Introduction: abstract

Exploring the use of subspace detectors for seismic survey signals observed on the IMS hydroacoustic network

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Marine seismic surveys make use of a ship-towed air-gun array. The compressed-air shots fired into the water generate impulsive sound wave fronts whose reflections are recorded to map the oceanic crust. These intense sounds cause depletion of the local zooplankton [1], and can impact the detection capability of the CTBTO hydroacoustic stations and their automated processing [2].

It is desirable to detect the presence of these surveys, also when at great remove and low SNR. To this end, we explore adaptation of the subspace detection method [3] from seismology to hydroacoustics. In implementing the requisite algorithms, use was made of the ObsPy Python framework [4].

[1] *McCauley, R.D. et al.* (2017) Nature Ecology & Evolution 1, 0195. https://doi.org/10.1038/s41559-017-0195

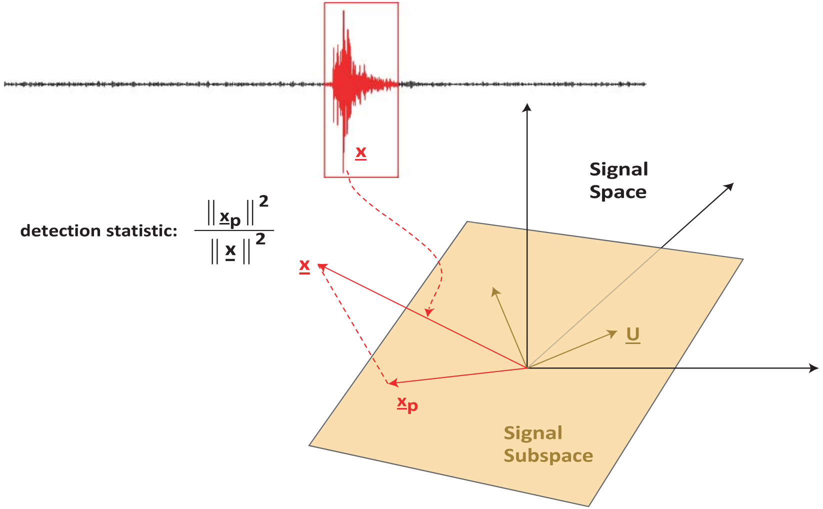
[2] *Brouwer, A., Le Bras R., Nielsen P. L., Bittner P., Wang H.* (2018) Assessing and Mitigating the Impact of Seismic Surveys on CTBTO Hydroacoustic Detections, EGU General Assembly PICO presentation EGU2018-8367.

[3] *Harris, D. B.* (2006). Subspace detectors: Theory. Lawrence Livermore National Laboratory Internal Report UCRL-TR-222758.

[4] *M. Beyreuther, R. Barsch, L. Krischer, T. Megies, Y. Behr and J. Wassermann* (2010). ObsPy: A Python Toolbox for Seismology, SRL, 81(3), 530-533, https://doi.org/10.1785/gssrl.81.3.530

Introduction: subspace detection

figure copied from [3]



Subspace detection [3] involves computing an orthonormal basis from signal templates through singular value decomposition. The signal subspace spanned by the first few such basis vectors will capture the most common template characteristics. Projecting signal onto this subspace will yield significant coefficients (detection) when the signal resembles the templates.

The signal projection operation is equivalent to cross correlation with each of the basis vectors. When the dimension of the basis is 1, the procedure reduces to cross correlating with a single template (matched filtering).

Subspace detection is able to accommodate an adjustable wider variation of signals than matched filtering, while having much higher sensitivity than energy detectors such as STA/LTA.

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Introduction: PICTURES survey

