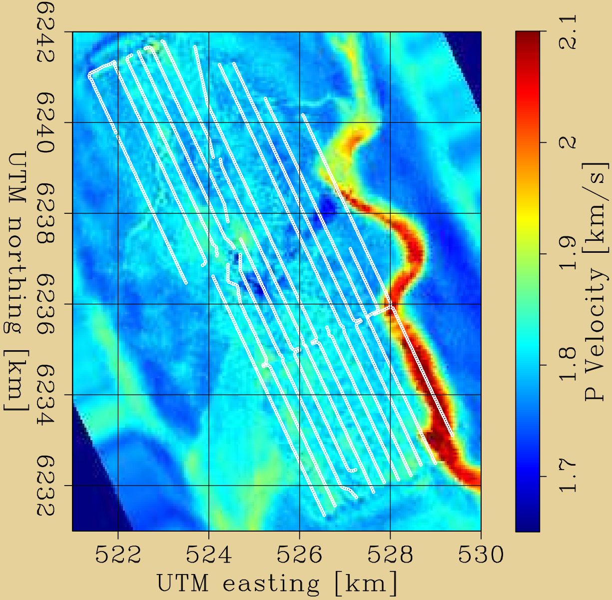
ASNT 0.75 – 1.00 Hz



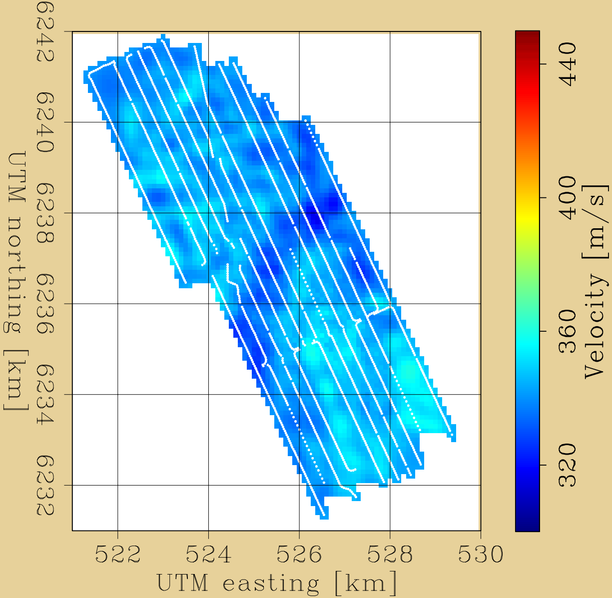
ASNT 0.50 – 0.75 Hz



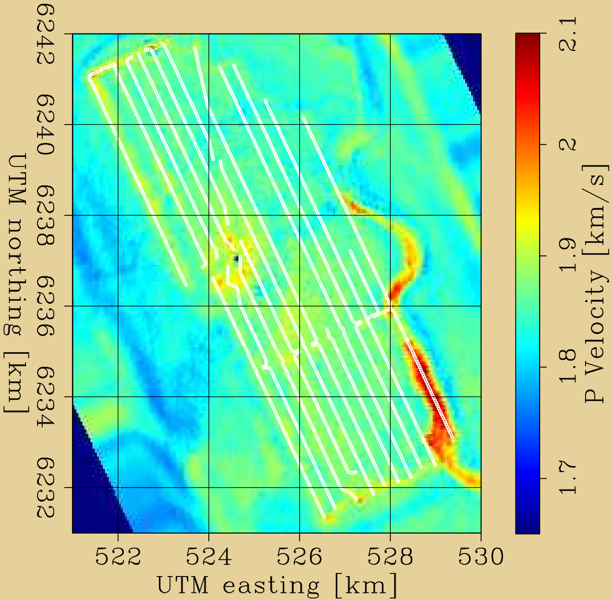
FWI 150 – 195 m


6242
6240
6238
6236
6234
6232
UTM northing [km]
522
524
526
528
530
UTM easting [km]
2.1
2
1.9
1.8
1.7
P Velocity [km/s]

