ROBUST 2D LOCALIZATION OF LOW-FREQUENCY CALLS IN SHALLOW WATERS USING MODAL PROPAGATION MODELLING

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ABSTRACT

We propose a new method to localize low-frequency calls in 2D in shallow waters from a sparse array of hydrophones using modal propagation modelling. An analysis of modal propagation modelling of transients signals in shallow water environment shows that the dispersive behaviour of the waveguide can be exploited to design a robust localization scheme without requiring any knowledge of the acoustics properties of the environment (bottom and water column) nor any simulation of propagation. The localization scheme also does not require synchronization of the array and is therefore independent of any clock drift. Promising results are obtained for Northern right whale gunshot calls from 'Bay of Fundy data set of the 2003 Workshop on Detection and Localization of Marine Mammals Using Passive Acoustics.'

RÉSUMÉ

Dans ce papier, un algorithme robuste de localisation 2D à partir des émissions transitoires dans des milieux petits fonds est proposé. Il s'appuie sur un modèle de propagation modale. Une analyse des phénomènes de dispersion induits par la propagation montre qu'il est possible, à partir d'un réseau lâche d'hydrophones, de proposer une méthode de localisation ne nécessitant ni la connaissance du milieu, ni l'exécution d'un code de propagation. L'algorithme de localization ne nécessite pas la synchroniozation du réseau et est par conséquent indépendant des dérives d'horloges. Des résultats encourageants sont obtenus pour localiser les émissions « gunshot » des baleines franches à partir du jeu de données de la Baie de Fundy, de 'l'Atelier de 2003 sur la détection, la localisation et la classification de mammifères marins par acoustique passive'.

1. INTRODUCTION

Localizing marine mammals in large ocean basins is needed to assess their use of the habitat in time and space and study the impact of global changes on ecosystems [Tho86] [Win04] [Sta07]. Localization may become crucial for some endangered species in relation with anthropogenic activities such as airgun seismic surveys, low-frequency military applications and collisions with ships [And01] . Even if visual observations from ships and planes may be used during daytime, passive acoustics localization methods can increase the spatial extent of localization, besides of being still active during night and bad weather conditions [Spi90] [Tho86]. Passive acoustics monitoring (PAM) appears to be suitable for integrated autonomous, real-time and long term alert systems to prevent collisions with ships [Sim06] if the animals produce sounds regularly enough and over a range of behaviours. After being emitted, marine mammal calls propagate along paths from the animal's position to one or several hydrophones. Then features such as time difference of times of arrival (TDoA) at each hydrophone [Lau03] [Spie90] or time-frequency dispersive pattern [Win04], are extracted from the measurements using signal processing techniques and used to estimate the source location. Passive acoustic localization techniques require a model of acoustic propagation in the environment, the knowledge of ocean acoustics properties at the emission time and a localization algorithm. Accuracy and robustness of the estimates depend on the emitted signal (bandwidth and level), the noise level, the adequacy between the propagation model and the reality [Cha04] and on monitoring of ocean acoustic properties. Existing methods range from direct-ray path propagation assumption associated with hyperbolic fixing [Lau04] [Des04] to more elaborated modal propagation and localization processing [Ebb06] [Win04]. Figures of merit of a localization scheme include localization's accuracy, robustness to weak knowledge about environment properties and real-time implementation capability for alert systems.