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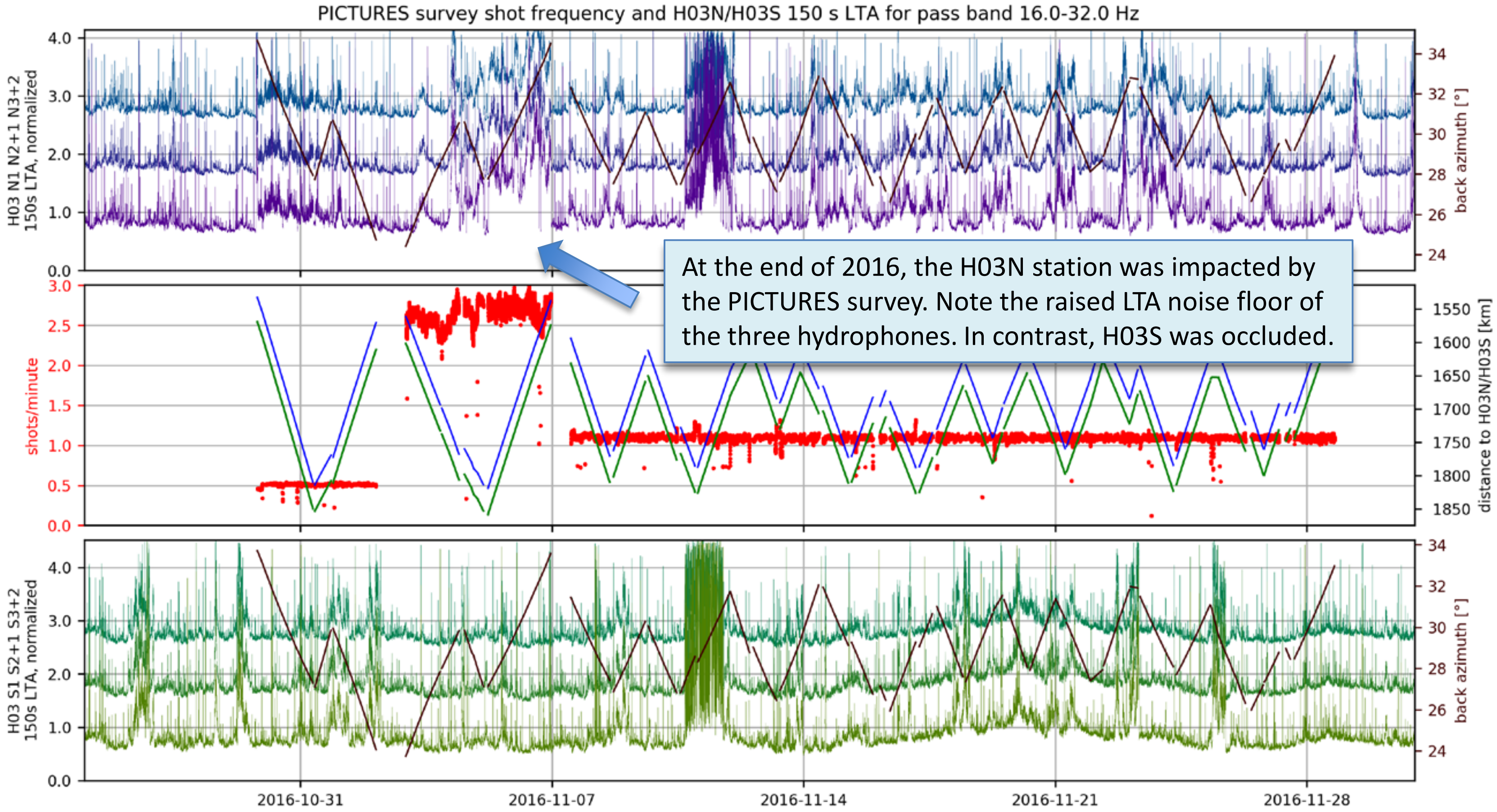

At the end of 2016, the H03N station was impacted by the PICTURES survey. Note the raised LTA noise floor of the three hydrophones. In contrast, H03S was occluded.

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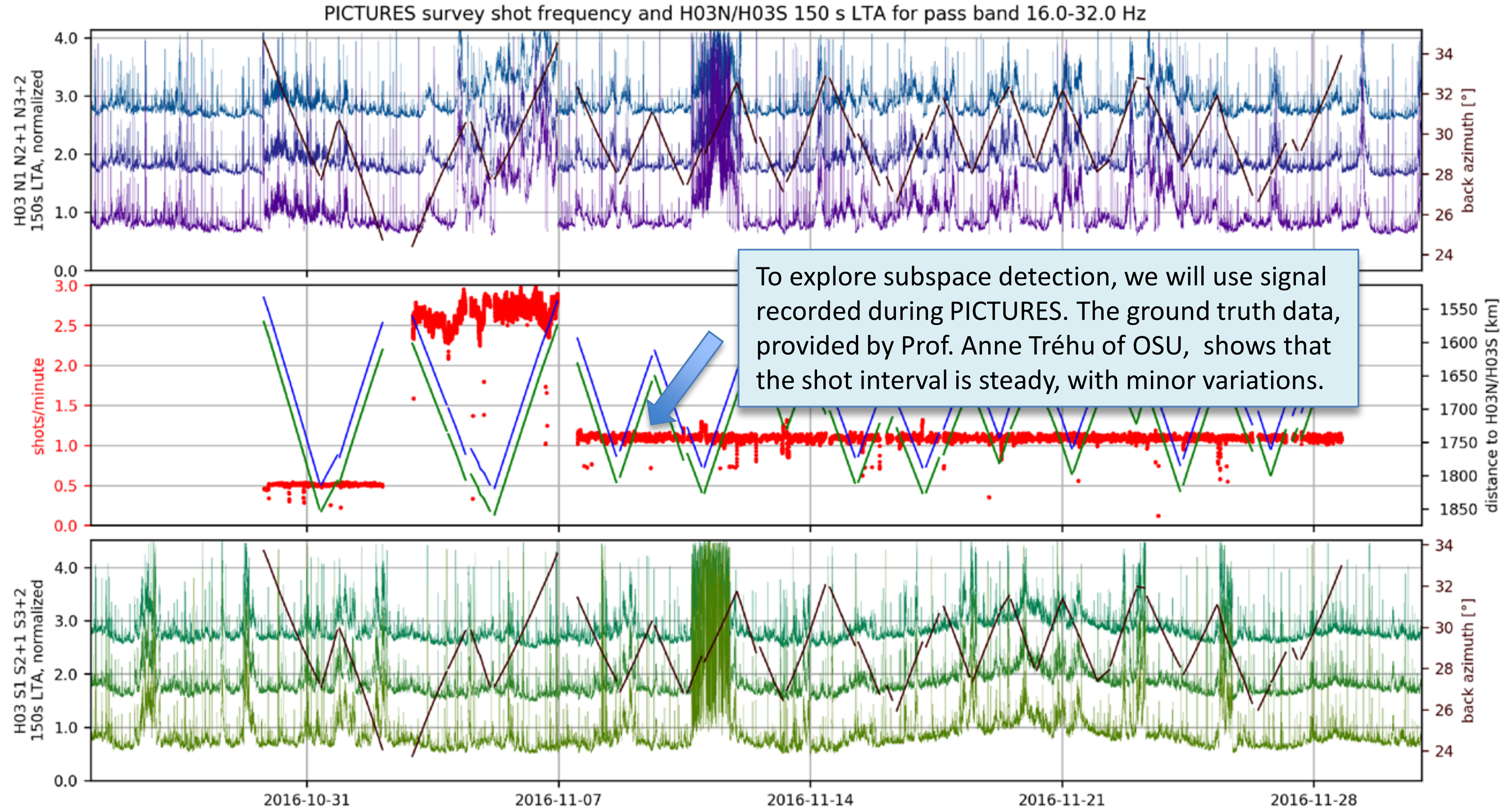

To explore subspace detection, we will use signal recorded during PICTURES. The ground truth data, provided by Prof. Anne Tréhu of OSU, shows that the shot interval is steady, with minor variations.