ASNT 0.25 – 0.50 Hz

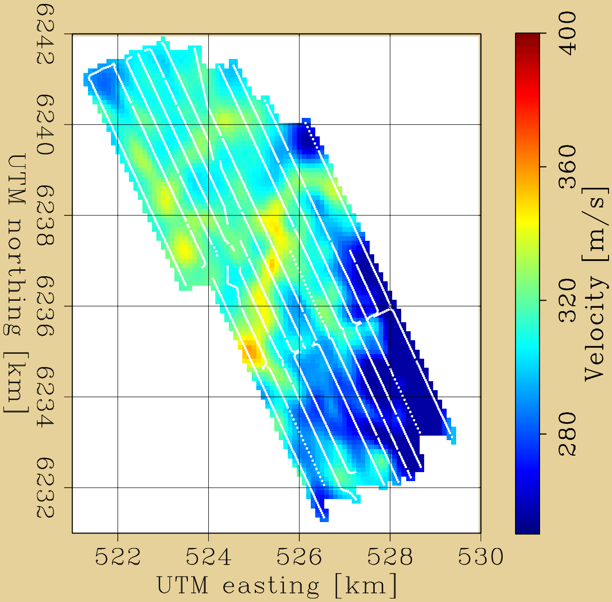


FWI 195 – 240 m

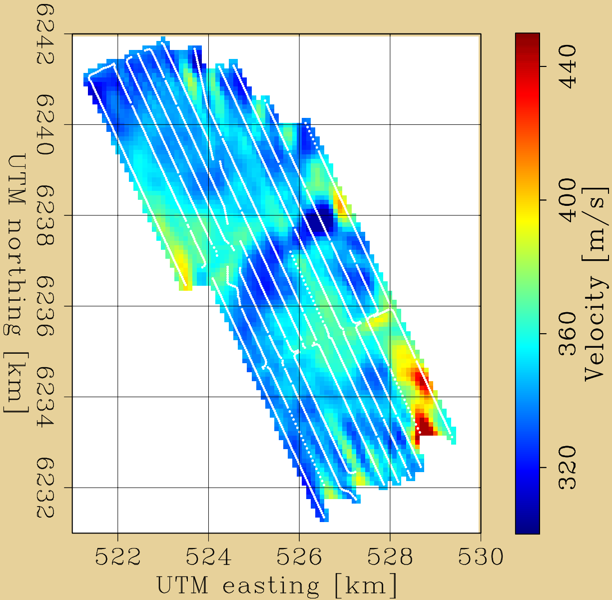


6242
6240
6238
6236
6234
6232
UTM northing [km]
522
524
526
528
530
UTM easting [km]
2.1
2
1.9
1.8
1.7
P Velocity [km/s]

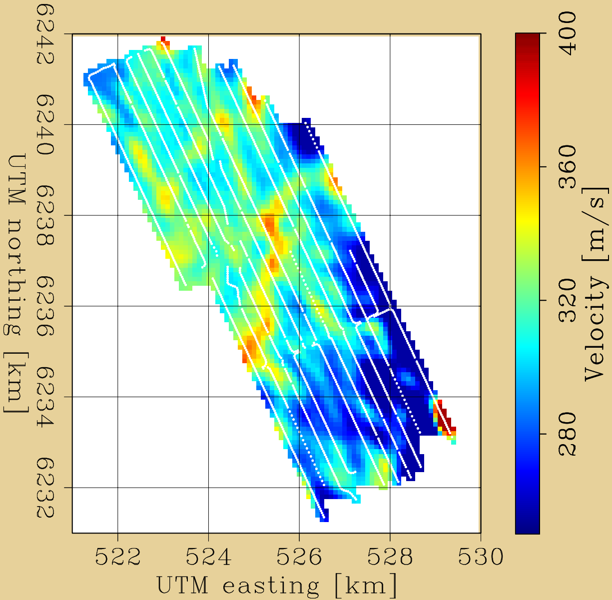
ASNT from 2.5 days of data 1.50 – 1.75 Hz



