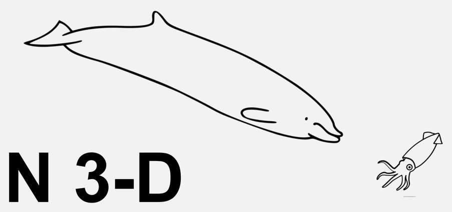
PASSIVE ACOUSTIC TRACKING OF WHALES IN 3-D



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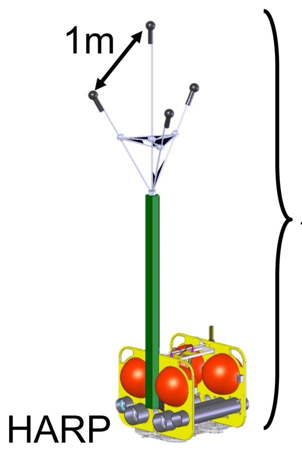
Project Overview

Project Objective: In this project, we propose *a data processing chain that can detect and track multiple whales in 3-D* from passively recorded underwater acoustic signals using volumetric hydrophone arrays.

Motivation: Passive Acoustic Monitoring is a non-intrusive method to study species of whales (e.g., beaked whales) that are hard to observe visually **[1]**. However, automating acoustic data processing remains a challenge as *human operators are often required for manual data annotation*.

Data: Two High-frequency Acoustic Recording Packages (HARPs) that were approximately 1km apart were used to collect the data **[2].**

- Array with 4 hydrophones (1m aperture)
- Sampling Frequency: 100kHz



One of the objectives of this deployment is to study the impact of sonar on the behaviors of the Cuvier's beaked whales in the region.

Beaked Whales

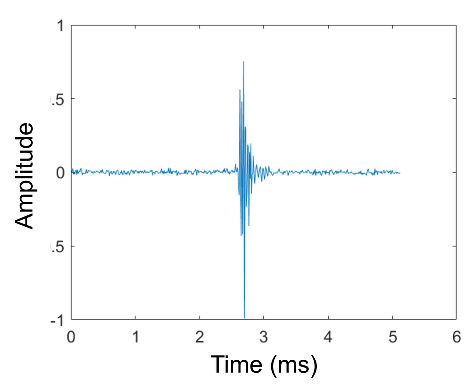
They are deep divers among the species of whales. Their echolocation clicks (shown below) are used to navigate and find prey underwater and characterized by their short pulse length (i.e., large bandwidth) **[1].**

Cuvier's Beaked Whales*
Ziphius cavirostris

Echolocation Click of a Cuvier's Beaked Whale

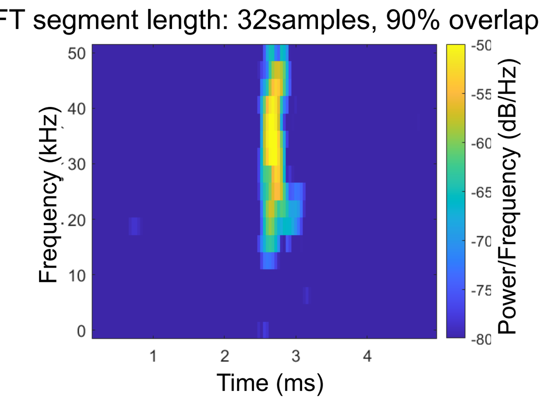
Odontocetes (toothed whales) transmit echolocation clicks (acoustic pulses) for self-localization, underwater-mapping, and prey-tracking

Time Series



Spectrogram

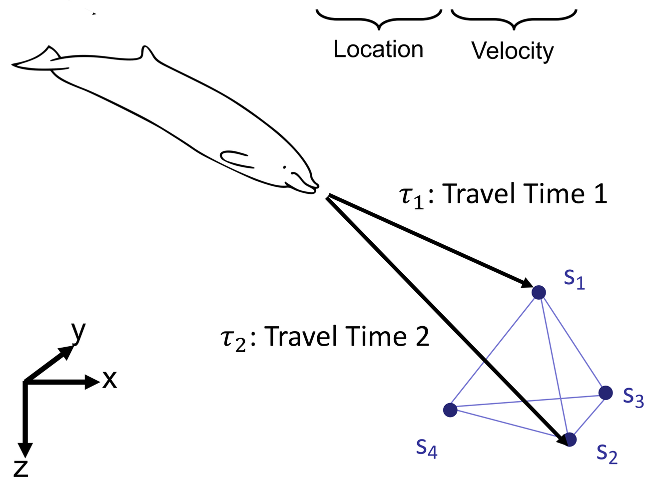
FFT segment length: 32samples, 90% overlap