The productive shallow waters of continental shelves are intensively used by low-frequency calling baleen whales (< 1 kHz) [Ric95]. Also, most of the documented collisions appeared to be there or near the continental shelf [Lai01]. Considering these facts, normal mode modelling seems to be an adequate model to deal with acoustic propagation of these whale calls [Jen00] [Win04]. Real data application of our contribution focuses on the localization of North Atlantic right whales gunshot calls in the Bay of Fundy, Canada. Nowadays, North Atlantic right whales (*Eubalaena glacialis)* population is less than 350 individuals and is in decline due to high human induced mortality [Van03]. Indeed, ship strikes accounted for 35.5% (16/45) of the documented North Atlantic right whale mortality between 1970 and 1999 [Kno01]. North Atlantic right whales sounds have been recently described [Mat01] [Van03] [Par05]. In general they are low-frequency sounds (< 1 kHz) with various waveforms (constant low-frequency, moan, upsweeping and downsweeping modulations and gunshot). Gunshot calls are a loud impulsive sounds (duration ~30 ms, bandwidth ~[10Hz,20kHz], [Par05]) frequently used by right whales in the Bay of Fundy, Canada [Van03]. They are produced by lone males or males in a social active group at or near the surface and seem to have some implication in reproductive display. The Canadian right whale Conservation Area in the Bay of Fundy is close to an internationally designated shipping lane used by numerous large carriers [Lau03] which was recently changed to minimise collision risk. Efficient localization of gunshot calls through PAM systems can help improving right whale conservation. Moreover, internal waves taking place in the Bay of Fundy produce large and rapid variations of sound speed profiles [Des04_a] [Cla06] that must be taken into account by appropriate localization algorithms.

In the present paper, we propose a method to localize (in a 2D horizontal plane) low-frequency transient signals in shallow water environments. Our scheme relies on a normal mode propagation modelling and a targeted area of emissions surrounded by a sparse network of hydrophones. By exploiting the dispersive behaviour of the acoustic channel and time-frequency signal processing, our method allows localizing the source without any knowledge of the ocean acoustics properties of the channel and without any requirement to run simulations from acoustic propagation models. This method can use exactly the same recording device as that used for TDOA localisation schemes and can advantageously replace them when shallow water and very low-frequency sounds are encountered. Our method is tested on three recordings from the dataset provided in support of the 2003 Workshop on Detection and Localization of Marine Mammals Using Passive Acoustics. Satisfactory results are obtained and the present paper aims at presenting this new potential localization scheme to the community.

The first part of the paper briefly presents the experimental material used in the field, the second part recalls the main features of normal mode propagation and the third part describes our localization scheme. Then a fourth part applies the method to real data, including comparisons with other classical methods. The last part discusses the results.

2. ACOUSTIC DATA SET

The data set that we used in this paper is the one provided in support of the 2003 Workshop on Detection and Localization of Marine Mammals Using Passive Acoustics. This dataset contains North Atlantic right whale sounds recorded in the Bay of Fundy during 2000 and 2002 [Des04_a]. None of these calls have an *in situ* visual ground truth. Among 16 recordings (9-10 September 2002), the dataset provides 5 30-s recordings containing gunshot calls. Recordings were performed by five OBH autonomous hydrophones moored on the bottom. A single hydrophone was located in each corner of a 14-km square, with the fifth located in the middle (c.f. table 1).

OBH	Deployment position		Water depth (m)
	Latitude (N)	Longitude (W)	
C	44.60073	66.49723	210
E	44.60237	66.31591	134
L	44.66203	66.40453	183
H	44.73051	66.31556	123
J	44.73038	66.49619	170

Table 1 : Dataset OBH positions

The OBH network was deployed in shallow waters with bathymetry varying from 100 to 200 meters. Sound speed profiles during the experiment were downward refractive or had a local minimum. They showed notable short-term variations. The sub-bottom structure in the area is mainly composed of a first *Lahave* clay layer over a thick layer of *Scotian drift* [Map77]. The weak compression sound speed in *Lahave* clay, which was smaller than the sound speed in water, implies a high level of dispersion for normal mode propagation. The OBH recordings were digitized using a 12-bit A/D converter with a sampling frequency of 1200 Hz. Figure 1 presents the recordings S035-2 at hydrophones H, L, E, C with a spectrogram representation in 10 to 100 Hz bandwidth (Kaiser window, β= 0.1102(180-8.7), length : 512 samples). One can clearly see:

- on the time-amplitude plots (panels C, D, E, F), the gunshot time of arrival on each OBH,
- on the time-frequency plots (panels G, H, I, J), a typical pattern of dispersive normal mode propagation. Each received gunshot has a multi-component structure and each component has its own time of arrival which depends on frequency (as the time delay between each echo increases with the range between the gunshot and the hydrophones, the time frequency structure of the arrival can be attributed without ambiguity to propagation and not to the gunshot itself).