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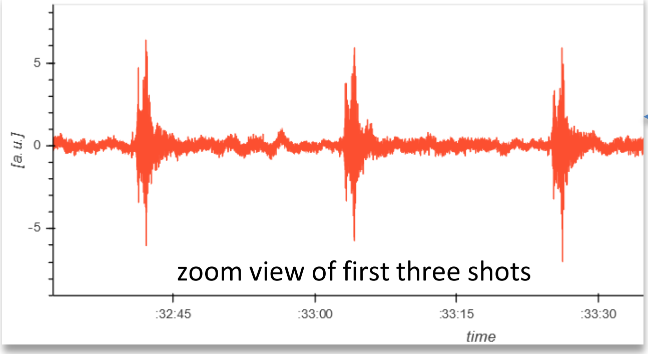
Introduction: aim

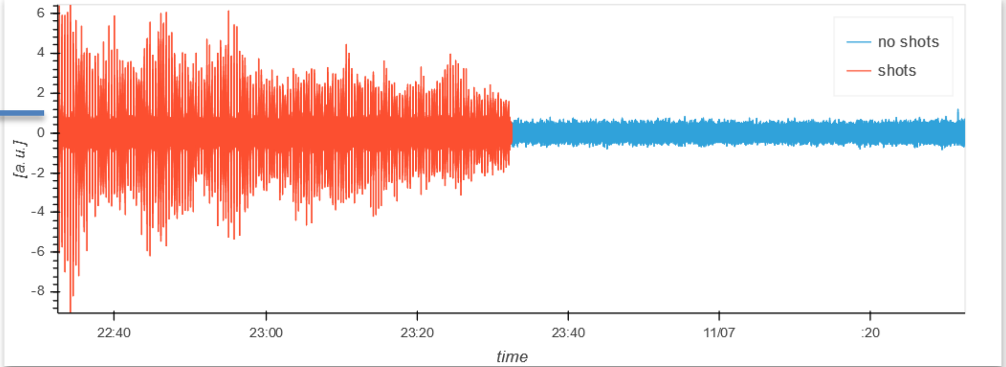
To construct a subspace detector, it is required to select and extract aligned signal templates from which to compute the basis. Since air gun survey shots manifest as impulsive hydroacoustic signals, the logical approach is to obtain templates from shot signals.

The aim is to develop automatic template extraction procedures that:

- do not require prior knowledge of a survey or its ground-truth data
- work with low-SNR shot signals
- compensate for shot arrival-time variations between hydrophones
- align and clip extracted shots

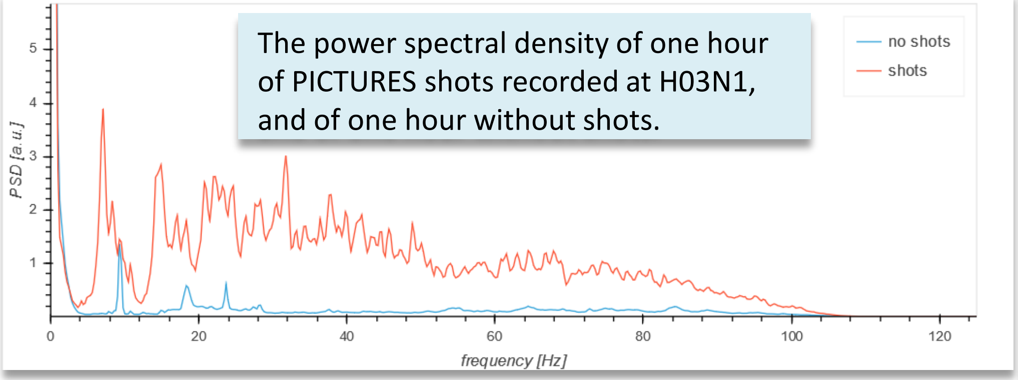
Introduction: pre-processing





The raw hydroacoustic data was obtained from the CTBTO [virtual Data Exploitation Centre]() (vDEC).

At the start of processing, the hydrophone traces are detrended and a broad 5-80 Hz bandpass filter is applied. As can be seen in the power spectral density plot on the right, this rejects the low-frequency oceanic noise but admits nearly all shot energy.



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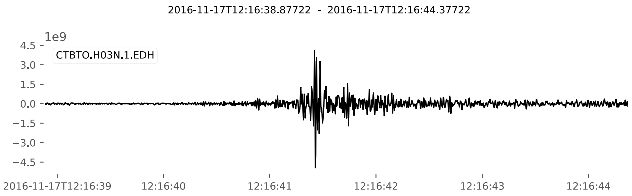
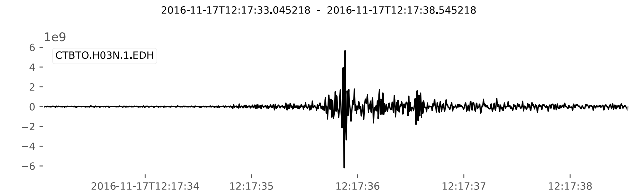
Picking and precise auto/cross correlation

The traces of all three hydrophones are subjected to a shot-tuned 1s/8s recursive STA/LTA trigger from which pick-on and pick-off times as well as an SNR measure are obtained.

