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MULTISCALE DATA VISUALIZATION AND EVENT ANALYSIS FOR A DISTRIBUTED UNDERWATER ACOUSTIC MONITORING SYSTEM

Bachelor's thesis

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Author’s declaration of originality

We hereby certify that we are the sole authors of this thesis. All the used materials, references to the literature, and the work of others have been properly acknowledged and cited. Generative artificial intelligence tools were used only for language editing, paraphrasing, and grammar correction of author-produced text. This thesis has not been presented for examination at any other institution.

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Abstract

Distributed Acoustic Sensing (DAS) converts fiber-optic cables into dense acoustic sensor arrays, but its application in freshwater environments remains largely unexplored. This thesis presents a modular, reproducible analysis and visualization system for the DASLakeZurich dataset. The dataset consists of synchronized DAS and hydrophone recordings from a controlled whale vocalization playback experiment conducted in Lake Zurich, Switzerland, in January 2022. The system processes multi-gigabyte HDF5 recordings into compact browser-ready artifacts and integrates DAS data, hydrophone recordings, spatial bathymetry, and hydrodynamic model output into a synchronized static multi-view interface organized around Shneiderman's overview-to-detail hierarchy.

Empirical analysis shows that DAS acoustic coupling is sparse and spatially non-uniform beyond what prior documentation implied. Orca-related response concentrates in two localized channel neighborhoods (channels 859–862 and 908–925 out of 946), confirmed through band-pass envelope analysis and normalized cross-correlation. Humpback response is weaker and more diffuse, consistent with lower coupling efficiency at frequencies below 1 kHz. Cable-wide coherent patterns reflect hydrodynamic rather than acoustic processes. No existing DAS software tool, including DASPy, DASCore, and DAS4Whales, provides the combination of interactive exploration, multi-modal synchronization, and metadata provenance implemented in the present system.

This thesis is written in English and is 34 pages long, including 6 chapters, 13 figures, and 1 table.

Lühikokkuvõte

Mitmetasandiline andmete visualiseerimine ja sündmuste analüüs hajutatud veealuses akustilises seiresüsteemis

Distributed Acoustic Sensing (DAS) muudab fiiberoptilised kaablid tihedaks akustiliste sensorite võrgustikuks, kuid selle kasutamine mageveekeskkondades on seni jäänud suuresti uurimata. Käesolev lõputöö esitab modulaarse ja reprodutseeritava analüüsi- ning visualiseerimissüsteemi DASLakeZurich andmestiku jaoks. Andmestik koosneb sünkroniseeritud DAS- ja hüdrofonisalvestistest, mis pärinevad kontrollitud vaalavokaliseerimise taasesituskatsest Zürichi järves Šveitsis 2022. aasta jaanuaris. Süsteem töötleb mitme gigabaidi suurused HDF5-salvestised kompaktseteks veebilehitsejas kasutatavateks artefaktideks ning ühendab DAS-andmed, hüdrofonisalvestised, ruumilise batümeetria ja hüdrodünaamilise mudeli väljundi sünkroniseeritud staatiliseks mitmevaateliideseks, mis põhineb Shneidermani overview-to-detail hierarhial.

Empiiriline analüüs näitab, et DAS-i akustiline sidestus on hõre ja ruumiliselt ebaühtlane suuremal määral, kui varasem dokumentatsioon viitas. Mõõkvaalaga seotud DAS-signaal koondub kahte lokaalsesse kanalipiirkonda (kanalid 859–862 ja 908–925 kokku 946 kanalist), mida kinnitavad ribapääsfiltri ümbrikuanalüüs ja normaliseeritud ristkorrelatsioon. Küürvaalaga seotud vastus on nõrgem ja hajusam, mis vastab madalamale sidestustõhususele sagedustel alla 1 kHz. Kaablit läbivad koherentsed mustrid peegeldavad pigem hüdrodünaamilisi kui akustilisi protsesse. Ükski olemasolev DAS-tarkvaralahendus, sealhulgas DASPy, DASCore ja DAS4Whales, ei paku käesolevas süsteemis rakendatud interaktiivse uurimise, multimodaalse sünkroniseerimise ja metaandmete päritolu jälgitavuse kombinatsiooni.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 34 leheküljel, 6 peatükki, 13 joonist, 1 tabelit.

List of abbreviations and terms

TalTech	Tallinn University of Technology
API	Application Programming Interface
C-OTDR	Coherent Optical Time-Domain Reflectometry
CLI	Command-Line Interface
CMV	Coordinated Multiple Views
CRS	Coordinate Reference System
CSS	Cascading Style Sheets
DAS	Distributed Acoustic Sensing
ETH	Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology)
HDF5	Hierarchical Data Format version 5
HTML	Hypertext Markup Language
IIR	Infinite Impulse Response
JS	JavaScript
JSON	JavaScript Object Notation
LV95	Swiss national coordinate system (CH1903+/LV95)
MAD	Median Absolute Deviation
NCC	Normalized Cross-Correlation
NPZ	NumPy compressed array format
RMS	Root Mean Square
STFT	Short-Time Fourier Transform
WAV	Waveform Audio File Format

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1 Introduction

Underwater acoustic monitoring has become indispensable for studying marine ecosystems. It is used not only for detecting biological activity, but also for identifying the effects of environmental change. In this context, distributed acoustic sensing (DAS) has attracted significant attention. This technology converts a standard fiber-optic cable into a dense array of continuous acoustic sensors, providing spatially distributed coverage at scales unattainable by traditional hydrophone systems at comparable cost. Open-ocean deployments have demonstrated the potential of this technology, including the detection of whale vocalizations along submarine telecommunication cables, but freshwater environments have received considerably less attention.

Lake deployments present their own challenges: the coupling of the cable to the lake bed is generally unstable, lake hydrodynamics generate structured low-frequency noise, and there are no established baselines for what good DAS performance should look like in an inland water body. The DASLakeZurich dataset, collected in Lake Zurich, Switzerland, in January 2022, is one of the first publicly available resources to directly address this gap. This controlled experiment uses a fiber-optic cable paired with co-located hydrophones, where known whale vocalizations were played back from an underwater speaker at known positions.

Working with DAS data is inherently complex. Each recording combines three dimensions: time, space along the cable, and frequency. The structure of the resulting data varies strongly with the application. Without specialized tools for making sense of the data, one must either write custom processing code for each analysis task or accept a heavily compressed representation that obscures important detail. The DAS software ecosystem has expanded considerably in recent years, but existing tools are built around signal processing and data management workflows. What these tools lack, however, is an interactive interface that integrates DAS with additional data sources such as hydrophone recordings, spatial maps, and environmental context. Such an interface would support the kind of open-ended, hypothesis-generating exploration that precedes formal analysis. This is particularly important for a dataset like DASLakeZurich, where the DAS response to acoustic events is weak across most of the cable, spatially confined to a small number of channels, and mixed with environmental signals that require careful interpretation to separate from biological signals. How to design a visualization for data with these properties, and what the Lake Zurich deployment can tell us about bioacoustic coupling in freshwater settings, are the two questions this thesis sets out to address.

The solution is a modular analysis and visualization system built specifically for the DASLakeZurich dataset, integrating DAS data, hydrophone recordings, bathymetry, and hydrodynamic model output in a synchronized multi-view interface. The data processing pipeline is designed to be reproducible, and while the system targets this specific dataset, its architecture is intended to generalize to similar deployments. The empirical results are sobering in some respects: bioacoustic coupling is indeed sparse, confined to a small subset of channels, and varies substantially by source type. At the same time, this variation is itself informative and is reflected in the spatial and spectral structure of the DAS response in ways that the visualization system can reveal. In addition, the environmental patterns visible along the cable constitute a second, distinct analytical thread alongside the biological signal.

The viewer is publicly accessible at https://prodbymedea.github.io/multiscale-underwater-acoustic-event-analysis/?shot=whales_humpback, and the full source code, including all pipeline scripts and frontend assets, is available at https://github.com/prodbymedea/multiscale-underwater-acoustic-event-analysis

2 Background and Related Work

2.1 Physical Principles of Distributed Acoustic Sensing

Distributed Acoustic Sensing converts a standard single-mode optical fiber into a dense array of acoustic sensors using coherent optical time-domain reflectometry (C-OTDR). A laser pulse is sent into the fiber, where it scatters back from tiny imperfections in the glass. Because the pulse is coherent, the returning light interferes at the detector and produces a phase signal. Any acoustic or vibrational wave that strains the fiber causes this signal to shift. Since the position of each scattering point is determined from the travel time of the light, every pulse produces a continuous profile of strain along the full length of the fiber (Hartog, 2017; Parker et al., 2014).

A key parameter is the gauge length, which sets the section of fiber over which the phase difference is measured. A longer gauge length gives a better signal-to-noise ratio, but misses fine spatial detail. A shorter one captures more detail, but at the cost of higher noise. The spacing between output channels can be chosen independently of the gauge length, which allows the sensors to overlap, but the spatial resolution is still limited by the gauge length itself. The pulse repetition rate determines the temporal sampling rate of the system and simultaneously constrains the maximum unambiguous fiber length: because each pulse must complete its round trip before the next is launched, higher repetition rates reduce the usable range. In the DASLakeZurich deployment the DAS channel sampling rate is approximately 5 kHz, providing a Nyquist frequency of 2.5 kHz and sufficient temporal resolution for the acoustic frequency ranges relevant to the recorded whale vocalizations (Lindsey et al., 2020).

Depending on the demodulation scheme, a DAS system returns either axial strain or its time derivative, strain rate. In either case the recorded quantity is mechanical deformation of the fiber, not acoustic pressure, and the conversion from an incident pressure wave to a measurable fiber strain depends on local cable-to-substrate coupling, cable geometry, and fiber orientation relative to the wavefield.

Three noise mechanisms are particularly relevant for underwater deployments. Fading noise arises from destructive interference in the Rayleigh speckle pattern at specific channel positions, making phase recovery ill-conditioned regardless of incident signal level. Instrument noise sets the broadband noise floor uniformly along the fiber. Coupling variability, caused by differences in mechanical contact between the cable jacket and the surrounding medium, introduces channel-to-channel sensitivity differences that may span orders of magnitude.

The combined effect is that DAS sensitivity is physically limited and spatially non-uniform: absence of a detectable response on a given channel reflects coupling and instrument conditions rather than physical absence of acoustic energy, a constraint that directly motivates the channel-selective analysis approach developed in this thesis.