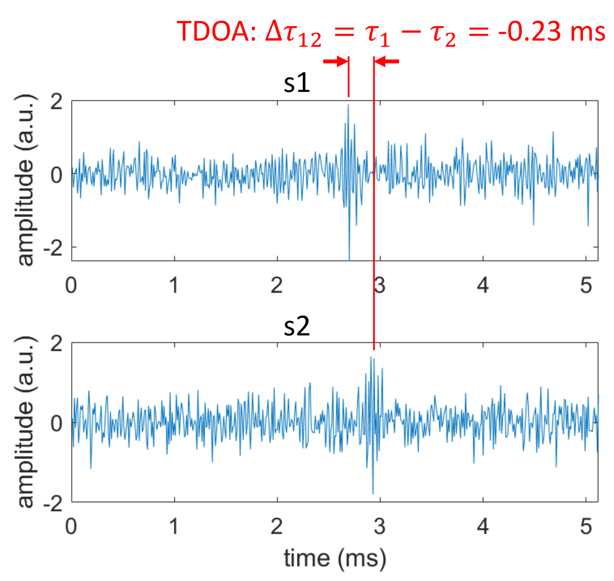
Whale State and Time-Difference-of-Arrival (TDOA) Measurements

Define the whale's state at time n as $\boldsymbol{x_n}$, a six-dimensional (6-D) vector with the whale's location and velocity in the 3-D Cartesian coordinates.**

Whale State: $\boldsymbol{x_n} = [x_n, y_n, z_n, \dot{x}_n, \dot{y}_n, \dot{z}_n]$ (Location, Velocity)



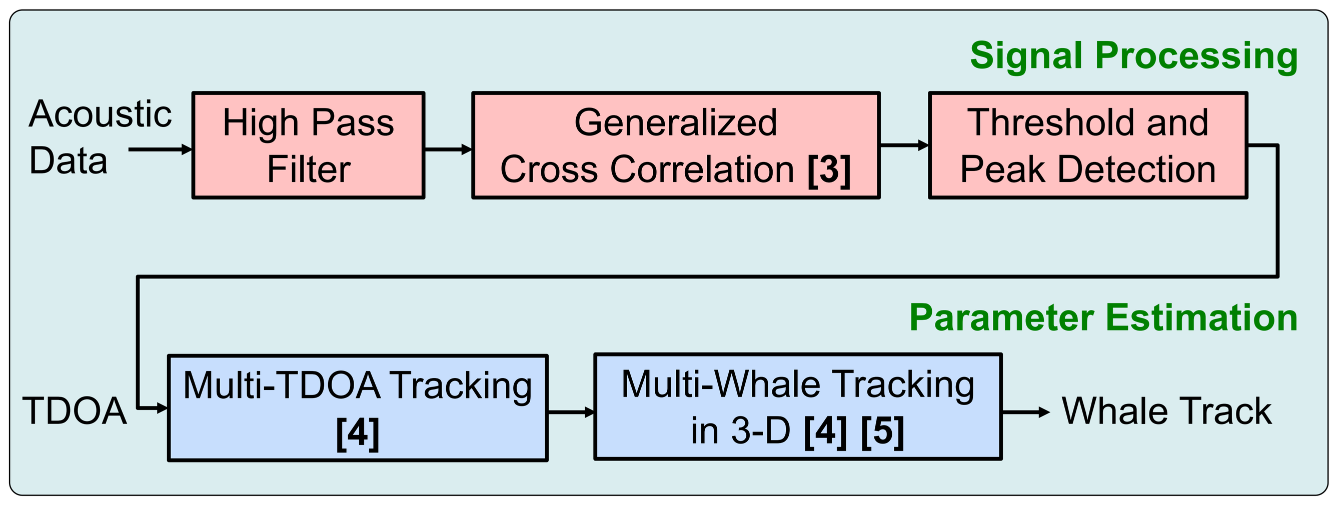
Measurements (TDOA): $\boldsymbol{y_n} = [y_1, y_2, y_3, y_4, y_5, y_6]$



The TDOA of the received signals between two sensors provides information on the potential locations of the whale and the presence of the echolocation click signals.