Picks coincident (within 2.5s) for all three hydrophones are marked as candidate shots.

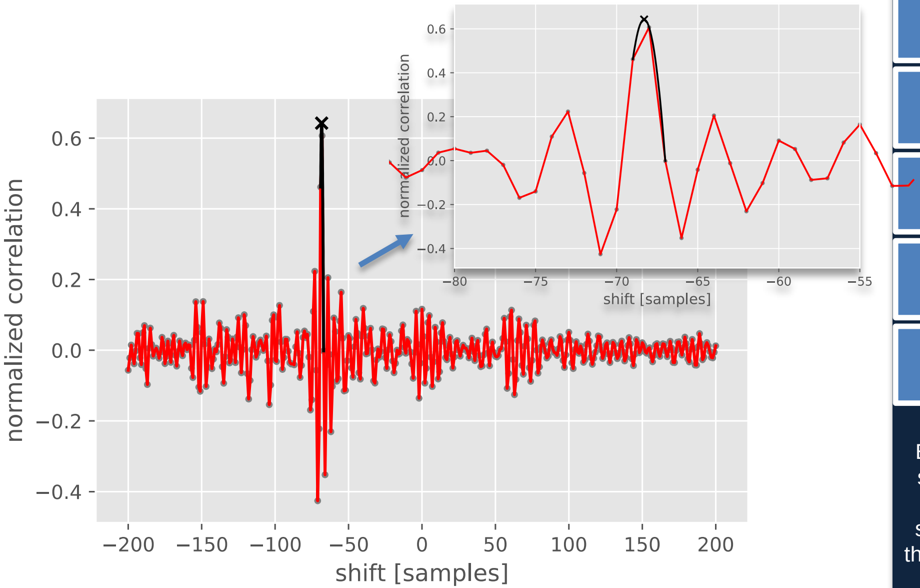
Trace slices are cut around these picks (see for example below) , but these are only very roughly shot-phase aligned.





Auto and cross correlation is used to refine the arrival time delay between different shots, and of a given shot between hydrophones.

To gain sub-sample precision in these time deltas, the point with maximum correlation coefficient and its two neighbours are interpolated with their uniquely-determined parabola.



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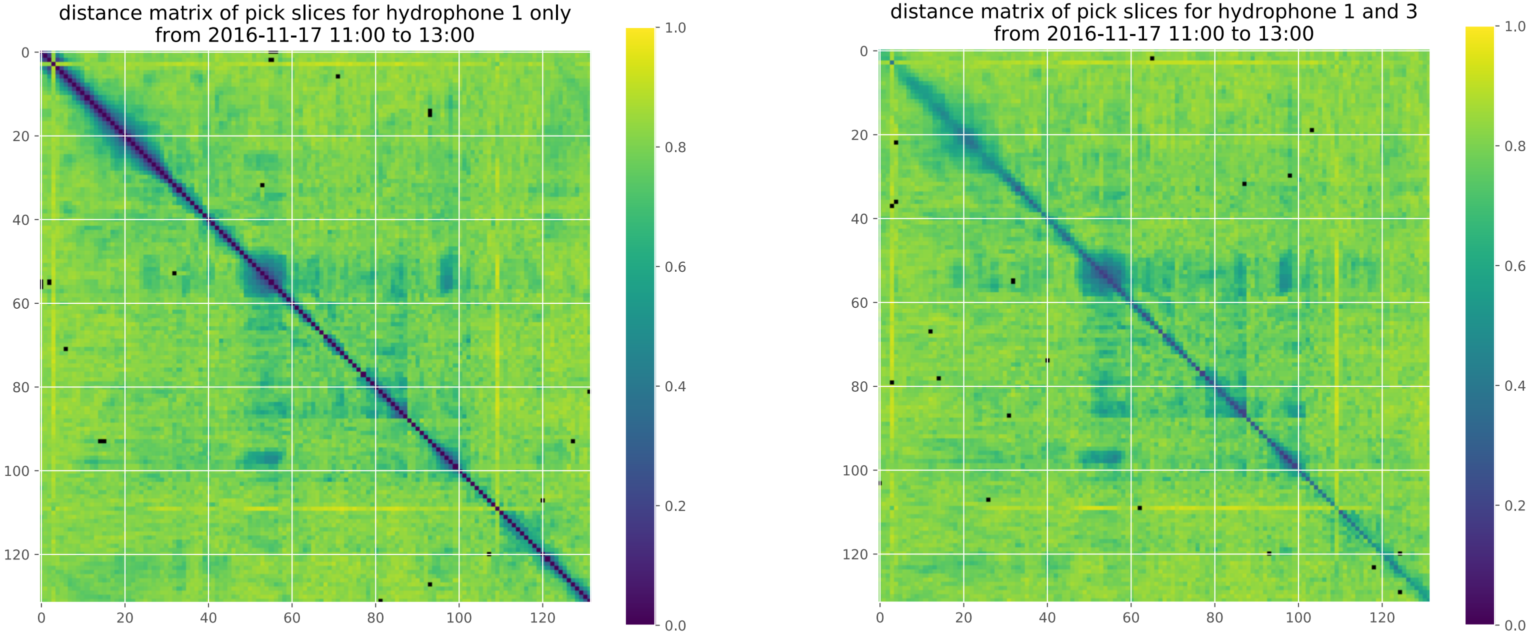
Prospecting



Plotting an auto correlation (left) or cross correlation (right) distance matrix, the colour range showing 1 minus the maximum correlation coefficient of pairs of pick slices numbered by set of coincident arrivals, provides a good way to visualize the prospect of constructing a subspace.

