CHAPTER 8

Model-based marine mammal localization methods

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1. Introduction

One of the main objectives of my work over the past 10 years has been to develop and apply passive acoustic methods to localize marine mammals. I've focused most of my work on widely-spaced arrays in which the spacing between elements is large compared to the distance to the animal. Although the literature on acoustic localization is rich (both in the bioacoustics and underwater acoustics communities) and though many of the issues are well-studied and understood, there remain quite a few challenging problems associated with passive acoustic localization of marine mammals. My efforts have been dedicated toward making slow but steady progress in a few interesting directions that hopefully contributed some useful ideas and approaches to the world of passive acoustic monitoring. Where possible, I've applied tracking results to glean information about marine mammal behavior and bioacoustics.

Passive acoustic localization of marine mammals is usually accomplished using arrival times and assuming that sound travels in a straight line between the source and receiver. For widely-spaced arrays, the call from an animal reaches two spatially separated receivers at different times because of differences in path lengths between the source and the receivers. This time difference of arrival, or TDOA, can be used to establish the position of a calling animal. For two hydrophones the TDOA gives a hyperbola as a locus of possible source locations. Multiple hydrophone pairs give multiple hyperbolas which intersect to reduce the ambiguity in source position. TDOA methods are generally well-developed and commonly used for marine mammal localization. In cases

where the arrival time of a call can be unambiguously established on all receivers, time-of-arrivals (TOAs) instead of TDOAs can be used for localization. In this case, call time is included as a variable – an approach that requires solving for more parameters than the TDOA approach, but which can be useful since it provides an estimate of call time and allows some error to be taken up by time. If present, reflections (e.g. arrivals that reflect of the sea surface or bottom) can be used to improve location estimates and/or to reduce the number of hydrophones required.

When propagation effects (e.g. refraction) are important such as in long-distance or shallow-water problems, straight-line propagation assumptions can give location estimates that have a significant amount of error or, in some cases, that are entirely incorrect. Several approaches have been used in past literature to deal with propagation effects. One possibility is to allow for different sound speeds between the source and different receivers (Spiesberger and Wahlberg, 2002). For more complicated sound propagation conditions, it is possible to use a tomographic approach that linearizes the problem locally (Spiesberger and Fristrup, 1990). It is also possible to maintain a fully non-linear formulation of the problem (Tiemann *et al.*, 2004; Thode, 2005), which is the approach that I use in most of my work (see methods section below).

Any approach that incorporates some aspect of sound propagation effects is referred to as a "model-based" approach. "Model-based" is just a matter of terminology, since even the "conventional" methods are based on a "model" of simple straight-line propagation. Although a full review of model-based localization is well beyond the scope of this article, here I provide a brief summary of some of the tricks and tips that I've learned and/or developed in the 10 year period since 2003 that are useful for passive acoustic localization of marine mammals. Readers interested in further detail can find them in the references listed and are always most welcome to contact me with comments or questions.

2. Methods and Materials

There are many variations of the model-based localization methods that I use, but the main theme is the same: A source is localized by finding the position that gives a predicted arriving signal that best matches the measured arriving signal. Matching is done in a probabilistic framework which results in high probabilities (or likelihoods) for areas where a whale is present and low probabilities in areas where a whale is not present. Model-based localization methods implemented in a probabilistic framework are useful for various reasons, including that they:

- Can improve results in situations where straight-line propagation assumptions fail or result in unnecessarily unacceptably large errors.
- Can make use of information in the arriving signal that goes beyond timing alone (e.g. amplitudes).
- Can be used to "invert" (or solve) for parameters of the problem other than just the animal position (including receiver positions, sound speed profiles and so on).
- Provide a convenient framework for incorporation of a-priori (previously known) information (such as a visual sighting) or known depth of calling.
- Provide a convenient framework for error/uncertainty analysis.

"Matching" can be performed in various ways but usually involves a least squares approach (e.g. minimizing the sum of squares of differences between modeled TDOAs and data TDOAs). It is possible to match different components of the signal, including: time-of-arrivals of direct and/or reflected signals, time-differences of arrivals, waveforms, and spectrograms. A few of these possibilities which I've worked with, along with some other issues, are discussed further below.