2.2 Underwater Acoustic Monitoring with DAS

Over the past decade, the deployment of DAS systems in underwater environments has expanded rapidly, driven largely by the availability of existing submarine telecommunication infrastructure. Sladen et al. (2019) demonstrated that seafloor telecom cables can record earthquakes and ocean-solid Earth interactions with sensitivity comparable to conventional seismometers. Williams et al. (2019) showed that dark fiber segments, which are unused cable pairs leased for scientific purposes, can detect microseisms and teleseismic arrivals across ocean basins.

The extension of underwater DAS to biological acoustic monitoring followed naturally from this seismological groundwork. Bouffaut et al. (2022) reported the detection and tracking of Arctic baleen whales along a 120 km submarine cable, demonstrating that fin whale 20 Hz calls produce coherent strain signals across tens of kilometers of fiber and that inter-channel travel-time differences can be used to constrain source bearing. This result is significant for the present project because it establishes a proof of concept for DAS-based bioacoustic monitoring under favorable coupling conditions, including a deep ocean floor, rigid cable-sediment contact, and high-amplitude low-frequency sources. These conditions differ substantially from the freshwater lake setting of the present study.

Freshwater and inland lake deployments of DAS remain substantially underrepresented in the literature. The DASLakeZurich dataset is among the first publicly available datasets to address this gap. The experimental setup consisted of a fiber-optic cable laid along the lakebed, a set of co-located hydrophone recorders, and an underwater speaker broadcasting known humpback and orca vocalizations from fixed positions. The availability of ground-truth source signals and positions makes this controlled design especially useful as a benchmark for assessing coupling efficiency and detection sensitivity under freshwater conditions. The dataset exposes several challenges specific to lake environments, including shallower water depths, more variable cable-sediment contact, stronger environmental noise from lake hydrodynamics, and shorter propagation distances that alter the spatial coherence structure of acoustic signals along the fiber.

A recurring theme across all underwater DAS deployments is that DAS and hydrophones respond to the same acoustic field in fundamentally different ways. A hydrophone measures acoustic pressure at a point, with a sensitivity that is largely isotropic and well-characterized by its frequency response. DAS measures axial strain along the fiber, which is a directional quantity: a wavefield propagating perpendicular to the cable produces negligible strain, while one propagating along the cable axis couples efficiently. Furthermore, the strain sensitivity depends on the acoustic impedance contrast at the cable-water or cable-sediment interface and on the mechanical properties of the cable jacket. As Lior et al. (2021) analyze in detail, the effective detection capability of underwater DAS is therefore a function of source azimuth, frequency, cable burial depth, and local substrate properties, none of which are uniform along a real deployment.The practical consequence, clearly visible in the DASLakeZurich data, is that DAS response to a given acoustic event is sparse and channel-localized: the same vocalization may produce a strong signal on a handful of channels and be entirely absent on neighboring ones, a pattern that cannot be interpreted as source intermittency and must instead be attributed to spatially variable coupling along the cable.

2.3 Existing DAS Software Tools

Several open-source software packages have been developed to support DAS data analysis, but existing tools are primarily focused on backend signal processing rather than interactive multimodal exploration.

DASPy (Hu & Li, 2024) is a Python toolbox designed for DAS seismology that provides a comprehensive set of signal processing routines, including denoising, filtering, and wave-field decomposition. Its visualization capabilities are limited to static Matplotlib figures, and it does not provide any mechanism for synchronized multi-panel exploration or integration with complementary data modalities such as hydrophones or spatial context layers. DASCore (Chambers et al., 2024) takes a data-model-first approach, defining a patch-based abstraction for fiber-optic time series that simplifies format conversion, metadata handling, and processing pipeline construction. While it includes basic plotting utilities, interactive visualization and multi-modal synchronization are outside its scope. DAS4Whales, an open-source toolkit developed specifically for bioacoustic DAS applications, provides f-k filtering routines and spectrogram primitives that were reviewed during the present project, but it likewise offers no synchronized multi-panel viewer or hydrophone integration.

The gap shared by all three tools is the absence of an interactive, synchronized, multi-modal exploration interface designed for domain-expert use. A researcher working with a dataset such as DASLakeZurich needs to inspect selected DAS channels in both time and frequency, relate hydrophone activity to distributed cable response, and interpret observations against spatial and environmental context. Existing tools do not support these tasks without substantial custom development. A detailed feature comparison with the present system is provided in Section 6.4.

2.4 Scientific Data Visualization Principles

Shneiderman (1996) formulated the visual information-seeking mantra as a task-oriented design principle for interactive information visualization: overview first, zoom and filter, then details on demand. Applied to DAS data, this hierarchy maps naturally onto the multi-scale structure of the dataset: a cable-wide DAS waterfall provides the overview of activity patterns along the fiber, channel selection and visual inspection of regions of interest support zoom and filter, and selected-channel waveform and spectrogram inspection deliver details on demand. This progression is not merely a design convenience; it reflects the epistemological workflow of a domain expert who must first orient themselves in a large, unfamiliar dataset before committing to channel-level interpretation.

Coordinated multiple views (CMV) extend this principle to multi-modal data by linking separate visual representations through shared interaction state. Roberts (2007) identifies synchronization of selection, navigation, and highlighting across views as the defining characteristic of CMV systems, essential when no single view can adequately represent all relevant dimensions of a dataset. In the present context, the DAS waterfall, spatial map, and selected-channel panels expose complementary dimensions of the same recording. The viewer supports coordinated interpretation by linking the selected DAS channel across the map, waterfall, and selected-channel views, while detailed time inspection is handled within the selected-channel panel. Munzner (2014) provides a formal framework for reasoning about such design decisions, and her nested model of visualization design informed several architectural choices described in Chapter 5.

Color mapping is a less prominent but practically important design consideration for DAS data specifically. DAS amplitude distributions are typically heavy-tailed and heterogeneous across channels, making linear color scales with fixed endpoints ineffective: a small number of high-amplitude channels can dominate the color range and make much of the cable appear visually featureless. For this reason, the system uses robust percentile-based scaling in several DAS views. The exact percentile range depends on the artifact and visualization mode: for example, quick-look DAS previews use symmetric robust clipping around zero, the DAS waterfall applies a symmetric percentile-based amplitude limit, and the DAS activity map is normalized from rolling-RMS values using percentile-based per-channel scaling. These choices reduce the influence of outliers while preserving relative structure across time and channel. For signed DAS quantities, diverging color scales centered near zero are used where the sign of the signal is meaningful; for activity maps, the displayed quantity is non-negative normalized activity rather than signed strain. These conventions are consistent with established practice in seismic and DAS visualization and are adopted here to make weak or spatially sparse structure more interpretable.

2.5 Robust Statistics for Signal Detection

Acoustic and seismic time series recorded in field conditions rarely satisfy the Gaussian noise assumptions that underlie classical signal detection methods. DAS data are particularly prone to heavy-tailed amplitude distributions, spatially variable noise floors, and transient artifacts from coupling variability and fading. Robust statistical estimators are therefore preferable to moment-based alternatives because their performance degrades gracefully in the presence of outliers.

The median absolute deviation (MAD), defined as the median of absolute deviations from the sample median, is the canonical robust scale estimator for such settings. When multiplied by the consistency factor 1.4826, it provides an asymptotically consistent estimator of the standard deviation under Gaussian assumptions. At the same time, it remains bounded even when up to 50% of observations are outliers, giving it a substantially higher breakdown point than the sample standard deviation (Rousseeuw & Croux, 1993). In the present system, MAD-based scaling is applied during DAS preprocessing, while MAD-based thresholding is used for the selected-channel band-pass support score, as described in Sections 4.3 and 4.6.

Percentile-based normalization serves an analogous role in the visualization pipeline. Because DAS channel amplitudes vary by orders of magnitude due to coupling variability, a single global normalization renders most channels visually uninformative. Mapping DAS amplitudes to robust percentile ranges ensures that the visual encoding reflects signal structure rather than isolated high-amplitude outliers or channel sensitivity differences. As Stowell (2022) notes in the context of computational bioacoustics, this design choice directly determines which patterns are visible to a human analyst.

3 Dataset and Experimental Context

3.1 The DASLakeZurich Dataset

The DASLakeZurich dataset (Rychen et al., 2023; Zenodo DOI: 10.5281/zenodo.7886409) is a publicly available collection of synchronized distributed acoustic sensing and hydrophone recordings acquired in Lake Zurich, Switzerland, in January 2022. The experiment was conducted by researchers from ETH Zurich as a controlled playback study: a battery-powered underwater speaker broadcast known acoustic signals at a series of positions around the sensor installation, while the DAS system and co-located hydrophone arrays recorded simultaneously. The dataset comprises 93 shot files across five experimental series, totaling approximately 25 GB, and represents one of the first publicly available freshwater DAS datasets designed specifically for acoustic source localization and bioacoustic monitoring research.

The DAS interrogation unit recorded strain-rate data at 5 kHz across 946 channels with GPS-synchronized timing. The hydrophone array consisted of three recorders with four channels each, sampled at 50 kHz. Each shot file is stored in HDF5 format and contains all modalities for a single broadcast event, including DAS data, hydrophone recordings, source signal, and positional metadata. These data are organized into groups, with acquisition parameters stored as attributes.

Spatial context for the deployment is provided by a separate file, Situation.h5, which contains bathymetric depth measurements of the lake, the georeferenced fiber track as a polyline of coordinates, boat tracks recorded during the experiment, and associated spatial metadata. This file is essential for map-based visualization: it supplies the geometric reference frame within which source positions, recorder locations, and DAS channel distances can be jointly displayed.

3.2 Experimental Shots and Subset Selection

The five experimental series span a range of source signal types and broadcast positions, including tonal sweeps, impulsive signals, and biological sound recordings. Of these, the Whales series is of primary interest because it uses recorded whale vocalizations as the broadcast source material. Within this series, two shots were selected as the primary working subset:

whales_humpback (2022-01-26--04-46-16--Humpback.h5): a broadcast of a humpback whale vocalization recording, with approximately 41 seconds of source/hydrophone data and about 33 seconds of DAS data available for visualization.

whales_orca (2022-01-26--04-47-42--Orca.h5): a broadcast of an orca vocalization recording, with approximately 107 seconds of source/hydrophone data and about 102 seconds of DAS data available for visualization.