3. DIRECT MODELLING: NORMAL MODE PROPAGATION

Considering that the energy in the vocalization is concentrated in the low-frequency band and propagating in shallow water waveguide, the normal mode propagation theory seems appropriate for the analysis. In a range independent environment, the transfer function between a receiver and an emitter r meters apart can be written as given in equation 1 (c.f Section 8) [Jen00] where $g_m(z)$ represents the modal function of index m, $k_r(m,f)$ the radial wave number of index m and frequency f, Rk_r the real part of $k_r(m,f)$ and Ik_r the imaginary part of $k_r(m,f)$, z_s is the source depth and z_r the receiver depth. The term $A(m,f,r,z_s,z_r)$ includes the attenuation between source and receiver; the term $P(m,f,r)$ includes the propagation time and propagation speed between source and receiver. From $P(m,f,r)$, phase speed v_φ and group speed (propagation speed of the energy) v_g of mode m at frequency f are defined by equation 2:

$$v_\varphi(m,f) = \frac{2\pi f}{Rk_r} \quad v_g(m,f) = 2\pi\frac{\partial f}{\partial Rk_r} \qquad Eq\ 2.$$

In shallow water environments, v_φ and v_g depend on both the frequency and the index m. That's why, different modes at the same frequency propagate with different speeds and one mode at different frequencies propagates with different speeds. So, if a source emits an impulse signal, the received signal after propagation in the channel contains several echoes, and for each echo, its frequencies arrive at different times, in that sense, normal mode propagation is said to be dispersive.

If one source emits a transient signal with a time-frequency modulation $t_e(f)$ (where t_e is the emission date of frequency f), theoretical received time-frequency structure RTF_s after a normal mode propagation of range r between source and receiver is given by equation 3:

$$RTFs(t,f) = \sum_{m=1}^{+\infty} A(m,f,r,z_s,z_r)\delta(t - t_e(f) - \frac{r}{v_g(m,f)})$$

$$Eq\ 3$$

where $\delta(t)$ stands for the impulse distribution.

To illustrate the dispersive propagation and previous formula, simulation is carried out. Using normal mode propagation code ORCA [Wes96], a synthetic gunshot emitted a time 0s is propagated in the *prior* Bay of Fundy waveguide (described in Section 2) over a 10-km range. Figure 2 gives the simulated received signal (noise free) and its spectrogram with the theoretical time-frequency arrival structure. The figure clearly illustrates the dispersive behaviour of the waveguide underlined in equation 3.

4. LOCALIZATION SCHEME

Our idea consists of using the dispersive behaviour of the waveguide to localize transient emissions. To design a localization scheme, we assume that:
- a sparse network of hydrophones is used to measure propagated signals,
- a source emits a transient signal with an unknown time-frequency modulation $t_e(f)$,
- from the recordings, we dispose of time-frequency processing that allows us to extract the time of arrival of any modal arrival for each frequency.

Times of arrival of mode with index m at frequency f measured at hydrophones n and n' are given by equation 4 (c.f Section 8) where $r(s,n)$ is the range between source s and receiver n. This implies that the TDoAs of modes with index m and m' at frequency f measured at hydrophones n and n' are given by equation 5 (c.f Section 8). If the ratio of $d(n,f,m',m)$ over $d(n',f,m,m')$ is computed, one obtains equation 6 (c.f Section 8). We can note that this ratio does not depend on the waveguide properties. So, if a geographical set of coordinates is defined with the origin set half way between hydrophones n and n', the x coordinate along a line between n and n' and the y coordinate perpendicular to this line, it is easy to show that the set of positions which satisfy $\frac{r(s,n)}{r(s,n')} = Q$ (where Q is a constant) is:
- if $Q \neq 1$, a circle with centre coordinates equal to $\left((-\frac{1-Q^2}{1+Q^2})\frac{L}{2}, 0\right)$ and radius equal to $\frac{QL}{\left|1-Q^2\right|}$ where L is the range between hydrophones n and n',
- if Q=1, the median between hydrophones n and n'.

$R(n,n',f,m,m')$ constrains the source to lie on a circle or on a line (under the assumptions that the channel is isotropic and range independent on the array area), it does not depend on waveguide acoustic properties, so it can be used to locate the source without any requirement about monitoring channel's properties, thus offering a robust localization scheme.