Other than outliers, which are presumably not survey-related, pick slices tend to correlate well with temporally co-located arrivals, and sometimes further out.

The individual dark pixels are NaN values resulting from the correlation shift limit being reached.

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Establishing a survey hypothesis

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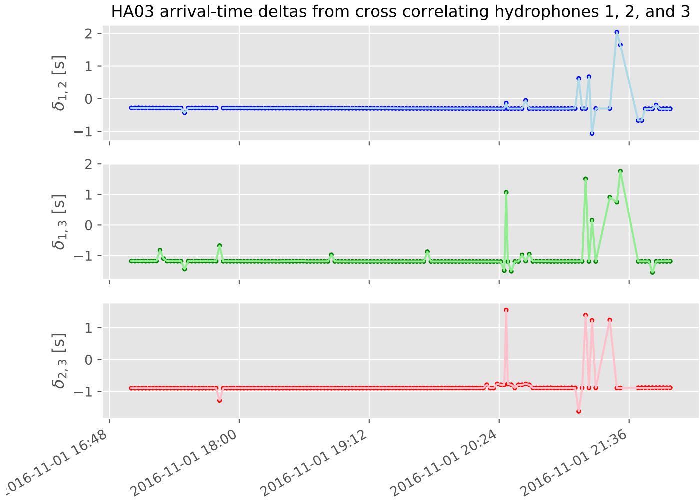
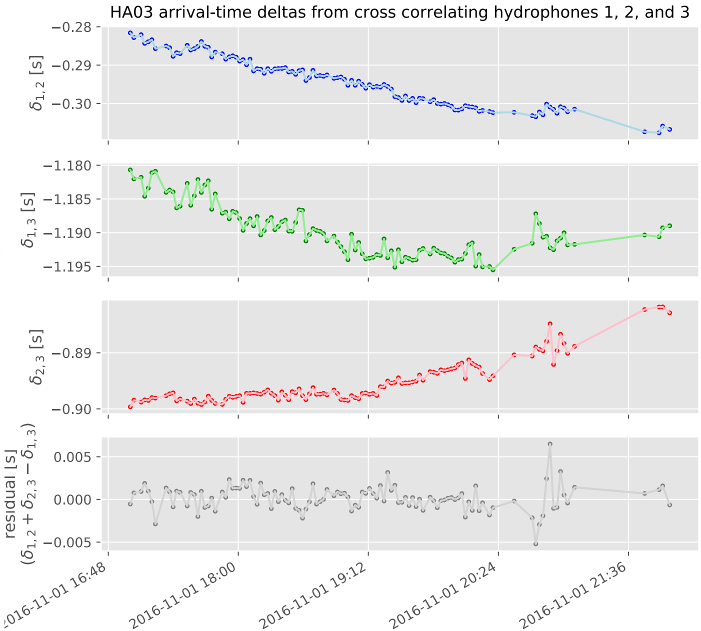


outlier removal



A survey hypothesis can be automatically established by collecting coincident arrivals with similar inter-hydrophone arrival time deltas: an ongoing survey can be assumed to be the predominant source of arrivals, and to have a slowly changing back azimuth and hence slowly changing deltas.

This is done through iterative joint outlier removal. If this retains a large fraction of the coincident arrivals, a survey is highly likely. Only these arrivals are kept for further analysis.

The residual $\delta_{1,2} + \delta_{2,3} - \delta_{1,3}$ of the delta measurements should be close to zero since for the true arrival times, the equality $(t_2-t_1)+(t_3-t_2)-(t_3-t_1)=0$ holds.

This provides a sanity check.

Note the sub-sample-period (0.004s) precision.

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Taking aim

To align hydrophone traces such that arrivals of the same shot from the survey coincide, values for $\delta_{1,2}$ and $\delta_{1,3}$ as a function of time are needed, with hydrophone 1 serving as a reference.

Instead of directly using the $\delta_{1,2}$ and $\delta_{1,3}$ values for this, a better result can be obtained by making use of both the the $\delta_{2,3}$ measurements and the fact that without measurement error, $\delta_{1,2}+\delta_{2,3}-\delta_{1,3}=0$. This is done via a least squares solution for $\delta^{i\ \mathrm{l.s}}_{1,2}$ and $\delta^{i\ \mathrm{l.s}}_{1,3}$ to the set of equations