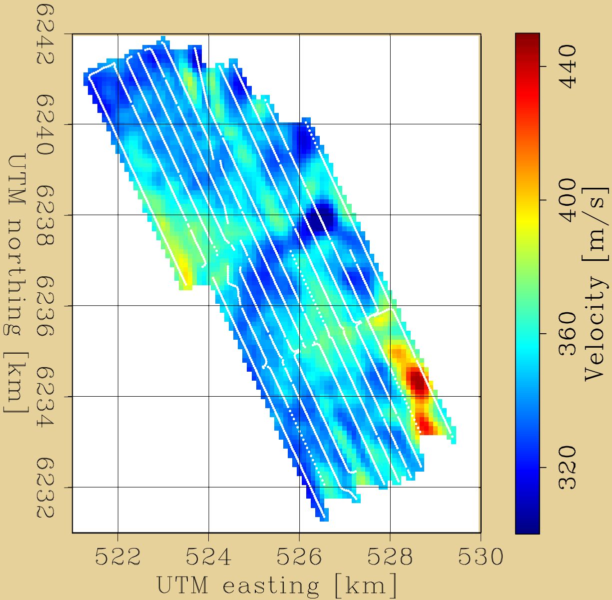
ASNT from 2.5 days of data 0.75 – 1.00 Hz



ASNT from 1 day of data 1.50 – 1.75 Hz



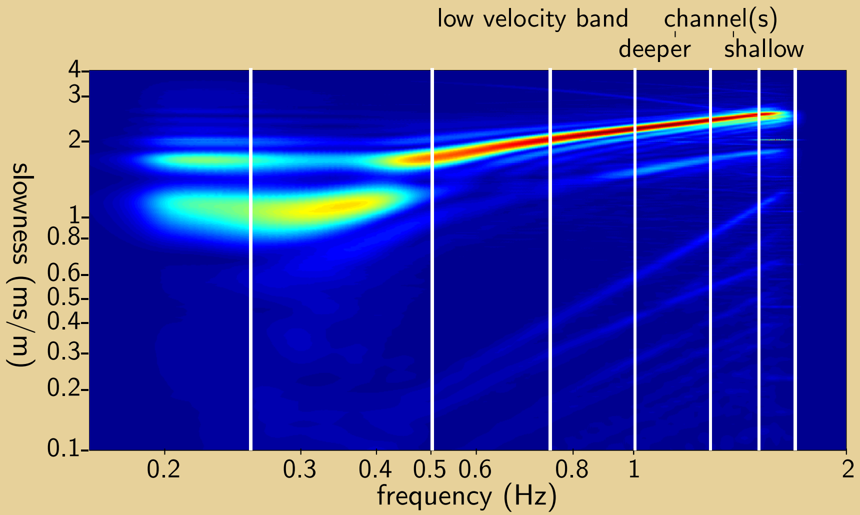
ASNT from 1 day of data 0.75 – 1.00 Hz



Conclusions

- Virtual sources from cross-correlating 5 days of noise recordings reveal a higher mode at higher frequencies and a spilled mode at low frequencies.
- Correlations converge faster for lower frequencies and smaller offsets.
- Subsurface features of known depths up to 250 m have been imaged using energy down to 0.5 Hz.

Conclusions



Conclusions

- Virtual sources from cross-correlating 5 days of noise recordings reveal a higher mode at higher frequencies and a spilled mode at low frequencies.
- Correlations converge faster for lower frequencies and smaller offsets.
- Subsurface features of known depths up to 250 m have been imaged using energy down to 0.5 Hz.
- Consistency between tomographic images (snapshots), obtained from different noise data portions, increases with lower frequency.
- Further quantification is needed to determine reliability of individual tomographic snapshots.

Acknowledgements

Joe Dellinger and Olav Barkved for helpful discussions and suggestions.

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