Then, our localization scheme follows these steps:
- step 1: perform a preliminary analysis of recordings to identify the hydrophones, the bandwidth and the modal indexes for which the modal arrivals are clearly resolved in a time-frequency plane,

- step 2: with a given time-frequency tool, extract the times of arrival $t_r(m,n,f)$ for any *m, n* and *f* selected in step 1 (in this paper, we look for *a prior* number of local maxima on the spectrogram computed with a Kaiser window, β=0.1102(180-8.3), L=512 samples),
- step 3: for each quintuplet *(m,m',n,n',f)* with *m',m,n,n',f* selected at step 1 and $m \neq m'$, $n \neq n'$, compute *R(n,n',f,m,m')*,
- step 4: estimate the source's location by solving the optimization problem described in equation 7 (c.f Section 8) where (x_m, y_n) are the coordinates of hydrophones *n*, and *N* is the number of quintuplets *(m,m',n,n',f)* selected at step 3 (in this paper, we evaluate *J(x,y)* on a discrete grid in *x* and *y* with a step of 5 m and search the global maximum of *J* on the grid but we can also envisage to use global or local optimization techniques).

5. APPLICATION ON REAL DATA

The localization scheme above designed is applied to 'S035-2' Bay of Fundy data set recordings which contain a gunshot call. Figure 1 illustrates the results. To obtain these localization results, our method was applied using hydrophones C, H, L, E, modal arrivals 1 and 2 and frequencies from 30 to 50 Hz (c.f. above step 1). Table 2 summarizes the localization results. Standard deviation of our method was assessed via 100 Monte-Carlo simulations with synthetics signals simulated with ORCA and with a signal to noise ratio similar to the real one (note that these Monte Carlo simulations help us to quantify the impact of recordings noise on localization accuracy but not the impacts of propagation and gunshot instabilities).

Method	x_{GS} (m)	y_{GS} (m)	Standard deviation x_{GS} (m)	Standard deviation y_{GS} (m)
Gervaise et al.	9225	-1248	420	110
Laurinelli et al. [Lau04]	8950	-970	760	620
Desharnais et al. [Des04]	8884	-848	---	---

Table 2 : S035-2, gunshot call localization results

6. DISCUSSION

The application of our method on real data from S035-2 recordings indicates that the gunshot localization is compatible with the solutions obtained by Laurinelli et al.'s ([Lau04]) and Desharnais et al.'s ([Des04]) methods, which somewhat confirms the validity of our approach. The precision of our scheme seems to be better than Laurinelli et al.'s approach but one must note that errors are not assessed the same way (Monte Carlo simulations with a statistical mean in our case, whereas Laurinelli et al.'s is obtained from the spread of hyperbole's intersections in the hyperbolic fixing method and does not have any statistical meaning). Similar good results were obtained on S070-3 and S013-1 recordings. For S093-4 and S110-5 recordings, signal to noise ratio were too low to be able to clearly separate the modal arrival on a spectrogram and our method fails.

Compared to other methods, ours takes into account true propagation model that really exists in the waveguide while Laurinelli et al.'s and Desharnais et al.'s methods assume an acoustic direct ray path (straight line or not) propagation. In this sense, the link between time of arrivals and source position is better explained in our scheme. Although gunshot calls contain frequencies from 20 Hz to 20 kHz, our method exploits only the low-frequency band while Laurinelli et al's and Desharnais et al.'s may use the full bandwidth. Therefore, time of arrival estimates are more precise for Laurinelli et al.'s and Desharnais et al.'s schemes. Without ground-truth it is difficult to establish which method is the most accurate. However, we underline the fact that our approach does not require any knowledge about acoustic properties of the waveguide, which is a major advantage for robustness. Wiggins et al. [Win04] proposes a localization scheme based on normal mode propagation with a single hydrophone while our approach requires several hydrophones. To succeed, Wiggins et al.'s scheme needs a normal mode propagation code and the knowledge of acoustic properties of the waveguide. When applying his method on Bering Sea calls, the waveguide structure was simple (a Pekeris waveguide) and group speed weakly depended on waveguide properties. This was not the case in Bay of Fundy waveguide whose bottom presents a multi-layer structure with a poorly compacted first layer and a time-space variable sound speed profile. Thus a localization approach that is robust to poor knowledge of acoustic properties of the environment offers significant additional advantages even if it requires several hydrophones.