Both shots use controlled playback sources with known signal content and position metadata, enabling comparison between the emitted source signal, hydrophone reference measurements, and the DAS response along the fiber. The two source types differ substantially in spectral content: humpback vocalizations are concentrated mainly in the low-frequency range below approximately 1 kHz, while orca vocalizations contain stronger mid-frequency components within the DAS analysis band, extending to around 2–2.5 kHz. This provides a natural comparison of DAS response across frequency ranges. A third shot, morning_00, was retained as a reserve comparison case for pipeline stress-testing but does not form part of the primary analysis.

3.3 Environmental Context

Interpretation of DAS recordings in a lake environment depends on the physical state of the water column, including temperature stratification, thermocline depth, and horizontal flow, all of which can affect acoustic propagation speed, refraction, and ambient noise conditions. To provide this environmental context, the project incorporates Delft3D-FLOW hydrodynamic model output for Lake Zurich, supplied as NetCDF files covering the recording date within an approximately seven-day model window.

The model output includes horizontal flow velocity, water temperature as a function of depth and position, thermocline depth, and water level, on a curvilinear grid of 212 × 34 horizontal cells and 75 vertical layers at approximately three-hour temporal resolution.

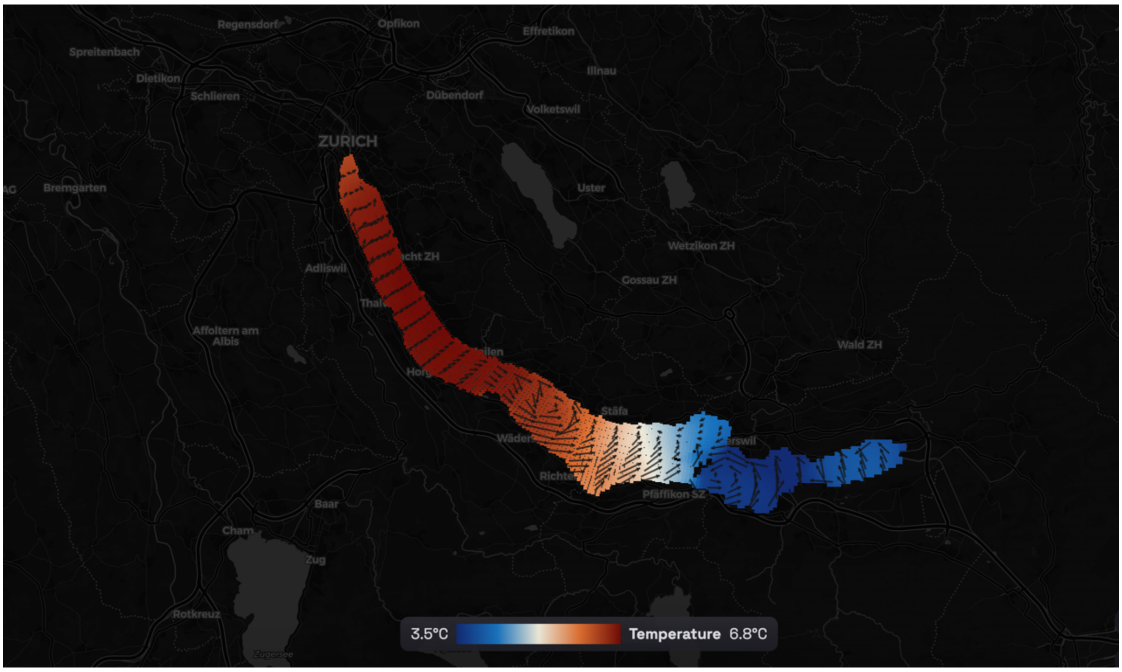

Figure 3-1 Prototype environmental context view showing Delft3D-derived temperature and horizontal flow fields for Lake Zurich.

For the prototype environmental branch, horizontal flow and temperature were selected as the main map-based context layers, while thermocline depth was retained as a secondary diagnostic layer because it is sparse in the inspected model file.

A practical challenge is the mismatch between coordinate reference systems: the model grid uses a projected metric frame while the DAS fiber track is expressed in the Swiss national coordinate system CH1903+/LV95. A verified transformation between these frames was not established during the present project. Resolving this coordinate alignment remains a prerequisite for producing fiber-collocated environmental time series, and the environmental branch is therefore presented as a contextual analytical layer rather than a spatially registered overlay on the DAS geometry.

4 Preprocessing and Event Analysis Pipeline

4.1 Pipeline Architecture Overview

The analysis pipeline is implemented as a sequence of modular, single-purpose command-line scripts. Each script consumes well-defined inputs and produces compact artifacts for downstream stages or direct viewer use. Individual stages can be re-run in isolation, and the frontend remains decoupled from backend execution by operating exclusively on generated artifact files.

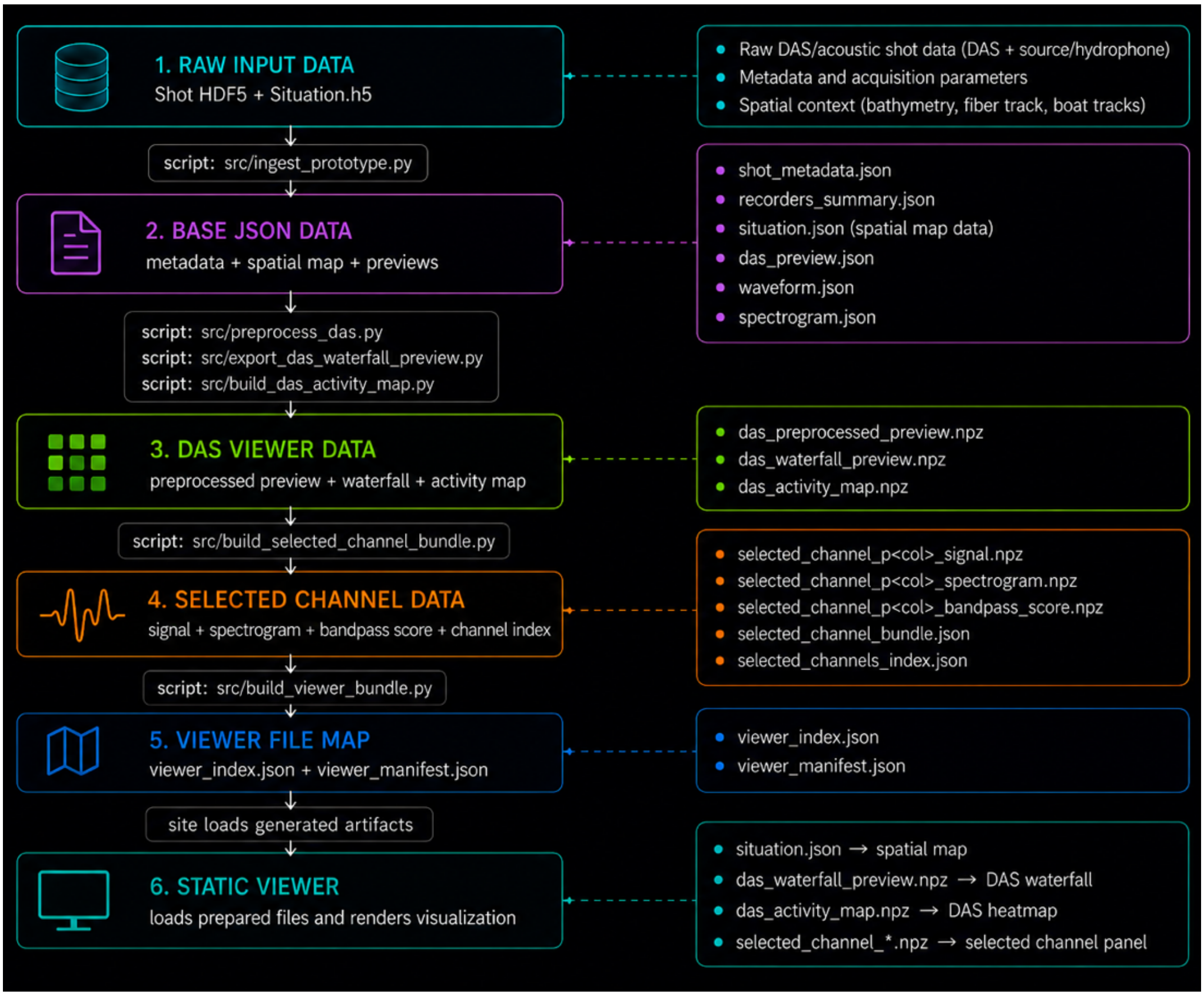

Figure 4-1 Full data flow from raw shot files to static viewer artifacts.

The data flow begins with raw HDF5 shot files and proceeds through ingestion and format conversion, DAS preprocessing, raw waterfall export, activity map construction, and selected-channel bundle assembly. All stages are orchestrated by scripts/build_viewer_all.sh, which rebuilds the complete output set from raw inputs in a single command.

When enabled, an optional environmental branch exports Delft3D-derived environmental products for the prototype dashboard.

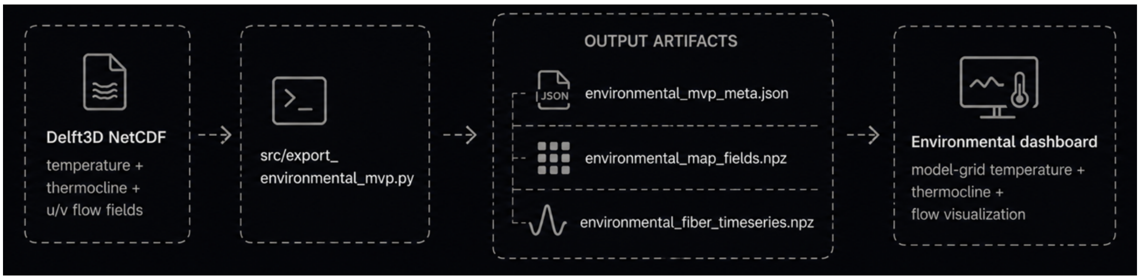

Figure 4-2 Optional environmental export branch for Delft3D-derived context data.

The viewer_manifest.json file, assembled during the final pipeline stage, serves as the contract between the backend and the static frontend. It enumerates all available artifacts for each shot, including JSON, NPZ, WAV, and metadata files, so the viewer requires no direct knowledge of the pipeline structure. In addition, most processing stages emit metadata companion JSON files that record the applied parameters. This allows the provenance of any artifact to be reconstructed without inspecting the source code.