$\delta^{i\ \mathrm{l.s.}}_{1,2}=\delta^{i\ \mathrm{meas.}}_{1,2}$

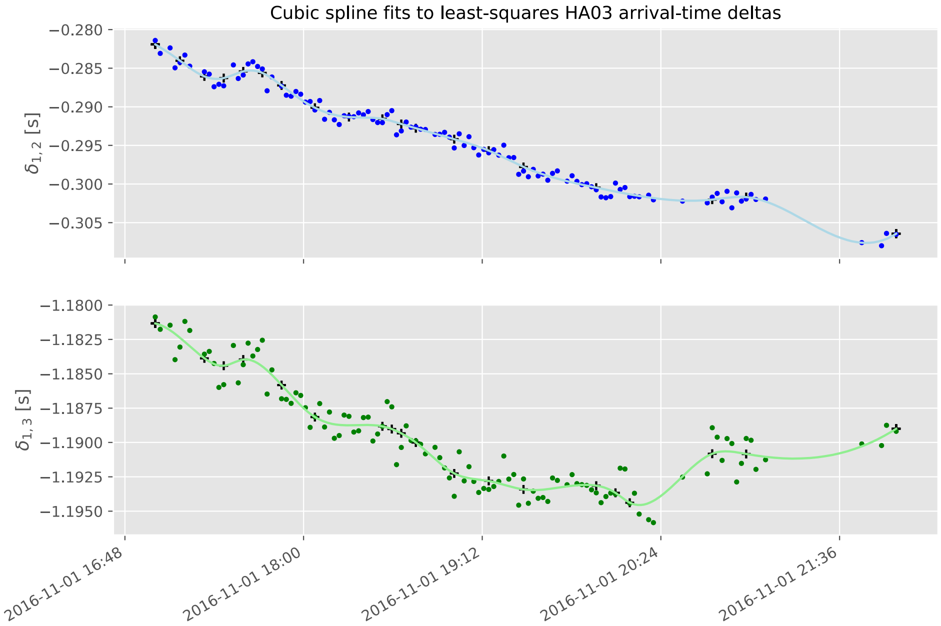
$\delta^{i\ \mathrm{l.s.}}_{1,3}=\delta^{i\ \mathrm{meas.}}_{1,3}$

$-\delta^{i\ \mathrm{l.s.}}_{1,2}+\delta^{i\ \mathrm{l.s.}}_{1,3}=\delta^{i\ \mathrm{meas.}}_{2,3}$

for every coincident arrival (shot) *i* in the survey subset.

The result, shown in the plot to the right, is subtly different from the measured $\delta_{1,2}$ and $\delta_{1,3}$ values shown on the previous slide.

In principle, the hydrophone positions and sound speed could be utilized to reduce the two remaining deltas to a back azimuth, but this would introduce further sources of error.



Further precision and a piece-wise analytical representation of $\delta_{1,2}(t)$ and $\delta_{1,3}(t)$ are obtained through cubic spline fits to the $\delta^{i\ \mathrm{l.s.}}_{1,2}$ and $\delta^{i\ \mathrm{l.s}}_{1,3}$ values.

The smoothing is adjustable, and in the example above has been set to a 6 points per spline knot (the + symbols) target.

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Aligning arrivals of different shots

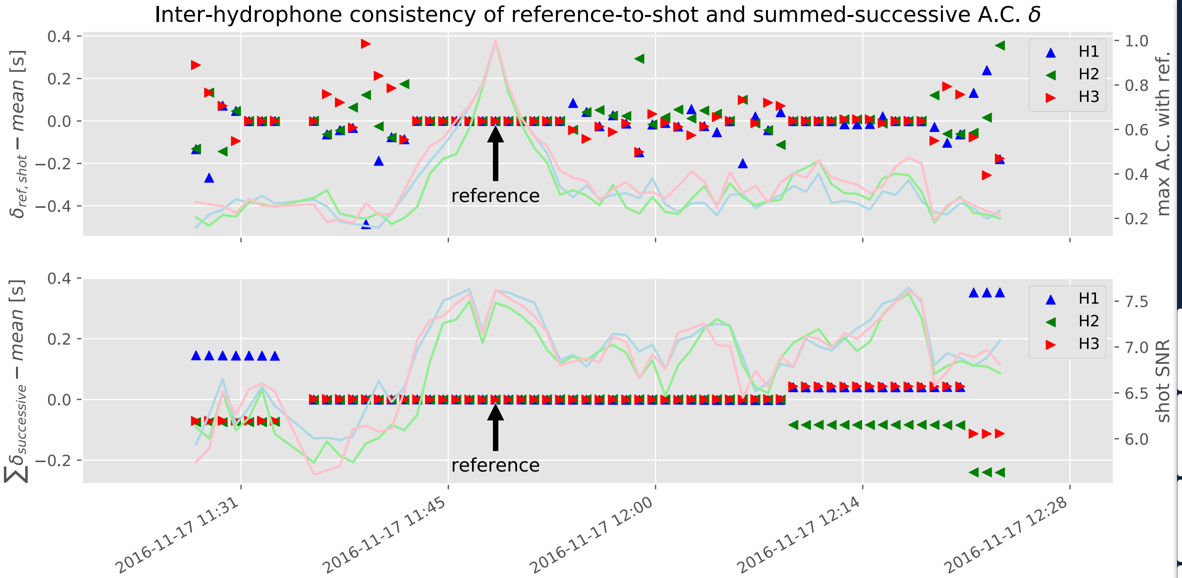
To align different arrivals on the same hydrophone, as required for template extraction, the precise time deltas between arrivals/shots (with outliers removed) must be determined. Two methods are tried:

A. direct reference-to-shot auto-correlation (top graph)

B. summed-successive auto-correlation (bottom graph).

For both, a reference shot with high SNR and good to-neighbour correlation is chosen.

Method A follows the approach used in seismology: using a master template. However, since the transfer function is not static on account of ship movement and ocean dynamics, the correlation soon drops off and errors occur.



Method B sums, starting from the reference, δ values determined for successive arrivals which have high correlation. Hence errors tend to be rare and small. However, once they do occur they persist in longer sums.

By doing so for the three hydrophone in parallel, the occurrence of an error can be determined easily as the same error is highly unlikely to occur for all three hydrophones simultaneously.

37 successive arrivals/shots surrounding the reference stay within one sample period of mismatch between hydrophones. Of these 37, the summed-successive $\delta_{ref,shot}$ values averaged over the three hydrophones are used for template extraction.

