DETECTION AND LOCALIZATION OF BLUE AND FIN WHALES FROM LARGE-APERTURE AUTONOMOUS HYDROPHONE ARRAYS: A CASE STUDY FROM THE ST. LAWRENCE ESTUARY

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ABSTRACT

The feasibility of using passive acoustic methods (PAM) to monitor time-space distribution of fin and blue whales in the Saguenay–St. Lawrence Marine Park was explored using large-aperture sparse hydrophone arrays. The arrays were deployed during summers 2003 to 2005 at the head of the 300-m deep Laurentian Channel. They were composed of 5 AURAL autonomous hydrophones moored at mid-water depths, near the summer sound channel. A small coastal array complemented the deployment in 2003. The apertures were from 20 to 40 km and the configurations were changed from year to year. The most frequent calls recorded were blue and fin whale signature infrasounds. Noise from transiting ships on the busy St. Lawrence Seaway often masked the calls on the nearest hydrophones. Sometimes this resulted in an insufficient number of receivers for localizing the whales using time difference of arrival (TDoA) methods. The technical characteristics of the arrays and data processing are presented, with an example of call detection and localization. Despite the difficulties inherent to this environment, PAM can be effectively implemented there, eventually for real-time operations.

RÉSUMÉ

La faisabilité d'utiliser la technologie de monitorage acoustique passif (PAM) pour suivre la distribution spatio-temporelle des rorquals bleus et communs dans le Parc Marin Saguenay–Saint-Laurent a été explorée à l'aide de réseaux d'hydrophones à maille lâche couvrant de grandes distances. Les réseaux ont été déployés pendant les étés 2003 à 2005 à la tête du chenal Laurentien, profond de 300 m. Ils étaient composés de 5 hydrophones autonomes AURAL mouillés à mi-profondeur, près du couloir de son estival. Un petit réseau côtier de faible ouverture complétait le déploiement en 2003. Les ouvertures des réseaux étaient de 20 à 40 km et leurs configurations étaient changées à chaque année. Les vocalisations les plus fréquentes étaient les infrasons identitaires des rorquals bleus et communs. Le bruit de navires transitant dans la Voie Maritime achalandée du Saint-Laurent masquait souvent les vocalisations sur les hydrophones les plus proches, ce qui parfois résultait en un nombre insuffisant de récepteurs pour localiser les baleines à l'aide de méthodes utilisant les différences de temps d'arrivée (TDoA). Les caractéristiques techniques des réseaux et du traitement des données sont présentées avec un exemple de détection et de localisation. Malgré les difficultés inhérentes à cet environnement, la technologie PAM peut y être efficacement implémentée, éventuellement pour des opérations en temps réel.

1. INTRODUCTION

The development of the methodology for localising whales from their sounds in their habitats was initiated by Watkins and Schevill (1972) in the 1970s. It was then rapidly applied to tracking whales over large distances (e.g. Cummings and Holliday 1985, Clark et al. 1986). Advances in electronics, computers and numerical analysis now make this PAM technology more accessible and affordable to small research budgets. Various systems have been used, including shore-cabled and radio-linked systems, drifting buoys, and arrays of autonomous recorders for versatile and long-term deployments (e.g. Janik et al. 2000, Hayes at al. 2000, Watkins et al. 2000, Tiemann and Porter 2004, Simard et al. 2004, Sirovic et al. 2007, Stafford et al. 2007). The goal of such PAM systems, is the continuous mapping of presence and distribution of whales over ocean basins (e.g. Greene et al. 2004, Simard et al. 2004, Sirovic et al. 2007, Stafford et al. 2007) and assessing their densities, (e.g. Ko et al. 1986, McDonald and Fox 1999, Clark and Ellison 2000), sometimes in quasi real-time (e.g. Thiemann and Porter 2004). Their performance in effectively accomplishing these tasks, depends on the characteristics of the targeted whale calls, the environment, the type of equipment used, its deployment and configuration. This performance may significantly vary from case to case.