4.2 Data Ingestion and Format Conversion

The raw dataset consists of dozens of HDF5 shot files totaling tens of gigabytes. Direct browser delivery is impractical due to file size and lack of native HDF5 support in browser runtimes. The ingestion stage transforms selected dataset content into compact JSON artifacts, while subsequent DAS export stages generate NPZ artifacts for browser-efficient visualization. HDF5 files are parsed using the h5py library, which provides efficient access to the hierarchical file structure and supports direct array slicing.

The ingest script inspects the HDF5 file structure and extracts DAS data, hydrophone recordings, source signals, and metadata from the available groups. HDF5 attributes stored as NumPy scalar types or byte strings are explicitly coerced before JSON serialization to ensure browser-readable output.

DAS data present the most significant size challenge: a single shot contains 946 channels and several hundred thousand samples at 5 kHz. The initial ingest stage exports a lightweight JSON preview using heavy channel and time downsampling. Subsequent DAS-specific stages produce NPZ artifacts for the viewer: a preprocessed DAS preview using channel subsampling and robust normalization, and a raw waterfall preview that preserves a compact contiguous DAS time window with configurable time and channel downsampling.

Hydrophone data are decimated from 50 kHz to 10 kHz before time-frequency analysis. This practical choice reduces data volume by a factor of five while preserving the 5 kHz Nyquist frequency required for all analysis bands used in this project. STFT representations are computed using scipy.signal.stft with a 1024-point Hann window. The resulting outputs are exported as JSON files within an approximate 2 MB per-artifact size budget.

Spatial context is extracted from Situation.h5 and exported as situation.json, including the downsampled bathymetric grid, fiber-track polyline, boat tracks, and related coordinate metadata.

4.3 DAS Preprocessing Chain

Raw DAS data contain several components detrimental to visualization and analysis: static per-channel offsets, low-frequency drift, large inter-channel amplitude differences, and occasional extreme transients. The preprocessing chain in src/preprocess_das.py addresses these through a channel-wise sequence of median removal, optional temporal filtering, and robust normalization.

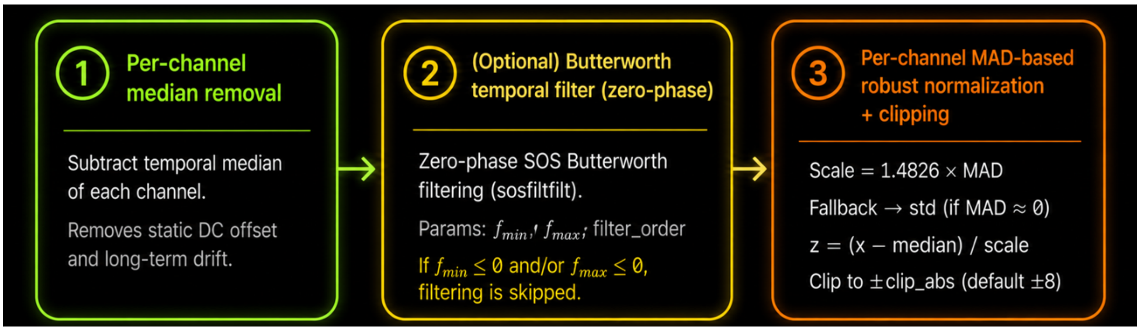

Figure 4-3 DAS preprocessing chain implemented in src/preprocess_das.py.

Per-channel median removal. The temporal median of each channel is subtracted from its time series, removing the static DC offset, before temporal filtering suppresses low-frequency drift. The median is preferred over the mean because it is robust to transient outliers that would otherwise shift a mean-based estimate substantially.

Temporal Butterworth band-pass filtering. A zero-phase IIR band-pass filter is applied using scipy.signal.sosfiltfilt. Zero-phase filtering preserves temporal alignment across channels. The default passband is 15–1200 Hz: the lower cutoff suppresses quasi-static drift, while the upper cutoff retains low- to mid-frequency structure relevant for humpback-oriented inspection. This is a practical baseline choice rather than a biologically optimized band; orca-focused analysis uses a narrower 2000–2350 Hz band in Section 4.6. Filter parameters are exposed via CLI and recorded in the metadata companion for reproducibility.

Per-channel MAD-based normalization and clipping. Each channel is normalized by scale = 1.4826 × MAD, which provides a robust estimator of standard deviation under Gaussian assumptions while being less sensitive to outliers (Rousseeuw & Croux, 1993). Channels where MAD ≈ 0 fall back to the sample standard deviation. The normalized signal is clipped to $\pm 8\sigma$ to prevent extreme outliers from compressing the display range.

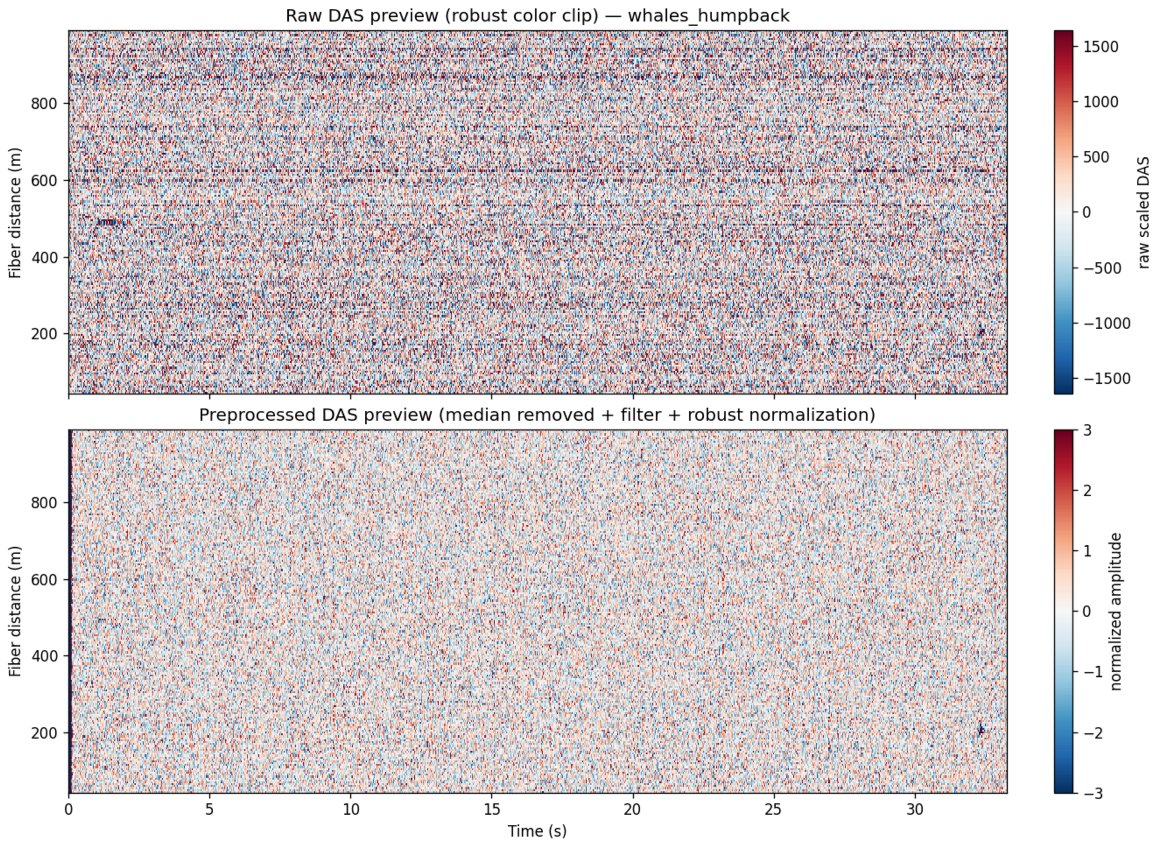

Figure 4-4 Example raw and preprocessed DAS preview for the Humpback shot.

Key dataset findings. Preprocessing and subsequent channel-level diagnostics revealed four properties consequential for the analysis. DAS acoustic sensitivity is sparse and hotspot-like. Orca-related response is concentrated primarily in channels ~859–862 and ~908–925 rather than being distributed uniformly across the 946-channel array. Humpback response is weaker and noisier than orca, consistent with weaker observed DAS response in the low-frequency band and a noisier low-frequency background; humpback interpretation therefore remains at support level throughout this thesis. Source localization from DAS alone was explored but produced unreliable results due to sparse coupling, and is not presented as a deliverable. Finally, cable-wide coherent patterns in the DAS waterfall are treated as background environmental or coupling-related structure rather than direct target detections, motivating the environmental context branch of Section 3.3.

4.4 DAS Activity Map Construction

The DAS activity map provides a compressed, cable-wide summary of energy distribution over time and serves as a processed context artifact for cable-wide activity interpretation. Rather than displaying raw or preprocessed DAS amplitudes directly, the activity map summarizes each channel through a normalized rolling root-mean-square (RMS) energy estimate. This is necessary because the inter-channel sensitivity differences established in Section 4.3 would otherwise dominate the visualization and obscure relative temporal structure along most of the cable.

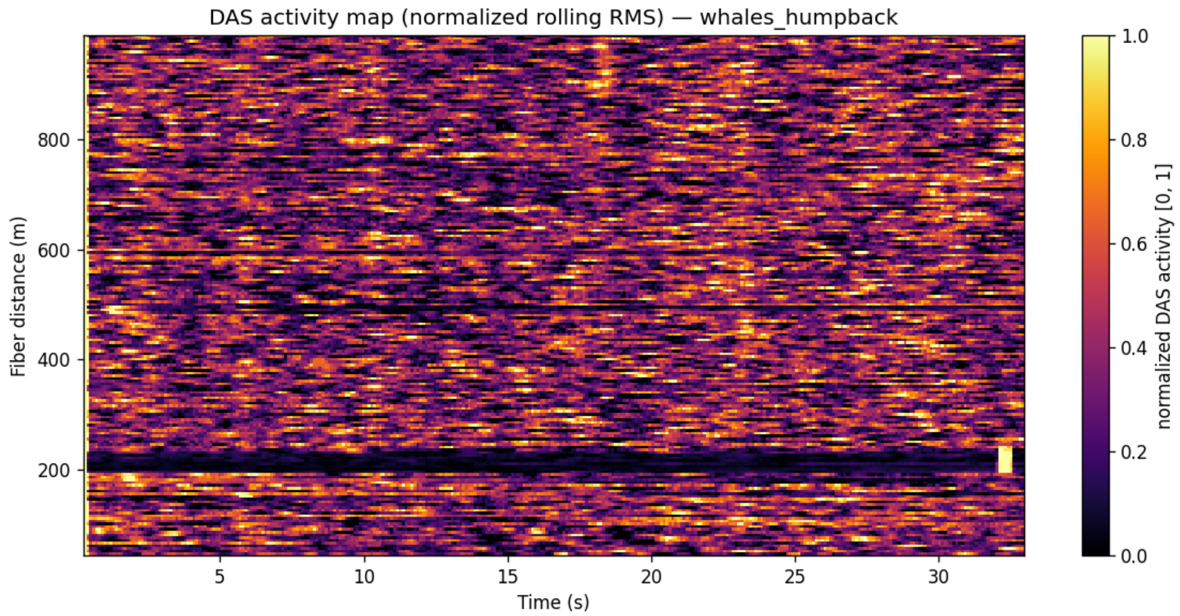

Figure 4-5 DAS activity map for the Humpback shot, computed as normalized rolling RMS activity.