2.1 Matching TDOAs

Estimating TDOAs from recorded data can be achieved in various ways, including detection followed by association of calls, cross-correlation of waveforms, and cross-correlation of spectrograms. Once TDOAs have been established, the animal position is found by assuming that errors are normally distributed and then maximizing the corresponding likelihood surfaces over all possible source locations.

For the model-based TDOA processor, the following surface is maximized over source position **w** (Tiemann *et al.*, 2004):

$$\varphi_{TDOA}(\mathbf{w}) = \prod_{i,j} \exp\left[\frac{-1}{2\sigma_{TDOA}^{\ 2}}\left(\Delta t_{ij} - \Delta \hat{t}_{ij}(\mathbf{w})\right)^2\right]$$

where Δt_{ij} is the TDOA for the call between phones i and j, $\Delta \hat{t}_{ij}(\mathbf{w})$ is the modeled TDOA between phones i and j for a call produced at position **w**, and $\sigma_{TDOA}^{\ 2}$ is the standard deviation in measured TDOAs due to uncertainties in receiver position, measured call arrival times, and sound speed profile.

2.2 Matching TOAs

Using TOAs instead of TDOAs can be useful when detection times can be precisely established. This is possible, for example, for impulsive calls such as ondontocete clicks, but not for long duration tonal calls such as some mysticete calls (since it is not possible to find the same position along the call in this case). When using TOAs, the search space includes call time in addition to position. Using TOAs is useful because call time is estimated and because some measurement uncertainty can be absorbed by the call time (hence giving better position estimates).

For the model-based TOA processor, the following surface is maximized over source position **w** and call time t (Nosal, 2007a; Nosal, in press):

$$\varphi_{TOA}(t,\mathbf{w}) = \prod_i \exp\left[\frac{-1}{2\sigma_{TOA}^{\ 2}}\left(t_i - \hat{t}_i(t,\mathbf{w})\right)^2\right]$$

where t_i is the detection time on phone i, $\hat{t}_i(t,\mathbf{w})$ is the modeled arrival time at phone i for a call produced at time t and position **w** and $\sigma_{TOA}^{\ 2}$ is the standard deviation in measured TOAs due to uncertainties in receiver position, measured call arrival times, and sound speed profile.

2.3 Use of reflections

Because they contain information about the position of a source, when reflected arrivals are present and can be extracted from the recordings, they can be used to help with localization. To make use of reflections, the TDOA/TOA methods above can be modified by adding a virtual hydrophone corresponding to each reflection. Reflections have been used to improve position estimates (e.g. Wahlberg *et al.*, 2001; Thode *et al.*, 2002; Zimmer *et al.*, 2003), to reduce the number of hydrophones required for localization (e.g. Cato, 1998; Aubauer *et al.*, 2000; Tiemann *et al.*, 2007), and to localize animals with non-synchronized hydrophones (Nosal and Frazer, 2006b).

2.4 Matching waveforms

Although it is usually the most robust, arrival time is not the only information about the location of an animal in recorded signals. For example, if transmission loss is appropriately modeled, amplitude of the arrival signal can also provide information. One approach that makes use of all possible sources of information is to match measured and modeled

waveforms. An algorithm that we developed that aims to accomplish this is called the pairwise waveform (PWW) processor (Nosal and Frazer, 2006; 2007b):

$$\varphi_{PWW}(\mathbf{w}) = \frac{\mathrm{Re}\left[\sum_{\omega}\sum_{i=1}^{N-1}\sum_{j>1}^{N} H_{ij}^{*}(\mathbf{w},\omega)H_{ji}(\mathbf{w},\omega)\right]}{\sum_{\omega}\sum_{i=1}^{N-1}\sum_{j\neq i}^{N}\left|H_{ij}(\mathbf{w},\omega)\right|^{2}}$$

where i, j are receiver indices, N is the number of receivers, ω denotes angular frequency, $H_{ij}(\mathbf{w},\omega) = R_i(\omega)G_j(\mathbf{w},\omega)$, $R_i(\omega)$ is the received signal at phone, $G_i(\mathbf{w}, \omega)$ is the modeled impulse response between phone i and position $\mathbf{w}$, and * denotes conjugation.