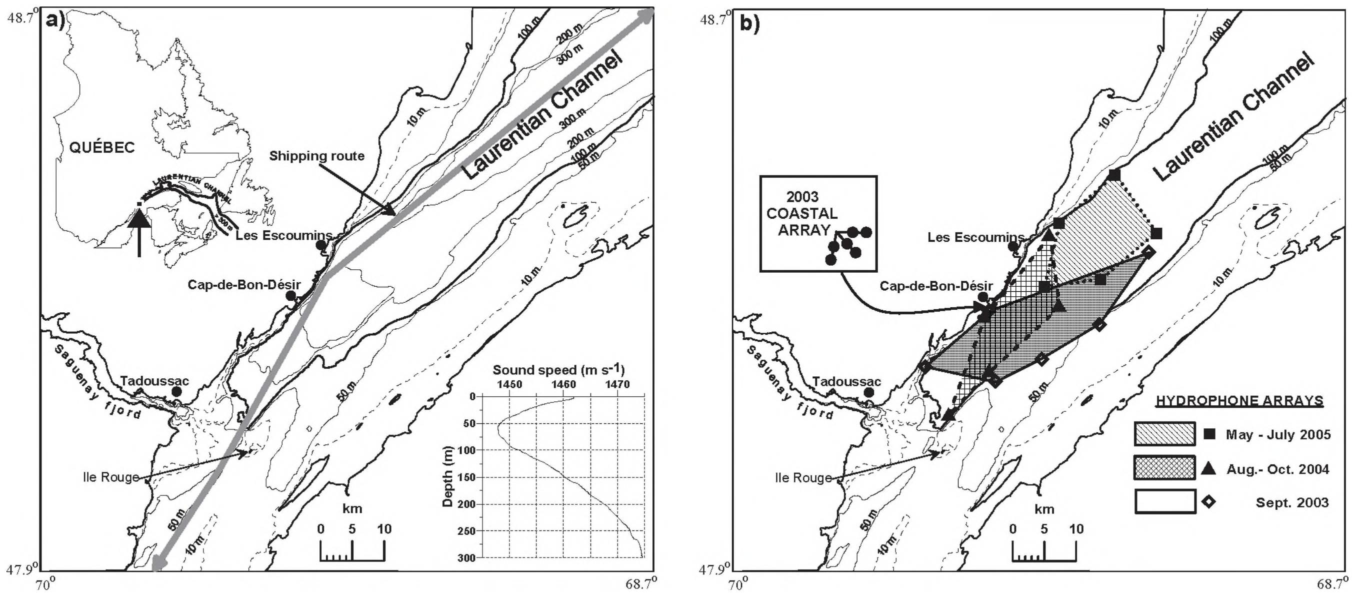

Figure 1. a) Study area at the head of the Laurentian channel in the Saguenay–St. Lawrence Marine Park, with bathymetry and typical summer sound speed profile. b) Configurations of the hydrophone arrays deployed in 2003-2005.

PAM's success first depends on the capacity to isolate the targeted calls from the rest of the acoustic signal in which they are imbedded, especially for distant sources and low signal to noise ratios (SNR). Call source level (SL), propagation loss, and the local "ocean noise" level determine detection ranges (c.f. Sirovic et al. 2007, Stafford et al. 2007). Whale calls' SLs vary considerably among species and within a species' vocal repertoire (e.g. Kuperman and Roux 2007, p. 199.). Ocean noise level also exhibits considerable variability in space and time, in response to fluctuating natural sources, such as wind, ice, rain, sounds produced by various organisms, and anthropogenic sources such as shipping (c.f. review NRC 2003). When a series of hydrophones are available at each node of the larger PAM array, beamforming and matched-field processing (c.f. Jensen et al. chap. 10) can improve signal detection by SNR enhancement. Signal processing can improve detection of some calls by exploiting their distinctiveness in time-frequency space compared to noise (e.g. Mellinger and Clark 2000). Sound speed structures over the water column can focus sounds from distant sources into sound channels, thereby reducing propagation loss from multiple interactions with absorptive and scattering surface and bottom interfaces. This is true for both the signal and the noise sources. The signal with the lowest transmission loss depends on the 3D spatial arrangements of the sources and the local propagation characteristics. The spatial arrangement, horizontal distance between the hydrophones, and their depth relative to the sound channel are relevant to the PAM problem. . The optimal configuration could be explored from simulation models.