Rolling RMS computation.

For each channel in the preprocessed preview, a short-time RMS energy is computed using a sliding window of 0.5 seconds with a hop size of 0.1 seconds, both configurable via command-line parameters. A naive implementation of a sliding-window sum of squared samples requires $O(N \times W)$ operations, where N is the number of time samples and W is the window length in samples, and becomes increasingly inefficient for long recordings with many channels. The implemented method instead uses a cumulative-sum strategy: the running sum of squared samples is computed once as a prefix-sum array, and the squared sum within each window is then recovered as the difference of two prefix-sum values in constant time. This reduces the total complexity to $O(N)$ per channel regardless of window length and avoids the need to maintain an explicit sliding buffer. The resulting RMS activity array is indexed by window-center times, stored as t_windows_s in the output artifact.

Per-channel percentile normalization.

After rolling RMS computation, each channel's energy trace is normalized independently to the range [0, 1] using a robust percentile mapping. The 5th and 99th percentiles of the channel's RMS values are used as lower and upper normalization bounds, so that the full color scale reflects the dynamic range of that channel's own activity rather than a global amplitude scale. This per-channel normalization is essential given the inter-channel sensitivity variation documented in Section 4.3: without it, the relatively few high-coupling channels would saturate the color scale, while the majority of the array would appear uniformly dark. Channels whose normalization range collapses to near zero are handled with a fallback denominator to prevent numerical instability.

Output.

The normalized activity map is stored as das_activity_map.npz, containing the two-dimensional activity array of shape (time windows × channels), the window-center time vector t_windows_s, the channel index array, and the along-cable distance vector. This compact representation is exported as a processed DAS activity context artifact and is also reused by downstream channel-level diagnostics and selected-channel ranking logic, where elevated mean activity is useful.

The activity map should be interpreted as a coarse spatial and temporal context layer rather than as a precise event detector. Because each channel is normalized independently, cross-channel amplitude comparisons are not physically reliable, and the 0.5-second window smooths over fine temporal structure. Its value lies in providing an overview of where along the cable and when within the recording elevated activity is present, before the analyst proceeds to selected-channel inspection for more detailed interpretation.

In the current static frontend, das_activity_map.npz is not the rendered DAS waterfall panel; the displayed waterfall is loaded from das_waterfall_preview.npz, described in Section 4.5.

4.5 Raw DAS Waterfall Preview Export

The static frontend displays the DAS waterfall panel using das_waterfall_preview.npz, generated by src/export_das_waterfall_preview.py. This artifact is intentionally different from the preprocessed preview and the activity map: it preserves raw DAS amplitude structure for visual inspection rather than applying median removal, band-pass filtering, MAD normalization, or event detection.

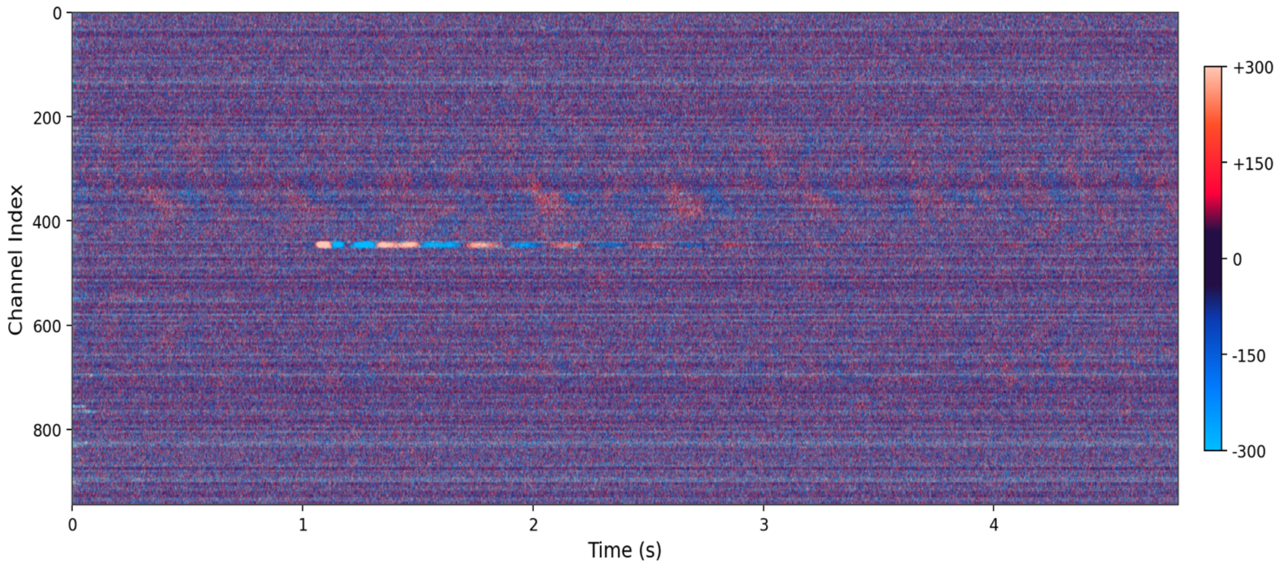

Figure 4-6 Raw DAS waterfall preview for the Humpback shot, generated from das_waterfall_preview.npz.

The exporter reads a compact contiguous time window from the native 5 kHz DAS dataset and stores the waterfall data together with time, channel, and along-cable distance axes. The standalone script can export up to 30,000 raw samples by default, while the full viewer build uses time and channel downsampling to keep the artifact browser-sized. The exported values remain native DAS counts unless amplitude scaling is explicitly requested; robust color clipping is applied only during frontend rendering.

This waterfall view is the main DAS panel rendered in the static viewer. It is used to inspect broad cable-wide structure and coherent patterns, while the activity map remains a processed rolling-RMS context artifact, and the selected-channel panels provide detailed waveform, spectrogram, and band-pass support inspection.

4.6 Orca Band-Pass Envelope Analysis

The clearest orca-related DAS support examined in this project was found in high-frequency bands close to the DAS Nyquist limit, especially around 2.0–2.5 kHz. This lies above the Nyquist limit of any downsampled preview representation. This stage therefore operates directly on native-rate (5 kHz) DAS data read from the HDF5 file, processing channels individually to keep memory usage bounded.

Band-pass filtering and envelope extraction. For each selected channel, the native-rate signal is band-pass filtered using a zero-phase Butterworth filter (sosfiltfilt) in two bands evaluated separately: 2000–2350 Hz and 2200–2450 Hz. The analytic signal is computed via the Hilbert transform, and its magnitude is taken as the instantaneous amplitude envelope. A short rolling RMS window of 40 ms smooths the envelope into a band-limited support score.

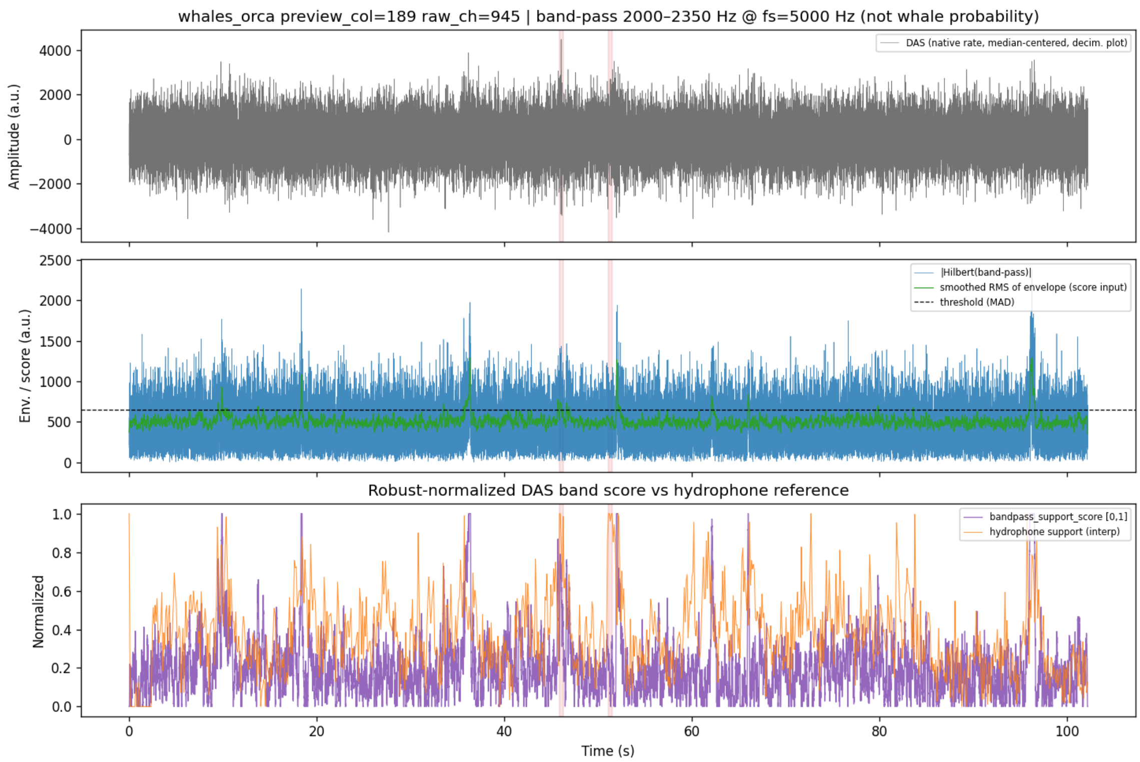

Figure 4-7 Orca band-pass diagnostic for preview column 189 / raw DAS channel 945 in the 2000–2350 Hz band.