* Cuvier's beaked whale images by *Whaleipedia*
** Beaked whale diagram by *Chris Huh*

Proposed Data Processing Chain

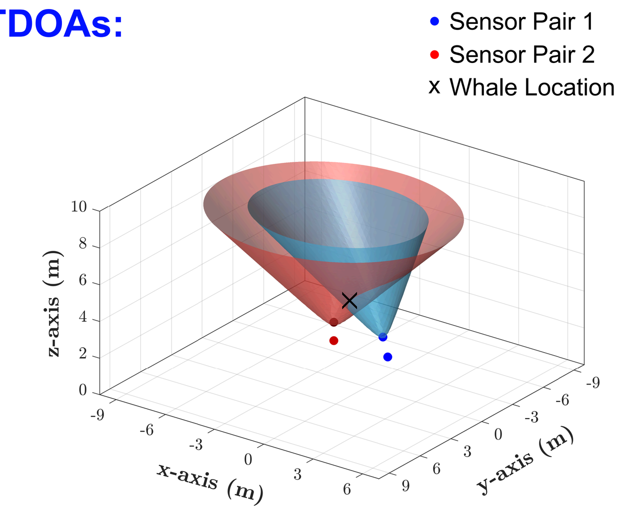


Signal Processing:

- Two arrays that consist of 4 hydrophones are considered.
- Extract a set of TDOA measurements for each pair of hydrophones on an array (12 sets of measurements total).
- Implement a generalized cross-correlation **[3]** algorithm that whitens the instrument noise specific to HARP to improve the detection rate.

3-D Tracking from Passive Acoustic TDOAs: Challenges

- A whale's state is 6-D. The *curse of dimensionality* makes grid-based approaches unfeasible.
- The 3-D TDOA measurement model requires the *fusion of hyperboloids.*
- *False TDOAs and missed detections impose a data association problem.*
- *The number of whales that are present is unknown.*



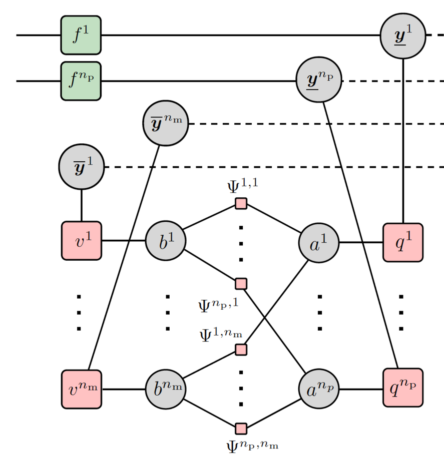
Each TDOA measurement gives rise to a hyperboloid. The resulting intersection of the two hyperboloids describes potential whale locations.

Particle-based Parameter Estimation: Particles and corresponding weights represent the posterior probability density function (pdf) of the state of interest. Two stages of graph-based multi-target tracking (MTT) based on the sum-product algorithm **[6]** are applied to address the aforementioned challenges:

- **Multi-TDOA Tracking [4]:** Estimate TDOA tracks; MTT in the TDOA domain rejects false TDOAs and closes gaps of missed detections.
- **Multi-Whale Tracking in 3-D [4][5]**: Estimate whale tracks in 3-D; MTT with *embedded particle flow* **[7][8]** can perform state estimation in 6-D despite the highly nonlinear measurement model.

Graph-Based Multi-Target Tracking (MTT)

Data association and track management are solved efficiently by representing the MTT model with a factor graph and using a sum-product algorithm for parameter estimation.