SNR not only affects the detection of calls, but also the capacity to precisely estimate their TDoAs on the hydrophone array (Clark and Ellison 2000, Buaka Muanke and Niezrecki 2007). High precision is essential for precise localisation (Spiesberger and Wahlberg 2002, Spiesberger 2004, 2005). Precise estimation of the TDoAs is hindered by low SNR and multipath propagation conditions where reflected and refracted signals overlap. TDoA accuracy also depends on proper synchronisation of the array, which is often problematic with the multiple independent clocks of autonomous hydrophone arrays (e.g. Thode at al. 2006, Sirovic et al. 2007).

Additional constraints for operational PAM setups include minimizing interfering noise from the hydrophone deployment accessories such as strumming from the mooring. Low-frequency vibration and flow noise (Haddle and Skudrzyk 1969) can arise due to strong currents often encountered on continental shelf habitats where whales vocalizing at low frequencies forage on aggregated preys (e.g. Simard and Lavoie 1999).

Examples of PAM applications used to non-intrusively study whales in their large-scale habitat from a sparse array of distant omnidirectionnal hydrophones are expanding around the world. Details of experiments from several case studies in different environments should help improve the development, efficient use, and robustness of this new methodology. The present paper contributes to this effort by presenting an example for blue and fin whale localization in the Saguenay–St. Lawrence Marine Park (SSLMP) located at the head of the Laurentian Channel in the Lower St. Lawrence Estuary (Fig. 1).

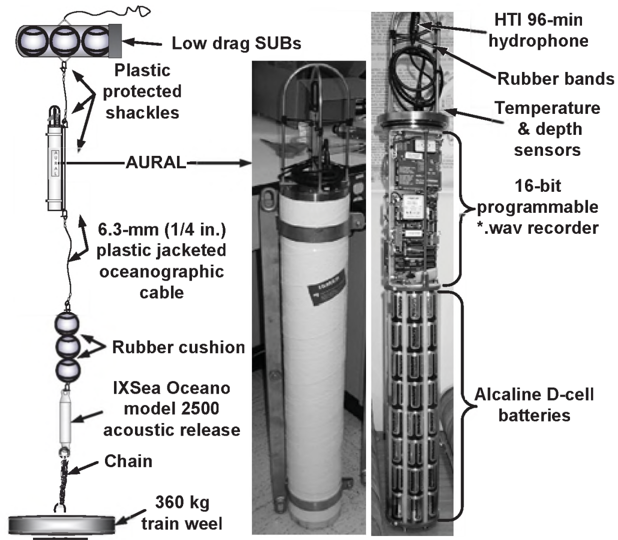

Figure 2. Typical mooring of an AURAL autonomous hydrophone.