2.5 Matching spectrograms

Since it is difficult/impossible to model the details of a waveform in many cases (due to uncertain/fluctuating environmental conditions, inexact models, incoherence etc.), waveforms do not always match well even at the correct position so the pairwise waveform processor can quickly break down. Spectrograms are much less sensitive to mismatch and fluctuations so it can be more useful to match spectrograms instead of waveforms. Our pairwise spectrogram processor is (Nosal and Frazer, 2006; 2007b):

$$\varphi_{PWS}(\mathbf{w}) = \frac{\mathrm{Re}\left[\sum_{t}\sum_{f}\sum_{i=1}^{N-1}\sum_{j>1}^{N} S_{ij}^{*}(\mathbf{w},t,f)S_{ji}(\mathbf{w},t,f)\right]}{\sum_{t}\sum_{f}\sum_{i=1}^{N-1}\sum_{j\neq i}^{N}\left|S_{ij}(\mathbf{w},t,f)\right|^{2}}$$

Where $S_{ij}(\mathbf{w},t,f)$ is the spectrogram formed from $H_{ij}(\mathbf{w},\omega)$ at time step t and frequency f.

2.6 Multiple animals

Localization can become more complicated when multiple animals are present. For the TOA/TDOA methods, single animal localization algorithms can be used if the calls can be separated and associated between receivers, for example if calls from different animals are well spaced in time or have different characteristics. If calls have short inter-

call-intervals and are stereotypical (as with odontocete clicks, for example) source separation can be a more challenging problem. I recently proposed a TOA/TDOA processor that can handle multiple animal datasets. The details are beyond the scope of this article, but can be found in Nosal (in press).

The waveform and spectrogram processors automatically deal with multiple animal problems without requiring further modification. Again, the details are beyond the scope of this article, but can be found in (Nosal and Frazer, 2006a; 2007b).

3. Applications

All processors discussed above produce an "ambiguity surface", which gives the relative probability of an animal at a given position. To illustrate the concept behind the processors presented in the methods section, consider the 2011 DCL (Oregon) Minke whale localization dataset from the Pacific Missile Range Facility processed using the TDOA processor. Figure 1 shows the resulting ambiguity surface for a single time step. Grey scale indicates the value of the processor and the peak in the ambiguity surface corresponds to the estimated source position. Once ambiguity surfaces have been formed, it is relatively straightforward to extract confidence intervals in position estimates (Nosal and Frazer, 2007a).

The 2005 DCL workshop (Monaco) localization datasets (Adam *et al.*, 2006) provided particularly clean and useful tests for localization methods. They contained about 25 minutes of sperm whale clicks – one dataset with a single animal and the other with multiple animals – recorded on widely-spaced bottom-mounted hydrophones at the Atlantic Undersea Test and Evaluation Center (AUTEC). Sperm whale clicks are an ideal source for localization because they are impulsive (so TOAs/TDOAs can be precisely estimated) and very loud (so they are heard over long distances and often have multiple reflections).

Using the single whale 2005 DCL dataset, we showed that surface reflection could be used to locate an animal when timing synchronization between the hydrophones is unknown (Nosal and Frazer, 2006b). In this work we matched the differences in arrival time between the surface reflection and direct arrival on individual hydrophones. It was shown that using model-based localization with a realistic depth-dependent sound speed profile gives position estimates that are more accurate than those

obtained using constant sound-speed assumptions. The timing offset for the hydrophones was later corrected (Morrisey *et al.*, 2006) after which TOAs could be used to refine the animal locations enough to allow us to estimate the beam pattern for the sperm whale (Nosal and Frazer, 2007a).