MAD-based thresholding. The smoothed envelope score is thresholded using the MAD-based formulation described in Section 2.5, with k = 3 by default. Time points exceeding the threshold are marked in signal_present_mask. This mask is used as a descriptive DAS support indicator only; it is not treated as whale probability or as a validated detector output.

Event contrast and channel selection. For Orca diagnostics, a simple event-versus-background contrast score is computed by comparing the mean band-pass support score inside hydrophone-marked event intervals with the mean score outside nearby guarded windows. This score is used as a heuristic ranking aid, not as biological validation. Additional channel-selection logic combines activity-map summaries, hydrophone-score correlation, event-window energy, and waveform contrast to identify useful selected-channel candidates for the viewer. Together with external NCC-based evidence in the 2000–2490 Hz band, these diagnostics support the conclusion that the Orca-related DAS response is sparse and channel-localized, with a primary neighborhood around channels 859–862 and a secondary zone around channels 908–925.

5 Interactive Viewer Architecture

5.1 Design Philosophy

The visualization system is organized around two guiding principles: a structured progression from overview to detail following established information-visualization theory, and transparency in which all processing choices are externalized as inspectable metadata.

The primary principle is Shneiderman’s visual information-seeking mantra: overview first, zoom and filter, then details on demand (Shneiderman, 1996). The map panel implements the overview level, presenting the spatial deployment context before any signal is examined. The DAS waterfall implements the intermediate level, exposing a compact cable-wide temporal preview of the recording so the analyst can identify regions of interest. The selected-channel panel implements details on demand, providing waveform, spectrogram, and band-pass support score for a chosen DAS channel.

This hierarchy is not merely structural. It reflects the epistemological workflow required for a dataset where signal-bearing channels are sparse and a substantial fraction of DAS patterns reflects environmental rather than acoustic processes. Beginning at the detail level without spatial and temporal context provides no principled basis for channel selection and no reliable way to distinguish localized acoustic response from cable-wide environmental coherence.

The second principle is transparency. Filter cutoffs, normalization settings, MAD threshold multipliers, window lengths, and ranking heuristics are all recorded in metadata JSON companions alongside their respective artifacts. The pipeline can be rebuilt from raw HDF5 inputs using a single script. In addition, every artifact can be traced back to the parameters and source files that produced it, ensuring both reproducibility and interpretive clarity.

5.2 System Architecture

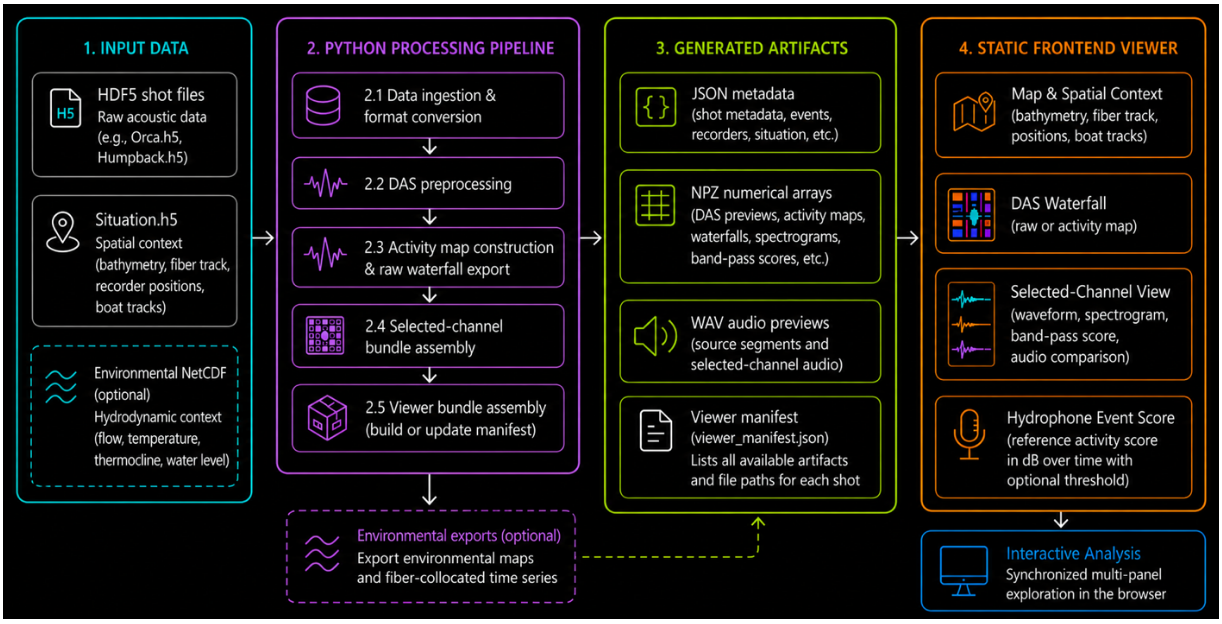

Figure 5-1 Static viewer system architecture, from raw HDF5 and optional environmental NetCDF inputs to generated JSON/NPZ/WAV artifacts and browser-based visualization.

The viewer is implemented as a static web application built from plain HTML, CSS, and JavaScript, loading precomputed artifacts via a lightweight local or static HTTP server. This was an explicit design decision reflecting the offline, analysis-first character of the project.

All computationally intensive processing is performed in advance by the Python pipeline. This includes filtering, normalization, spectrogram computation, and selected-channel ranking heuristics. The viewer is responsible only for loading, synchronizing, and rendering precomputed results, with no heavy runtime signal processing or server-side persistent user state. A dynamic backend would add architectural complexity without providing analytical benefit. The static approach also improves deployability: the viewer requires no Node.js, npm, or backend runtime, and can be launched after a single-command pipeline rebuild without additional setup. This aligns with the transparency principle described in Section 5.1. Every visualization element traces directly to a concrete artifact file on disk.

Asset resolution. Because available artifacts vary depending on which pipeline stages have been run, the frontend probes a prioritized list of candidate paths for each required resource, falling back gracefully when artifacts are absent. This logic is instrumented with browser-console logging for straightforward diagnosis during development.

Data formats. HDF5 is not suitable for direct browser consumption due to size and lack of native support. The pipeline exports two browser-oriented formats: JSON for structured metadata and small numeric arrays, and NPZ for larger numerical artifacts such as DAS waterfall previews, activity-map artifacts, and selected-channel data, where binary compression substantially reduces transfer size.

Viewer manifest. Each shot's artifact set is indexed by viewer_manifest.json, which enumerates asset paths and shot-level metadata such as available time ranges and selected-channel configuration. The manifest is the primary contract between the backend pipeline and the frontend, decoupling the viewer from the pipeline's internal directory structure and making it straightforward to add new artifact types without restructuring the viewer.

5.3 Panel Descriptions

The viewer interface is organized into four coordinated panels corresponding to the overview-to-detail hierarchy of Section 5.1. No single panel provides sufficient context for analysis; the value of the system lies in its coordinated juxtaposition.

Spatial Map Panel. The map panel provides geographic and geometric deployment context. It renders the bathymetric depth field from Situation.h5 as a spatial background, with the fiber-optic cable track shown as a continuous orangered line serving as the spatial reference for all channel-indexed DAS data. Recorder positions are marked as labeled point symbols, the acoustic source position is displayed when available from shot_metadata.json, and boat tracks are rendered as auxiliary polylines for operational context. Together these layers constitute the spatial overview level.

Figure 5-2 Spatial context panel of the interactive viewer showing bathymetry, fiber trajectory, recorder positions, boat tracks, source location, and selected DAS channel.

DAS Waterfall Panel. The waterfall panel renders all 946 DAS channels simultaneously on a time × channel canvas, with color encoding raw amplitude in native DAS counts without per-channel normalization. Robust clipping is applied during rendering to make the bulk of the amplitude structure visible despite heavy-tailed distributions, preserving physical amplitude relationships between channels and making cable-wide coherent patterns and inter-channel contrasts directly visible. The panel loads das_waterfall_preview.npz when present, falling back to das_preprocessed_preview.npz otherwise. The waterfall is explicitly positioned as a context and orientation layer rather than an event detector.

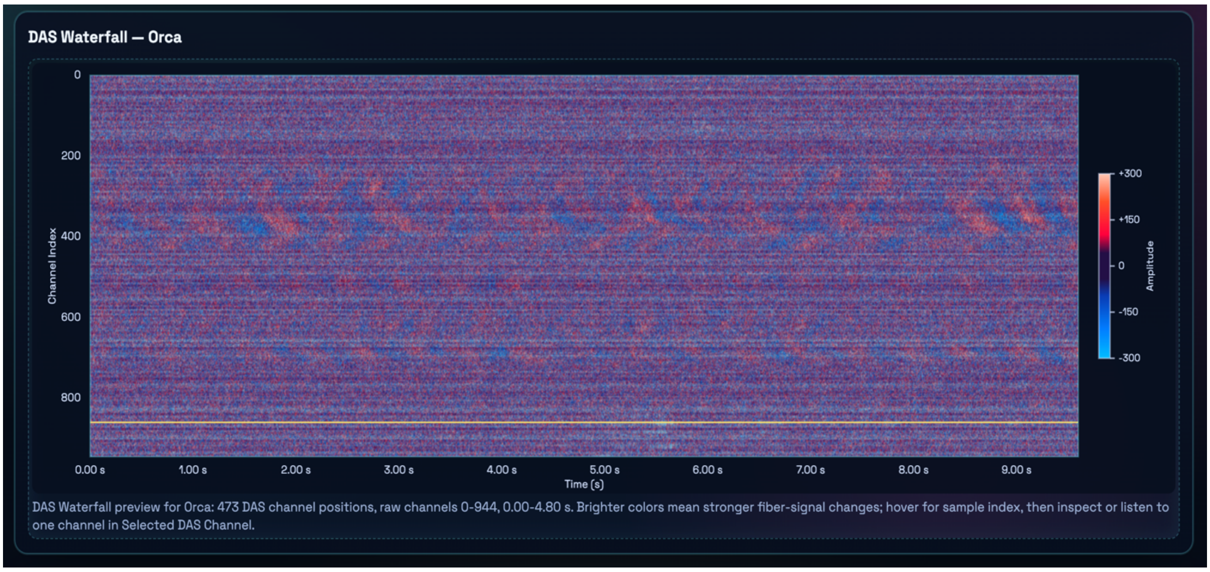

Figure 5-3 DAS waterfall panel showing the exported raw DAS waterfall preview as a time × channel overview layer.