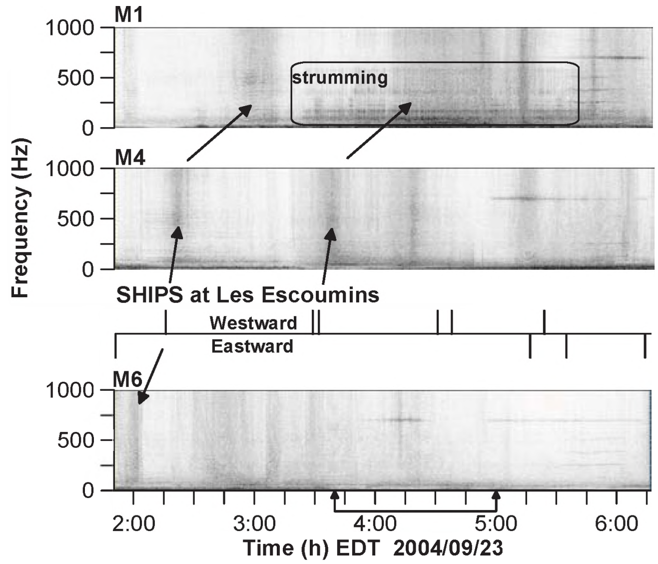

Figure 3. Spectrograms showing typical non-synchronized noise patterns while ship transits throughout the study area from upstream (M1) to dowstream (M6) with their reporting time at the pilot station, 10 km upstream of M4. Period corresponding to Fig. 4 is pointed on X axis.

2. MATERIAL AND METHODS

Study site

For centuries, North-West Atlantic baleen whales have migrated to the head of the 300-m deep Laurentian Channel during summer for feeding on prey concentrated along its bordering steep slopes by strong tidal upwelling processes (Simard and Lavoie 1999, Lavoie et al. 2000, Simard et al. 2002, Cotté and Simard 2005). The summer water column in this part of the North-West Atlantic is characterized by a prominent Cold Intermediate Layer (CIL) centered around 60 m, creating a well defined sound channel at these depths (Fig. 1a). The bottom is composed of more than 200 m of silt overlying the bedrock in the trough with sand and gravel on the surrounding shallow areas. The high tidal energy of this environment generates fronts, semidiurnal upwelling at the channel head, and propagating internal tide and high-frequency internal waves, moving the CIL depth by up to 100 m (c.f. Saucier and Chassé 2000). These processes modify the propagation conditions in time and space, notably by swinging the sound channel up and down. Shipping noise from St. Lawrence Seaway traffic is high. Levels in the 18-22.6 Hz and 35.6-89.8 Hz targeted call bands can reach 130 dB re 1 μPa_{rms} and exceed 102 dB re 1 μPa_{rms} more than 50% of the time (Simard et al., unpublished results from 15960 h of recordings).

Equipment

The PAM arrays were deployed in the study area during summers of 2003 to 2005 (Fig. 1b). They were made up of 5 AURAL autonomous hydrophones (Multi-Electronique Inc, Rimouski, Qc, Canada) programmed for 16-bit continuous sampling (M1-mode) after 17 or 23 dB amplification. The AURALs also recorded the ambient temperature and depth. The temperature compensated crystal oscillators of their clocks minimized temperature effects on clock drifts. The instruments were anchored with typical oceanographic moorings, taking special care to minimize the noise from the mooring components (Fig. 2). All hydrophones were HTI 96-min (High Tech Inc., Gulport, Ms, USA) with a nominal receiving sensitivity (RS) in the low frequency band (< 2 kHz) of -164 dB re 1 V/µPa, confirmed by calibration at the Defense Research Development Canada (Dartmouth, NS, Canada) facility. The hydrophones were placed at intermediate depths in the water column near the summer sound channel axis (Fig. 1a). After the first deployment in 2003, the hydrophones were deployed in deeper water farther from the channel slopes in order to avoid local maximum tidal currents (c.f. Lavoie et al. 2000, Saucier and Chassé 2000) that were generating vibrations of the mooring and flow noise. In 2003, a coastal array of 6 HTI 96-min hydrophones with an aperture of ~650 m was also deployed along a cape in the middle of the study area (Fig. 1b). The acquisition system consisted of a 16-bit ChicoPlus Servo-16 data acquisition board (Innovative Integration, Simi Valley, CA, U.S.A.) connected to a PC. The exact locations of these hydrophones on the bottom were determined from hyperbolic fixing (receiver and sources inverted) by sending series of 8-kHz pulses from the IXSea Oceano acoustic release transmitter (Marly-le-Roy, France) from a network of surrounding stations surveyed by the R/V Coriolis II. CTD profiles (SBE 19, Seabird Electronics, Bellevue, Wa., USA) from the study area were used to compute sound speed profiles.