Our localization scheme can advantageously be used in a real-time anti-collision (between whales and ships) alert system in situations where low-frequency calls are frequent because it does not require the monitoring of acoustic properties of the waveguide, which simplifies the experimental PAM implementation and it does not require to run a propagation code, so a fast real-time localization may be achieved. However, it requires real-time implementation of time-frequency processing.

Because our scheme works on TDoAs between the arrivals of modes on a same hydrophone (see Eq 5), it is not sensitive to clock's drifts, which is a major difficulty with non-cabled hydrophone arrays (c.f. Simard and Roy, 2008 [Sim08])

In this paper, our approach was applied to right whale calls, but it can be used with any low-frequency calls with clear time-frequency modulation in shallow waters, for example with North Pacific right whales, Humpback whales in the Bering sea [McD02] , eastern North Pacific blue whales [Ole07], blue whale (*Balaenoptera musculus*) in the St. Lawrence Estuary [Ber06] .

6. FUTURE WORK

As a perspective for future work, we plan to:

- look for larger dataset to test the proposed approach (any contributions are welcomed),
- estimate the source's depth using the normal mode propagation assumption and the time-frequency analysis of the recorded signals,
- include this localization scheme in a larger acoustic perspective to perform passive geoacoustic inversion of waveguide properties using marine mammal calls [Ger07] .

7. ACKNOWLEDGEMENTS

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8. EQUATIONS

Equation 1

$$H(f) \approx (2\pi)^{1/2} \sum_{m=1}^{+\infty} A(m,f,r,z_s,z_r)P(m,f,r)$$

$$A(m,f,r,z_s,z_r) = g_m(z_s)g_m(z_e)\exp(-Ik_r(m,f)r)/\sqrt{Rk_r(m,f)r}$$

$$P(m,f,r) = \exp(-j(Rk_r(m,f)r)$$

Equation 4

$$t_r(m,n,f) = t_e(f) + \frac{r(s,n)}{v_g(m,f)} \qquad t_r(m,n',f) = t_e(f) + \frac{r(s,n')}{v_g(m,f)}$$

Equation 5

$$d(n,f,m,m') = t_r(m,n,f) - t_r(m',n,f) = r(s,n)(\frac{1}{v_g(m,f)} - \frac{1}{v_g(m',f)})$$

$$d(n',f,m,m') = t_r(m,n',f) - t_r(m',n',f) = r(s,n')(\frac{1}{v_g(m,f)} - \frac{1}{v_g(m',f)})$$

Equation 6

$$R(n,n',f,m,m') = \frac{d(n,f,m,m')}{d(n',f,m,m')} = \frac{r(s,n)}{r(s,n')}$$

Equation 7

$$(x_s,y_s) = \arg\min_{x,y}(J(x,y))$$

$$J(x,y) = \sum_{i=1}^{N}[(x-x_n)^2 + (x-y_n)^2 - R^2(m,m',n(i),n'(i),f)((x-x_{n'})^2 + (x-y_{n'})^2)]^2$$