Selected-Channel Panel. The selected-channel panel is the primary interpretive view, implementing the details-on-demand level. For a user-selected exported DAS channel, it provides three coordinated subviews: a time-domain waveform, a STFT spectrogram with robust percentile-based intensity scaling, and an optional band-limited energy trace for orca-oriented inspection. For both whale shots, a source-versus-DAS audio comparison block is available, allowing the broadcast source segment and the DAS-derived playback signal to be played side by side in the browser for qualitative assessment of temporal structure preservation.

Figure 5-4 Selected-channel inspection panel showing waveform, spectrogram, band-pass score, and source-versus-DAS audio comparison for a selected Orca DAS channel.

Hydrophone Support Panel. The hydrophone support panel renders a continuous reference activity score derived from the hydrophone/source recording. It is shown as a passive timing reference rather than as an interactive control panel. The trace helps identify acoustically elevated intervals in the reference signal, but it does not drive navigation or selection in the other panels. Interpretation of whether these intervals have a corresponding DAS expression is performed through the DAS waterfall and selected-channel views.

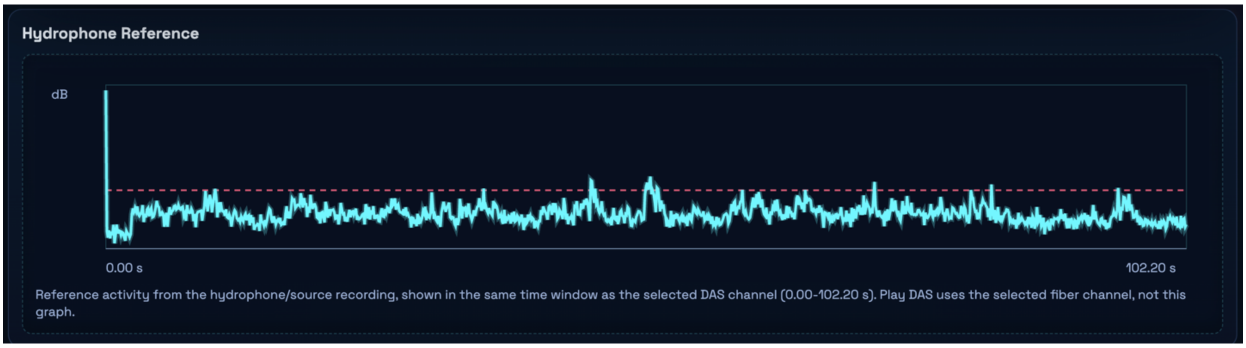

Figure 5-5 Hydrophone reference panel showing the continuous support score used for timing comparison with DAS views.

5.4 Synchronization and Interaction

The viewer maintains a coordinated interaction state for shot selection, map-based channel selection, and selected-channel inspection. Rather than propagating a single global time cursor across all panels, the interface links the spatial overview to detailed DAS channel views while keeping time inspection local to the selected-channel panel.

Map click and channel snapping. For shots with multi-channel exports (whales_orca and whales_humpback), clicking near the fiber track computes the nearest exported channel by along-cable distance and updates the selected-channel panel accordingly. This closes the loop between spatial overview and detail view: a cable region identified as spatially interesting on the map can be selected directly without navigating a channel index list. The snapping logic uses fiber geometry from situation.json and distance metadata from selected_channels_index.json, with graceful fallback when the click is too far from the fiber or when no exported selected-channel data are available.

Selected-channel time cursor. Time interaction is handled locally within the selected-channel panel. Pointer interactions on the selected-channel spectrogram, band-pass score, or waveform update the selected-channel cursor, and the audio scrubber uses the same cursor during DAS playback. This cursor is used for detailed inspection of the selected channel rather than as a global navigation state for the entire viewer.

Reference and context views. The hydrophone panel is rendered as a passive reference activity trace over the selected-channel time window. It supports timing comparison with the selected DAS channel, but it does not drive navigation or selection in the other panels. The DAS waterfall provides a compact raw amplitude overview for orientation, while the map supports spatial navigation and channel selection. Together, these interactions provide coordinated interpretation without implying full synchronized multi-view playback.

5.5 Viewer Bundle Assembly

The viewer bundle assembly stage connects the outputs of all preceding pipeline stages into a coherent, manifest-driven package that the static frontend can load without further configuration. It relies on several assembly and validation scripts that together implement the reproducibility guarantee described in Section 5.1: given access to the raw HDF5 input files, the complete artifact set can be rebuilt and validated from a single command.

build_viewer_bundle.py assembles the per-shot viewer_manifest.json file that serves as the central contract between the backend pipeline and the frontend. The script iterates over the expected artifact locations for a given shot, verifies that each file exists, and records its relative path in the manifest under a standardized key. Optional shot-level artifacts, such as selected-channel and source audio comparison files, are included in the manifest when present and omitted when absent, allowing the frontend to degrade gracefully to a reduced feature set without error. The script also writes a global viewer_index.json that enumerates all available shots and their readiness status, which the frontend uses to populate the shot selector on initial load.

build_selected_channel_bundle.py generates the per-column NPZ exports consumed by the selected-channel panel. For each configured preview column, the script reads the corresponding native-rate DAS channel from the HDF5 file, applies the shot-appropriate preprocessing and band-pass filtering, computes the STFT spectrogram and band-pass support score, and writes the results to three NPZ files: selected_channel_p*_signal.npz, selected_channel_p*_spectrogram.npz, and selected_channel_p*_bandpass_score.npz. A selected_channels_index.json file is written alongside these exports, recording the default preview column, the raw DAS channel index, the along-cable distance, and the recommended band-pass band for each exported column. For both whale shots, the script additionally exports a source reference WAV segment and an audio comparison JSON, enabling the source-versus-DAS playback feature of the selected-channel panel. After completing all exports, the script patches the existing viewer_manifest.json to add the selected-channel references, so that manifest assembly and selected-channel export can be run in either order without producing an inconsistent manifest state.

check_viewer_ready.py validates the complete artifact set for the supported whale shots by checking the expected output files, inspecting key NPZ arrays, and reporting summary fields such as DAS waterfall shape, activity-map shape, hydrophone score range, and time overlap. It reports whether each required artifact group is present and whether the shot is viewer-ready. When run with the JSON option, its output can also be written to a compact readiness report for documentation or deployment checks.

build_viewer_all.sh is the single-command orchestration script that runs the complete pipeline from raw HDF5 inputs to a validated viewer-ready artifact set. It invokes the ingestion, DAS preprocessing, activity map construction, waterfall export, selected-channel bundle assembly, and viewer bundle assembly stages in dependency order, passing configured parameters to each stage and halting on any non-zero exit code. Running this script with access to the raw data files reproduces the complete output directory from scratch, fulfilling the reproducibility requirement articulated in Section 4.1.

6 Results and Discussion

6.1 Pipeline Reproducibility

The analysis pipeline was designed for full reproducibility: every processing stage is an independent command-line module, every output artifact is accompanied by a metadata companion JSON, and the complete artifact set can be rebuilt from raw HDF5 inputs via a single orchestration script. Full pipeline rebuilds were performed for both primary shots, confirming stable artifact generation and consistency between the recorded metadata parameters and the values documented in this thesis.

6.2 DAS Coupling Asymmetry: Orca vs. Humpback

The most substantive empirical finding of this project is the pronounced asymmetry in DAS response between the orca and humpback playback shots. Both shots use the same fiber-optic cable, the same interrogation unit, the same preprocessing pipeline, and a source position in the same general region of the lake. The qualitative difference in DAS response is therefore unlikely to be explained by system configuration or preprocessing choices alone, and is interpreted here as reflecting differences in how each source type couples into the fiber-optic DAS measurement.

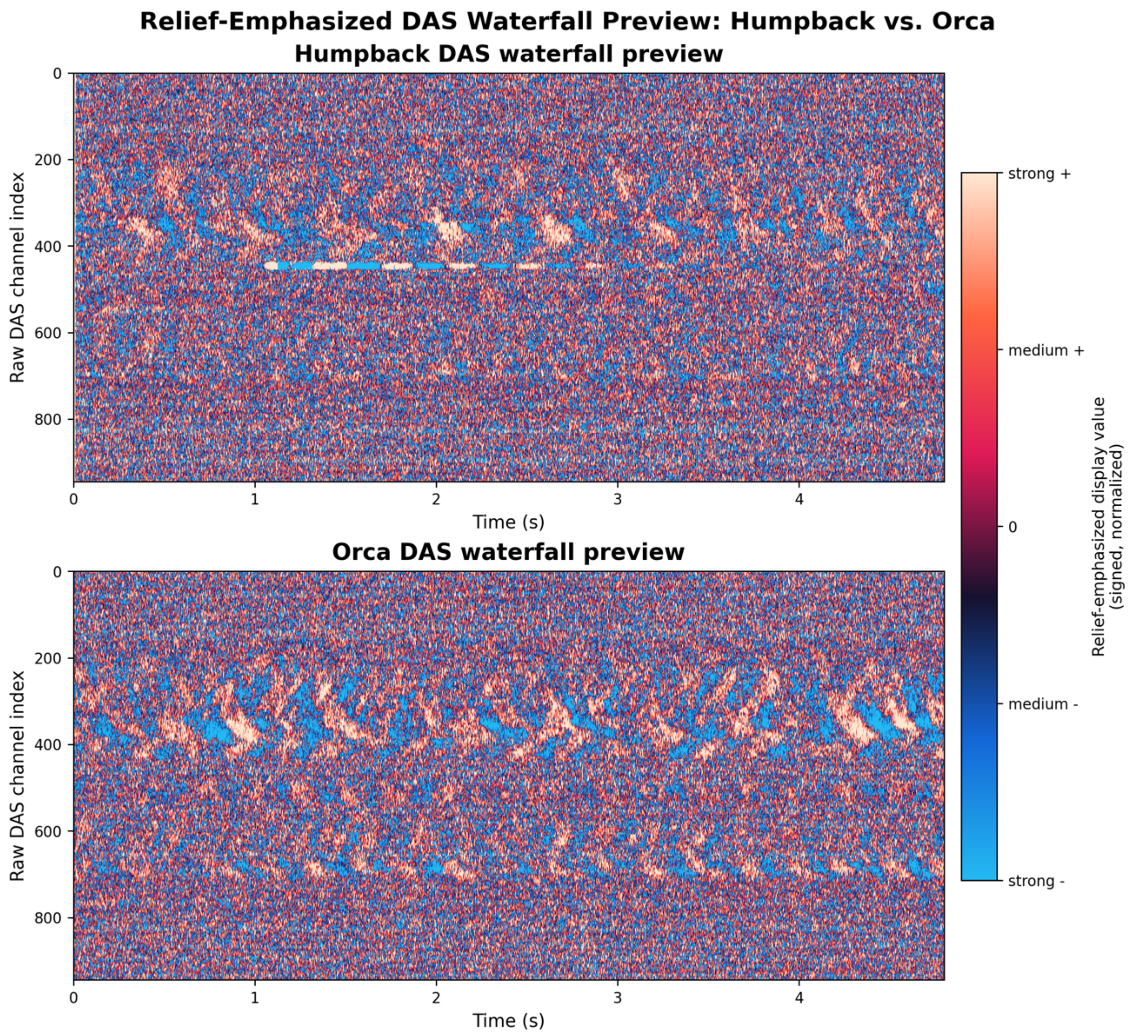

Figure 6-1 Relief-emphasized raw DAS waterfall previews for the Humpback and Orca shots, generated from das_waterfall_preview.npz using display-only smoothing and contrast enhancement to make coherent cable-wide structures more visible.