Synchronization

The synchronization of the autonomous hydrophones exploited a combination of means: starting and stopping the AURALs with a PPS (pulse per second) impulse from a GPS receiver, simultaneous recording of same acoustic

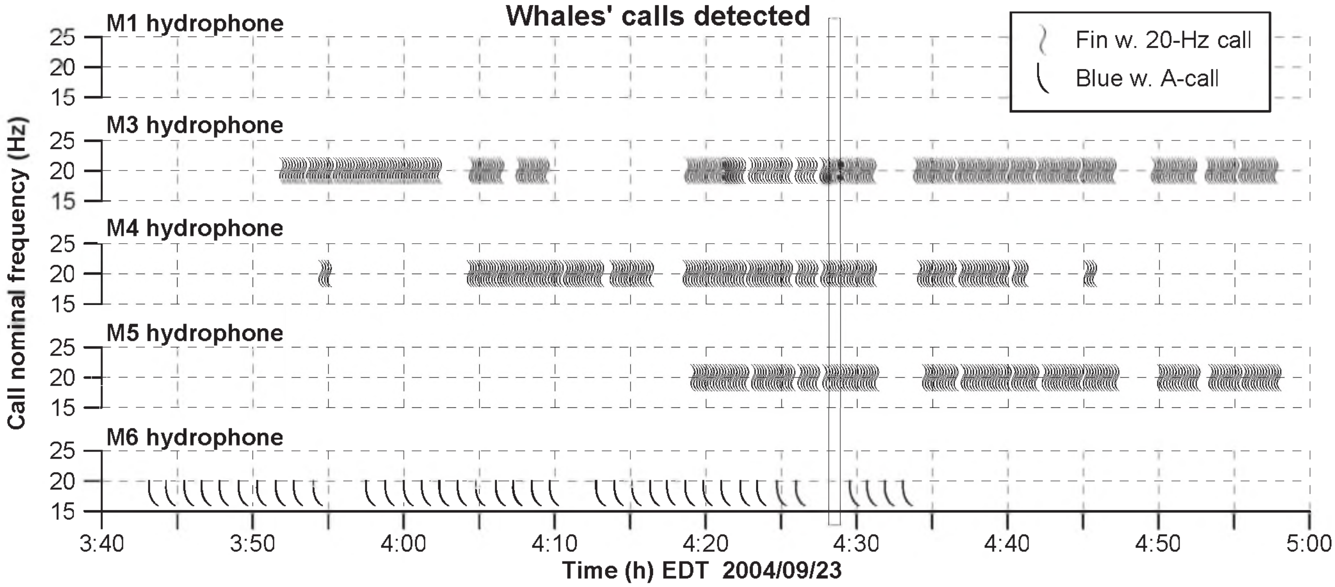

Figure 4. Blue and fin whale calls series detected on the hydrophone array during the period pointed on Fig. 3. The bar marks the 1-min sequence used for the localization shown in Figs. 5, the hyperbole traces and isodiachron clouds of Fig. 6.

signals on all units, cross-checking with the coastal array clock, and linear interpolations assuming constant drift of the internal M1-mode clocks over the deployment periods. This drift was quite stable from one instrument to the other and estimated to 4.1 ± 0.1 s d^{-1}. The relative drift for estimating the TDoAs at the hydrophones was < 0.2 s d^{-1}. It was also consistent over years, and therefore seems to be a characteristic of the particular instrument's clock. Other synchronization approaches could be tested. (see Discussion).