9. FIGURES

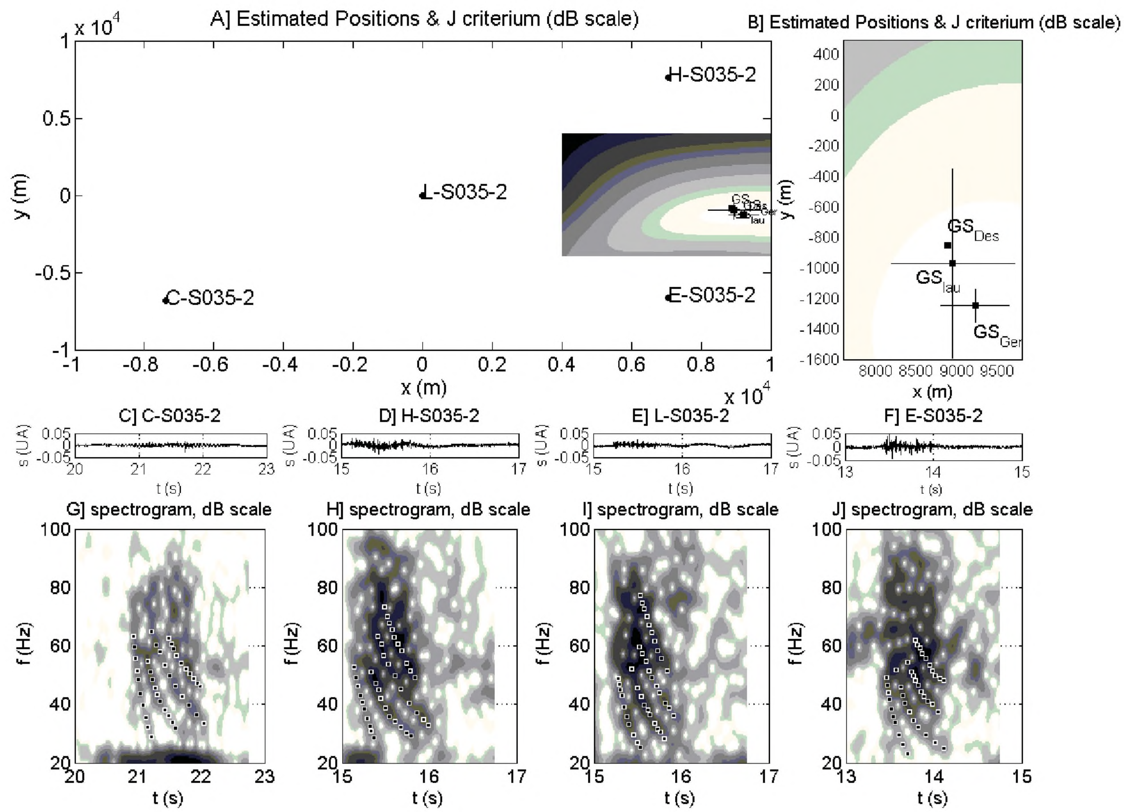

Figure 1) A : Estimated gunshot position and mapping of criteria J, B : zoom around the estimated positions, black square GS_{Ger} : estimated position with standard deviation from our method, black square GS_{Des}: estimated position with Desharnais et al.'s method, black square GS_{Lau} : estimated position with standard deviation from Laurinelli method; Panels C, D, E, F : received signals by OBHs C, L, E, H; panels G, H, I, J: :received signal spectrogram (Kaiser window, β=0.1102(180-8.3), L=0.5s) with estimated time-frequency law of modal arrivals (black square)

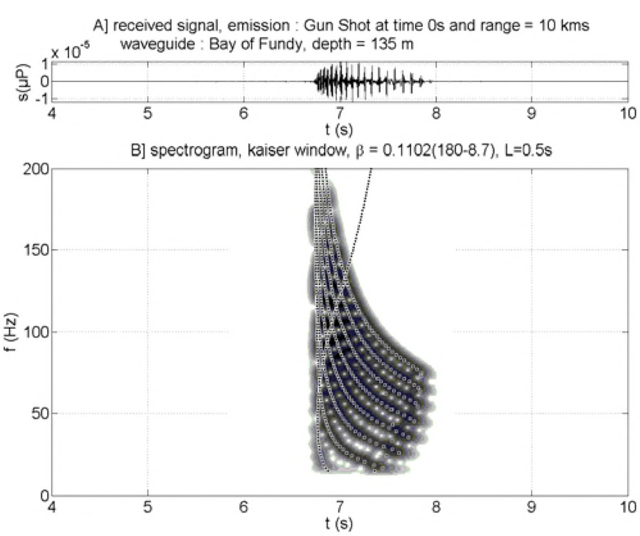

Figure 2) A] received waveform; B] gray scale map: received waveform spectrogram in dB scale, black squares: theoretical time-frequency structure of arrivals

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