Factor graph representation of MTT

- $\underline{\boldsymbol{y}}^j\ \bar{\boldsymbol{y}}^j$ Augmented state of a "legacy" and "newborn" target, respectively
- f^j State-transition process of target j
- $v^j\ q^j$ Measurement model of "newborn" and "legacy" targets, respectively
- $\Psi(a^j, b^m)$ Association constrain between measurement m and target j

The SPA enables efficient computation of marginal posterior pdfs, i.e.,

$$f(\boldsymbol{x}_i|\boldsymbol{z}) = \int f(\boldsymbol{x}|\boldsymbol{z})\,\mathrm{d}\boldsymbol{x}_{\sim i} \quad \text{with} \quad \boldsymbol{x} = [\boldsymbol{x}_1^{\mathrm{T}}\ \boldsymbol{x}_2^{\mathrm{T}} \cdots \boldsymbol{x}_N^{\mathrm{T}}]^{\mathrm{T}}$$

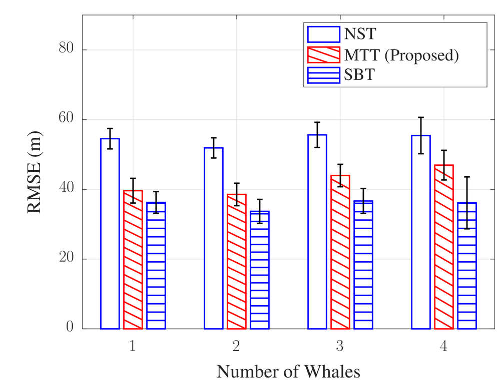
Particle Flow

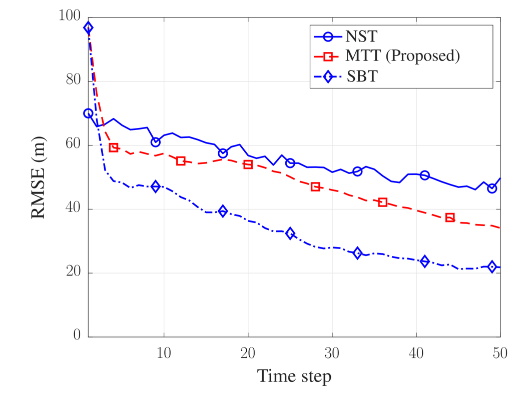
To avoid particle degeneracy, particles are actively "migrated" to regions of high likelihood **[7]**. This migration is performed sequentially and at each time step across pseudo-time steps. Particle motion is described by a partial differential equation. Asymptotically optimal importance sampling is performed by computing particle weights from inverted flow equations **[8]**.

Key Results

Simulation: Comparison of 3-D Tracking Approaches

Four sets of 200 Monte Carlo simulations of odontocete tracks are generated and tracked using three different approaches. Each set of Monte Carlo simulation has an increasing number of simultaneously present odontocetes, ranging from 1 to 4.





Simulate Methods:

- **Nonsequential tracking (NST) [2]** combines the direction of arrivals of the echolocation clicks at each array but does not filter the results.
- **Multi-Target Tracking (MTT) [5]** with embedded particle flow.
- **Single Bernoulli tracking (SBT) [7]** determines the existence and tracks a single target in the presence of missed detections and false positives.