Data analysis

Call detection requires initial SNR enhancement by de-trending the spectrogram as the first noise filtration step (details in Mellinger 2004, Mouy 2007). Fixed-template time-frequency call detection algorithms (e.g. Mellinger and Clark 2000) then generally performed well for the stereotyped infrasound calls of blue (A and B calls) and fin (20-Hz pulse) whales (Mouy 2007). A time-frequency contour detection algorithm combined with DTW (dynamic time warping) classification algorithm (*ibid.*) was used for the variable blue whale D call (Berchok et al. 2006). TDoA estimation was generally easier using spectrogram cross-coincidence (i.e. computing the time lag required to best match the call blueprint on the binary images of the spectrograms at hydrophone pairs from a logical AND on the pixel values of 0 or 1, e.g. Simard et al. 2004, Fig. 5) than by cross-correlating the filtered signal in time domain because of noise interference. Localization was performed by hyperbolic fixing (Spiesberger and Fristup 1990), isodiachrons and Monte-Carlo simulations (Spiesberger and Whalberg 2002, Spiesberger 2004), and by an acoustic propagation model (Tiemann and Porter 2004) (details in Roy et al. 2008).

3. RESULTS

Ships transiting in both directions along the study area increased noise over the whole spectrum for 0.5-1 h around the ships' closest point of approach to the hydrophones (Fig. 3). During ships' ~ 3-h transits, their intense noise successively polluted the hydrophones of the array along their route. At times, strong currents induced strumming and flow noise that polluted the calls' band at tidal peaks, thus negatively impacting the hydrophones located in the maximum flow.

Call time series for the 80-min period marked on Fig. 3 show a 26-min sequence where 3 hydrophones detected 20-Hz fin whale calls (Fig. 4, 4h19 to 4h45). This call series comprised two ~15-min bouts separated by 3 min. The calls are repeated at ~11-s intervals, but occasional calls, named backbeats, lag their preceding call by ~17-s (Fig. 5; c,f, Samaran 2004), a characteristic that can help confirm adequate time alignments. TDoAs were estimated from spectrogram cross-coincidence for 21 1-min sequences (e.g. Fig. 5). The whale was found to be close to M4 hydrophone on the northern slope of the Channel; the locations on land allowed easy removal of ambiguous localizations (Fig. 6). The whale showed slight displacements (< 0.5 km from hyperbolic fixing) during this 26-min period from both localization methods. The localization uncertainty was ~1.2 km from the radius of the isodiachron Monte-Carlo localization cloud (4000 simulations taking into account an error of 20-m in hydrophone position, 0.5 s in TDoAs, and 5 m s^{-1} in effective sound speed). The mean distance between the locations of the peak density of the isodiachron Monte-Carlo simulations for each of the 21 sequences of 1 min and the hyperbolic fixing solutions was 100 m (SD = 32 m).