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Cutting phase-aligned templates

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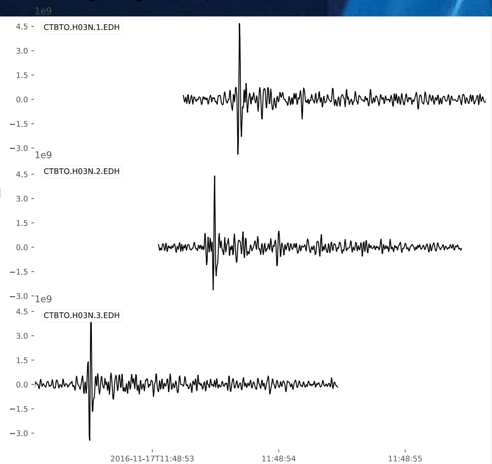
Using the spline fits, which provide shot arrival time delays $\delta_{1,2}(t)$ and $\delta_{1,3}(t)$ between hydrophones, and using the precise $\delta_{ref,shot}$ inter-shot delays, phase-aligned templates are cut with bounds wide enough to comfortably capture all shot signal.

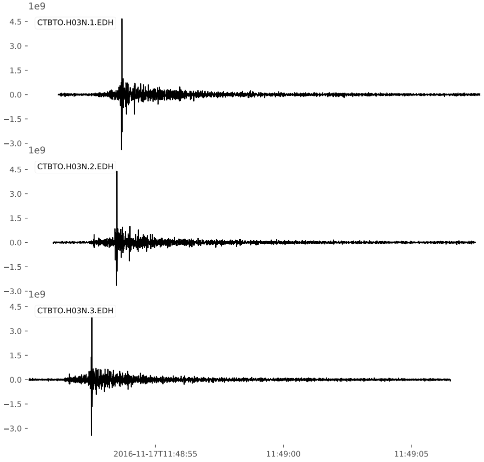
All wide phase-aligned templates are summed after enveloping (below). This provides a high-SNR representation of the shot signal amplitude evolution, allowing for automatic selection of tight template bounds by moving out from the maximum until a threshold of energy is included.

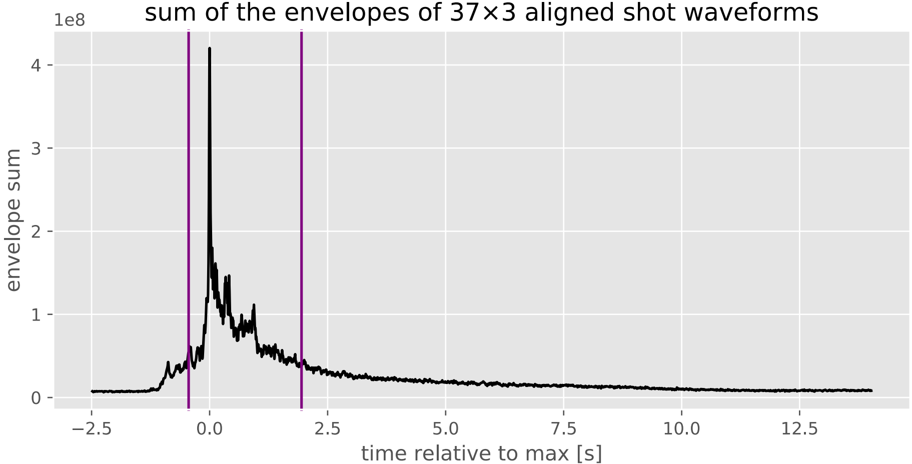
Here, 90% energy was chosen.

Note the extended coda.

Templates cut to the tight bounds (shown on the right for the reference shot) are multiplexed and used for basis construction.







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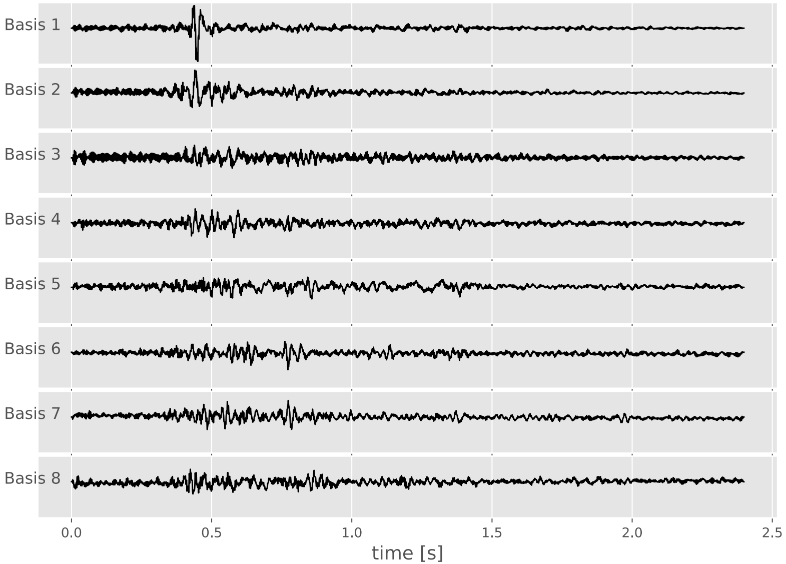
Subspace basis

After singular value decomposition of a matrix constructed from multiplexed tight templates, a *U* matrix results with orthogonal column vectors that can be used as basis vectors for a signal subspace.

The plots below show the first eight of these basis vectors in order of decreasing *σ* value.