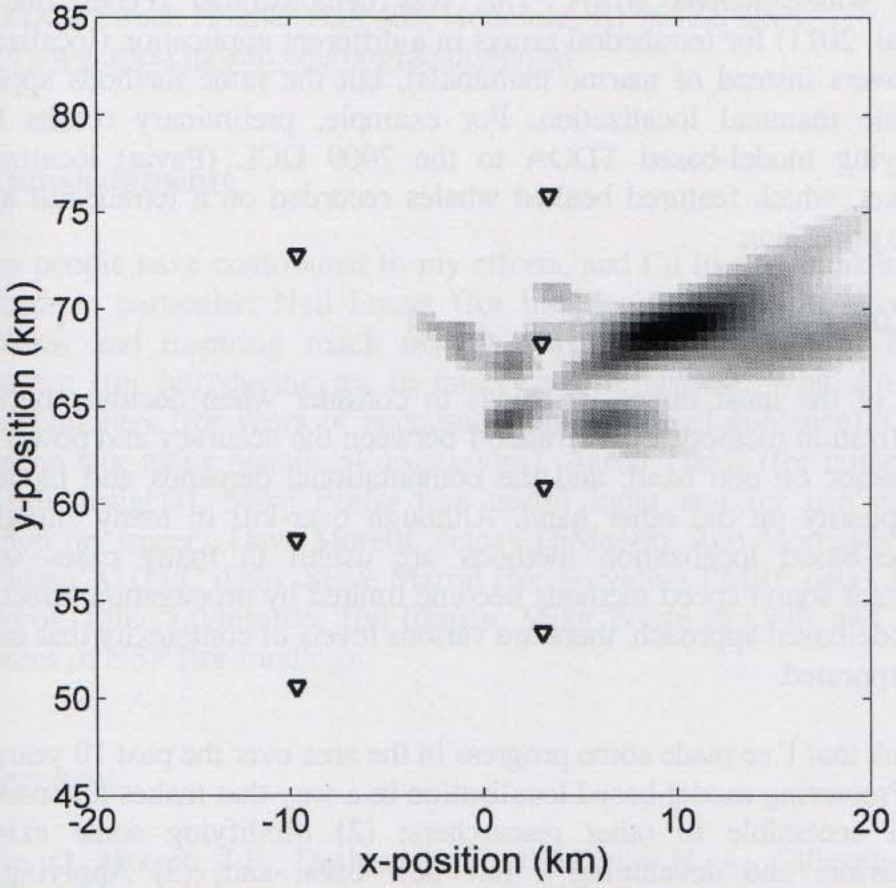


Figure 1: Ambiguity surface for a time step from the 2011 DCL (Oregon) localization dataset showing hydrophone positions as triangles and areas of high/low probability of a source (Minke whale) present in black/white. The surface was created using the model-based TDOA processor.

In Nosal and Frazer (2008) we used the 2005 DCL workshop dataset to test the pairwise waveform and pairwise spectrogram processors. The resulting tracks were within tens of meters of the tracks obtained using the TOA method. It was shown theoretically that the PWW processor is a generalization of the TDOA processor.

Although shown to be applicable for sperm whale clicks, the benefit of the PWW and PWS processors are more pronounced for calls with longer duration and higher variability. For example, they were shown to be useful for localizing multiple singing humpback whales through

simulation (Nosal and Frazer, 2006a; 2007b) – a case where TDOA/TOA methods become challenging to implement. Application to real data is an ongoing topic of research.

Usefully, model-based TDOA can be used with compact arrays as well as with widely-spaced arrays. This was demonstrated (Fedenczuk and Nosal, 2011) for tetrahedral arrays in a different application (localization of divers instead of marine mammals), but the same methods apply to marine mammal localization. For example, preliminary results from applying model-based TDOA to the 2009 DCL (Pavia) localization dataset, which featured beaked whales recorded on a tetrahedral array, were promising.

4. Conclusions

One of the most important things to consider when deciding between localization methods is the tradeoff between the accuracy and power of a processor on one hand, and the computational demands and modeling complexity on the other hand. Although over-kill in many situations, model-based localization methods are useful in many cases where constant sound-speed methods become limited by propagation effects. In a mode-based approach, there are various levels of complexity that can be incorporated.

I think that I've made some progress in the area over the past 10 years by: (1) Presenting model-based localization in a way that makes it somewhat more accessible to other researchers; (2) Modifying some existing processors and developing a few new ones, and; (3) Applying the processors to real datasets to demonstrate their usefulness and to learn a bit about marine mammal bioacoustics.

5. Future Work

There are many interesting and useful areas related to model-based localization that remain to be expanded or explored. For example, despite some progress (e.g Baggenstoss, 2011; Nosal, in press), the problem of localizing multiple animals is still a challenge in many cases. Furthermore, the idea of inverting for parameters other than source position (such as sound speed and hydrophone position) can be further explored and applied (as in Thode *et al.*, 2000). I'm also interested continued efforts to modify and apply model-based methods for compact arrays. Another direction in which I hope to work is in applying model-based localization methods to existing or new datasets.

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