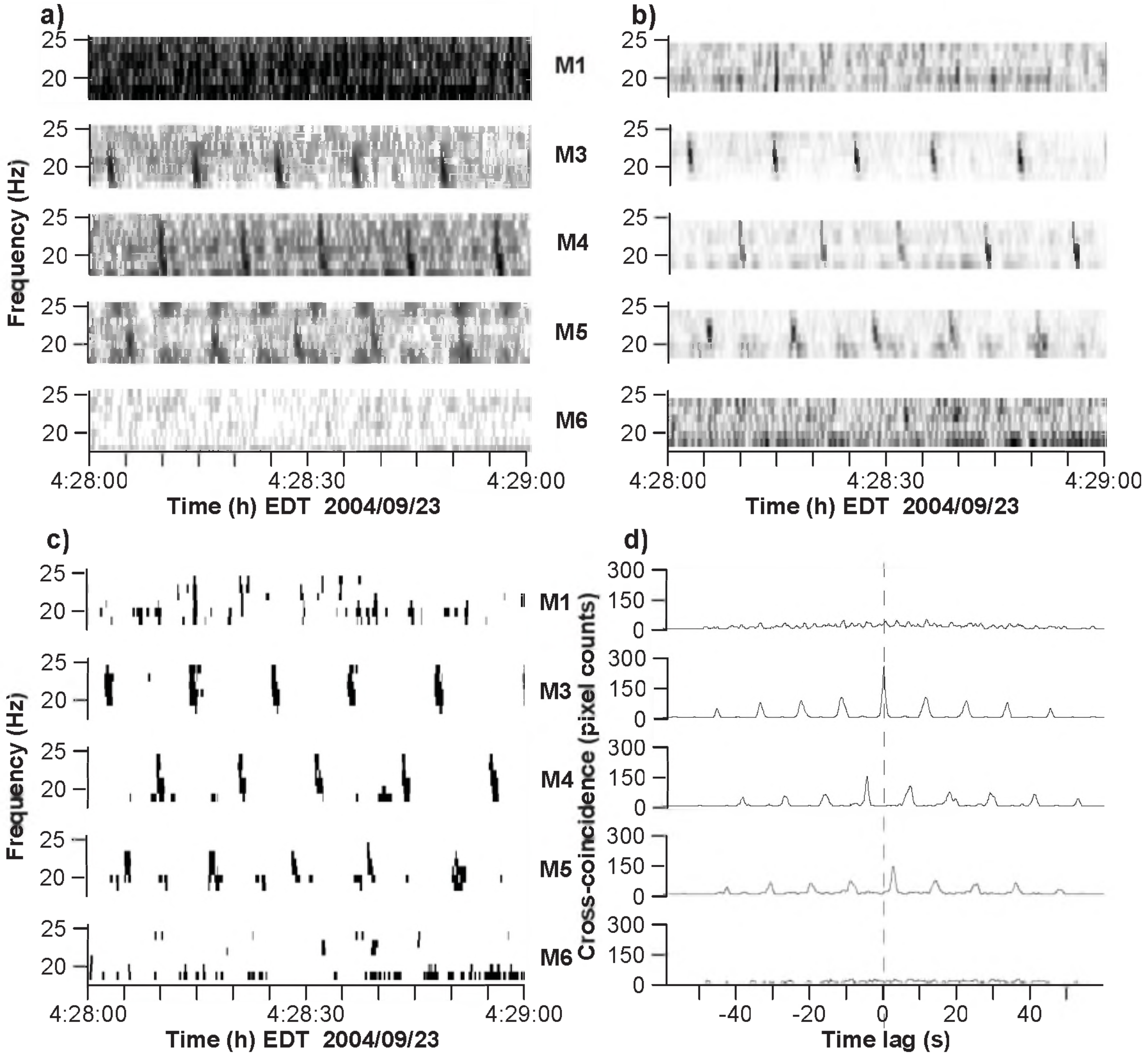

Figure 5. Example of signal processing for TDoA estimation for the 1-min segment pointed on Fig 4.: a) Spectrograms of the calls where same relative dB palette is applied to all hydrophones; analysis window 0.1 s, frequency resolution 1 Hz. b) Images of the spectrograms in a) where the palette is specific to the hydrophone and frequency view, and the extreme frequencies were trimmed out. c) Binary images of b) retaining only the strongest 5% intensities. d) Cross-coincidence of images in c) resulting from a logical AND operation using M3 hydrophone as reference to estimate TDoAs from peak values.

4. DISCUSSION

Despite the difficulty of applying PAM to track whales in a highly-fluctuating and noisy environment such as the head of the Laurentian Channel, the results show that it is feasible for a significant proportion of the time, using a sparse array of hydrophones. Even though detection and localization was not always possible because of masking noise, the frequent vocalisations and the low displacement rate of the whales allowed their mapping with a reasonably good resolution in time and space. With a good knowledge of the oceanographic, propagation and noise characteristics of the study area, it is possible to effectively implement PAM technologies to monitor whales in this meso-scale basin over long periods from a sparse array of autonomous hydrophones.