Orca response. The orca vocalization recording spans a broad frequency range, and the project analyses its high-frequency DAS support using 2000–2350 Hz and 2200–2450 Hz band-pass diagnostics, together with an external 2000–2490 Hz NCC summary. In that NCC summary, the DAS cable exhibits the clearest localized support in two spatial neighborhoods: a primary hotspot around raw channels 859–862 and a secondary zone around channels 908–925. Within these neighborhoods, the band-pass envelope analysis of Section 4.6 reveals elevated energy during candidate time windows, a contrast ratio above background inconsistent with random noise fluctuation, and temporal structure that partially tracks the modulation of the source signal. The normalized cross-correlation analysis supports this spatially localized interpretation: channels outside the identified neighborhoods show no consistent relationship with the hydrophone reference. While the original dataset documentation notes non-uniform channel sensitivity, the present analysis shows that bioacoustically interpretable DAS response is not merely weaker on some channels but effectively absent across most of the 946-channel array. This degree of sparsity has direct practical consequences for analysis strategy.

Humpback response. The humpback vocalization recording is concentrated in the low-frequency range below approximately 1 kHz. The DAS response is weaker in absolute amplitude, more spatially diffuse, less temporally consistent with the hydrophone reference, and does not produce a clear spatial hotspot under the channel ranking procedure of Section 4.6. This asymmetry is most plausibly explained by the frequency dependence of DAS coupling efficiency: at lower frequencies, the acoustic wavelength in water exceeds the DAS gauge length, reducing the strain induced per unit of acoustic pressure, while low-frequency environmental noise constitutes a larger fraction of the total DAS signal. The weaker humpback response is therefore a physically motivated consequence of source characteristics and coupling geometry, not a pipeline failure.

Implication for visualization design. The coupling asymmetry between orca and humpback validates the multi-level design approach of this thesis. A system displaying only cable-wide metrics would not surface the orca hotspot structure and would present both shots as similarly uninformative. The fact that the same pipeline produces qualitatively different and physically interpretable results for two source types provides evidence that the system correctly reflects the underlying data rather than imposing analytical artifacts.

6.3 Environmental and Non-Whale Structure

Not all structure visible in the DAS waterfall corresponds to the broadcast acoustic source. A recurring observation across both shots is the presence of cable-wide coherent patterns, namely slowly varying features that span many channels simultaneously and persist over time scales longer than individual whale vocalizations. These patterns are inconsistent with a localized acoustic point source and are more consistent with hydrodynamic excitation of the cable, slow mechanical drift in fiber coupling, or large-scale environmental processes affecting many channels simultaneously.

Several channels exhibit consistently low DAS amplitude throughout both recordings regardless of source activity. This persistent spatial structure is consistent with the coupling variability mechanism described in Section 2.1: channels where the cable makes poor mechanical contact with the lakebed, or where fiber geometry is unfavorable relative to the dominant wave propagation direction, show suppressed response regardless of source activity.

The environmental context branch described in Section 3.3 was incorporated to provide potential explanatory variables for these non-whale patterns. Delft3D-FLOW model output, including temperature profiles, thermocline depth, and horizontal flow, characterizes the physical state of the lake during the experiment and provides a visual inspection interface through which cable-wide DAS patterns can be qualitatively related to hydrodynamic conditions. This points toward a broader interpretive framing: the DASLakeZurich cable is not a passive receiver in a quiet medium but an active mechanical element in a dynamically evolving lake environment, and disentangling acoustic, hydrodynamic, and deployment-geometry contributions is a prerequisite for reliable bioacoustic interpretation.

6.4 Comparison with Existing Tools

The feature comparison introduced in Section 2.3 is expanded here into a full evaluation matrix including f-k filtering support and metadata provenance granularity.

Table 1 Comparison of existing DAS software tools with the present work.

Dimension	DASPy	DASCore	DAS4Whales	This work
Interactive viewer	—	—	—	✓
Multi-modal sync	—	—	—	✓
Selected-channel inspection	—	—	partial	✓
Map integration	—	—	—	✓
Hydrophone support	—	—	—	✓
Metadata provenance	partial	✓	—	✓
f-k filtering	✓	partial	✓	—

DASPy and DASCore address backend signal processing and data management respectively, without the synchronized multi-modal exploration capabilities targeted here. DAS4Whales is the closest in scientific motivation but limited to signal processing primitives without a synchronized viewer or hydrophone integration. A notable capability present in existing DAS processing toolkits but not implemented in the present viewer pipeline is f-k filtering, which separates wavefields by apparent propagation velocity in the frequency-wavenumber domain and would be a natural preprocessing addition in future work. The artifact-level metadata provenance rating reflects the artifact-level companion JSON approach of the present system. This approach records not only applied parameters but also input file paths, time alignment decisions, and interpretive notes, thereby going beyond the parameter-level logging available in DASPy and DASCore.

6.5 Limitations and future work

The most fundamental limitation is imposed by the dataset itself. DAS coupling in the Lake Zurich deployment is too sparse and sensitivity-limited for reliable automated detection or source localization, and localization attempts produced unreliable results as noted in Section 4.3. Extending the system toward a detection pipeline would require better cable-sediment coupling, a higher-sensitivity interrogation unit, or a more favorable source geometry. These hardware decisions fall outside the scope of this thesis but constitute the natural next step for the underlying scientific programme.

The physical mechanism behind coupling variability remains an open question. The fact that the strongest orca-frequency response is concentrated around channels 859–862 rather than being distributed across the full array may reflect local sediment type, cable burial depth, jacket stiffness, or fiber orientation. However, characterizing these effects would require meter-scale ground-truth information about the cable deployment geometry that is not available in the public dataset.

The frontend viewer is a functional research prototype sufficient for the exploratory tasks demonstrated in this thesis, but lacks persistent user state, interval export, and a responsive UI layout. These are deliberate scope decisions, and the static architecture of Section 5.2 is well suited to extension without a framework migration.

The environmental context branch remains at an early stage, visualizing Delft3D output in model grid space pending the CRS alignment described in Section 3.3. Once resolved, fiber-collocated environmental time series could enable more systematic comparison between cable-wide DAS structure and modeled hydrodynamic conditions.

Finally, machine learning was deliberately excluded: the dataset is small, ground-truth labels are limited to controlled playback intervals, and the primary goal was understanding data through visualization. A natural future direction would be to use the candidate intervals and channel rankings produced by the present pipeline as weak supervision signals for a lightweight detector.

References

- Hartog, A. H. (2017). *An Introduction to Distributed Optical Fibre Sensors*. CRC Press.

- Parker, T., Shatalin, S., & Farhadiroushan, M. (2014). Distributed acoustic sensing — a new tool for seismic applications. *First Break*, 32(2), 61–69.

- Lindsey, N. J., et al. (2020). Fiber-optic seismology. *Annual Review of Earth and Planetary Sciences*, 48, 309–336.

- Sladen, A., et al. (2019). Distributed sensing of earthquakes and ocean-solid Earth interactions on seafloor telecom cables. *Nature Communications*, 10(1), 5777.

- Williams, E. F., et al. (2019). Distributed sensing of microseisms and teleseisms with submarine dark fibers. *Nature Communications*, 10, 5778.

- Bouffaut, L., Taweesintananon, K., Kriesell, H. J., Rørstadbotnen, R. A., Potter, J. R., Landrø, M., Johansen, S. E., Brenne, J. K., Haukanes, A., Schjelderup, O., & Storheim, F. (2022). Eavesdropping at the speed of light: Distributed acoustic sensing of baleen whales in the Arctic. *Frontiers in Marine Science*, 9, 901348.

- Lior, I., et al. (2021). On the detection capabilities of underwater distributed acoustic sensing. *Journal of Geophysical Research: Solid Earth*, 126(3), e2020JB021073.

- Hu, M., & Li, Z. (2024). DASPy: A Python toolbox for DAS seismology. *Seismological Research Letters*, 95(5), 3055–3066.

- Chambers, D., Jin, G., Tourei, A., et al. (2024). DASCore: a Python library for distributed fiber optic sensing. Seismica, https://doi.org/10.26443/seismica.v3i2.1184

- DAS4Whales (2023). Open-source toolkit for DAS bioacoustic analysis. GitHub. https://github.com/DAS4Whales/DAS4Whales (accessed May 2026).

- Shneiderman, B. (1996). The eyes have it: A task by data type taxonomy for information visualizations. *IEEE Symposium on Visual Languages*, 336–343.

- Roberts, J. C. (2007). State of the art: Coordinated & multiple views in exploratory visualization. *CMV '07*, 61–71.

- Munzner, T. (2014). *Visualization Analysis and Design*. CRC Press.

- Rousseeuw, P. J., & Croux, C. (1993). Alternatives to the median absolute deviation. *Journal of the American Statistical Association*, 88(424), 1273–1283.

- Stowell, D. (2022). Computational bioacoustics with deep learning: a review and roadmap. *PeerJ*, 10, e13152.

- Rychen, J., Paitz, P., Edme, P., Smolinski, K., Brackenhoff, J., & Fichtner, A. (2023). Test experiments with distributed acoustic sensing and hydrophone arrays for locating underwater sound sources [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.7886409

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