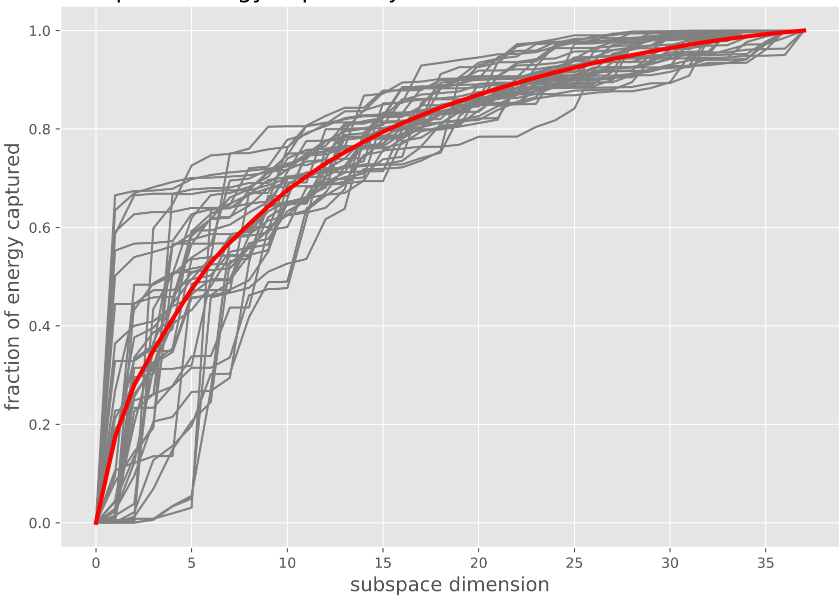
hydrophone-multiplexed basis vectors of subspace



Fraction of energy of the 37 multiplexed templates captured as a function of subspace dimension. The red line represents the average.

The first 5 basis vectors are sufficient to capture 50% of the template energy.

template energy capture by detector as a function of dimension



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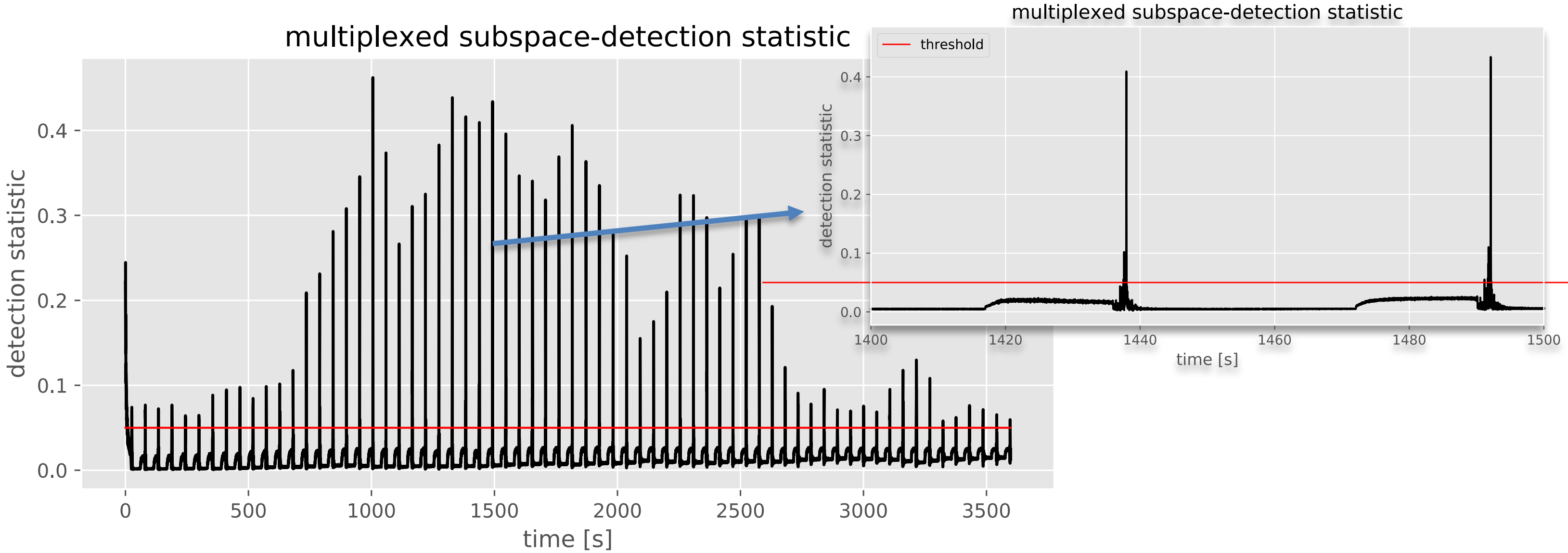
Subspace detection

Using a modified detection statistic, the so-constructed subspace detector is able to pick out shots with very high sensitivity when applied to a hydrophone-multiplexed signal stream. Though the amplitude of the statistic drops off away from the time period covered by the templates, this is likely partly due to only a single pair of average $\delta_{1,2}$ and $\delta_{1,3}$ phase alignments having been applied to the entire stream prior to multiplexing.



Conclusions

- Subspace detection is a viable method for hydroacoustics.
- Good detection sensitivity was demonstrated.
- A single non-multiplexed subspace constructed from and applied to all three hydrophones should result in slower drop-off.
- Parabola interpolation provides sub-sample-period precision in measuring time delays via auto/cross correlation. This improvement can readily be added to HASE.
- Neither method A nor B tried for determining $\delta_{ref,shot}$ seems optimal, though B works better. Weighted least-squares optimization using the full correlation matrix is an option.