Further attention should be given to determining the optimal hydrophone density and 3D spatial arrangement, regular clock synchronisation, and minimization of masking from mooring strumming, vibrations and flow noise. Covering the hydrophone with open-cell foam or membranes might reduce flow noise for short-term deployments, but bio-fouling negates their long-term use. Choosing the hydrophone location after considering currents' 3D spatial structure helped to reduce the problem. Hydrophones less sensitive to vibrations and flow noise, but still affordable to limited research budgets, would be desirable. Directional sensors (e.g. Greene et al. 2004) able to simply and accurately determine the source direction under noise conditions should also help improving PAM efficiency.

Our simple synchronization approach was successful but other more elaborated methods could be explored. Spiesberger (2005) proposed a Monte-Carlo method to

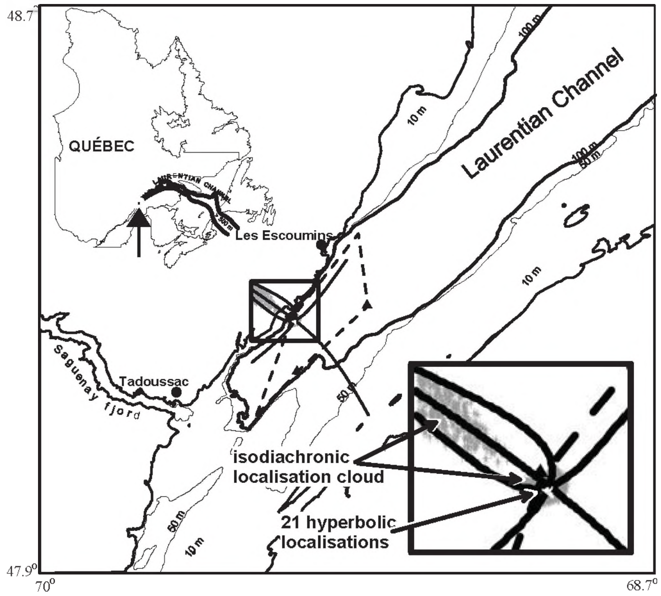

Figure 6. Localization of the 20-Hz call series shown in Fig. 4. Hyperbolic localizations every 1-min intervals between 4h19 and 4h45 (white line). The solution at 4h28 is shown with hyperboles and the isodiachron clouds of possible localizations (in gray), whose peak density is 54 m away from the hyperbolic solution.

assess probability distributions of all localization variables, including TDoAs. This approach could be adapted to track relative clock drifts at different times from the differences between the observed and estimated TDoAs of a series of independent sources recorded by the array. Thodes et al. (2006) proposed a matched-field modeling approach for synchronizing a small line array of autonomous hydrophones by simultaneous geoacoustic inversions for both whale localizations and clock offsets, combined with cross-correlation of diffuse background noise.

To choose the optimal array configuration for the study area, propagation modeling could be used to provide detection and localization probability maps under the observed local noise probability density function in the call bands and published SLs for the targeted signature calls. Augmenting the hydrophone density of the array to minimize masking by shipping noise, which depends on the relative distance between the ship and whale and their SLs difference (c.f. Simard et al. 2006a), appears the simplest way of enhancing the detection and localisation probability over the whole study area.

Efficient signal processing algorithms are required to minimise noise and multipath interferences in detecting and identifying the calls. Time-frequency domain algorithms with adequate resolution proved to be effective at this task as well as for reasonably estimating TDoAs. Localization error will never be eliminated due to imprecision associated with the input variables. Isodiachronic Monte-Carlo localization proved helpful to assess the extent of this localization uncertainty, but robust error estimation methods need further research (Roy et al. 2008). Tracking of a fixed sound source emitting at regular intervals appears highly suitable to accurately monitor the localization error, especially under such variable environments.

PAM information was not available in real-time but only after the recovery of the array at the end of the observation period. Real-time PAM (e.g. Tiemann and Porter 2004) is often required for management and protection purposes, mitigation of anthropogenic activities, and implementation of early warning systems. Such low-cost telecommunicating real-time detection, classification and localization systems are presently in development and experimentation (Simard et al. 2006b) and could eventually become versatile alternatives to cabled real-time PAM systems.

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