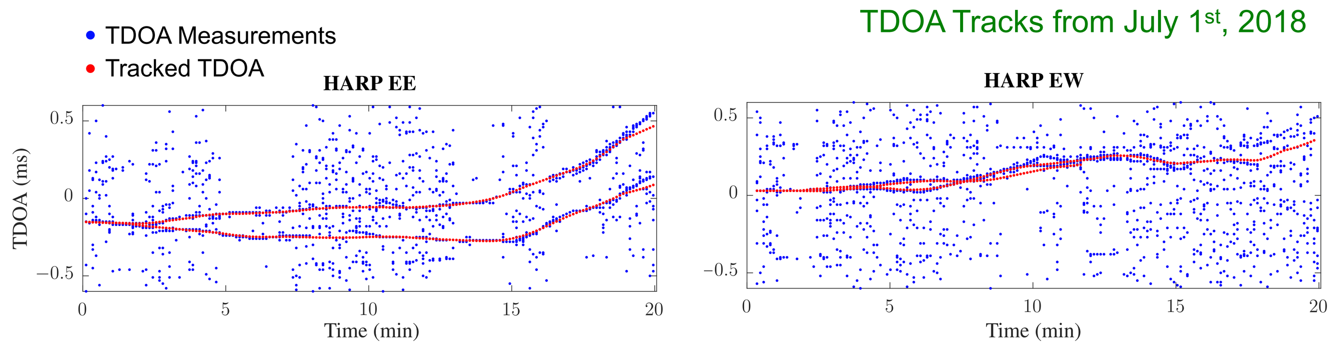
(NST) and (SBT) are provided with the correct data association solution subject to missed detections and are applied to each whale track individually. (MTT) performs data association and track management automatically, i.e., it does neither know the correct data assoc. solution nor the number of whales. ***Despite not knowing the correct data association solution, the proposed MTT method can provide accurate whale tracks.***

Real Data Processing

HARPs are located on the east and the west of the deployment site and are referred to as HARP EE and HARP EW, respectively.

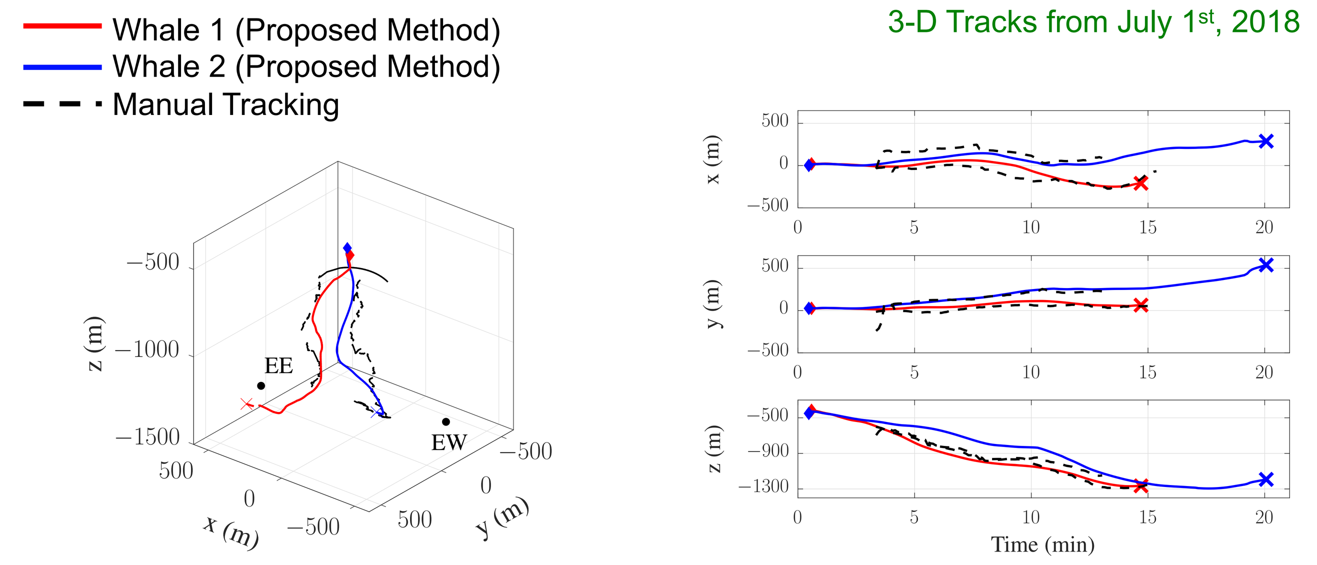
Multi-TDOA Tracking [4]: For each of hydrophone pairs, two whales are successfully tracked in the TDOA domain.

TDOA Tracks from July 1st, 2018



Multi-Whale Tracking in 3-D [4][5]: The TDOA tracks (red dots) from above are used as input for the 3-D tracking stage. ***Our result matches that of manually annotated tracks.***

3-D Tracks from July 1st, 2018



Tracking in 3-D

3-D tracks in their respective dimensions

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