Passive acoustic detection and localization of whale: effects of shipping noise in Saguenay - St Lawrence marine park

Yvan Simard, Nathalie Roy, Cedric Gervaise

Passive acoustic detection and localization of whales: Effects of shipping noise in Saguenay–St. Lawrence Marine Park[a)]

Yvan Simard[b)] and Nathalie Roy[c)]
Maurice Lamontagne Institute, Fisheries and Oceans Canada, 850 Route de la Mer, Mont-Joli, Québec G5H-3Z4, Canada. Marine Sciences Institute, University of Québec at Rimouski, 310 Allée des Ursulines, Rimouski, Québec G5L-3A1, Canada

Cédric Gervaise[d)]
E3I2, EA3876, ENSIETA, GIS Europole Mer, 2 Rue François Verny, 29200 Brest, France

The performance of large-aperture hydrophone arrays to detect and localize blue and fin whales' 15−85 Hz signature vocalizations under ocean noise conditions was assessed through simulations from a normal mode propagation model combined to noise statistics from 15 960 h of recordings in Saguenay–St. Lawrence Marine Park. The probability density functions of 2482 summer noise level estimates in the call bands were used to attach a probability of detection/masking to the simulated call levels as a function of whale depth and range for typical environmental conditions. Results indicate that call detection was modulated by the calling depth relative to the sound channel axis and by modal constructive and destructive interferences with range. Masking of loud infrasounds could reach 40% at 30 km for a receiver at the optimal depth. The 30 dB weaker blue whale *D*-call were subject to severe masking. Mapping the percentages of detection and localization allowed assessing the performance of a six-hydrophone array under mean- and low-noise conditions. This approach is helpful for optimizing hydrophone configuration in implementing passive acoustic monitoring arrays and building their detection function for whale density assessment, as an alternative to or in combination with the traditional undersampling visual methods.

I. INTRODUCTION

Passive acoustic monitoring (PAM) systems for continuously detecting and tracking whales from their specific calls over ocean basins have been explored since a few decades [cf., review by Mellinger *et al.* (2007)]. With the technological developments in electronics and computers, they became more accessible and are now rapidly spreading worldwide to monitor whales in their habitats over long periods. The capacity of these systems to achieve the targeted objectives in particular environments relies on the actual characteristics of the vocalizations, local ocean noise, and propagation conditions [Stafford *et al.* (2007)].

To assess this efficiency in monitored habitats, local noise characteristics must first be established, ideally over a long-term period representative of what is sought for the PAM application. Ocean noise actually experienced by marine mammal in their critical habitats can have several effects on the animals, notably on their communications [Richardson *et al.* (1995); NRC (2003); Southall *et al.* (2007)]. Low signal to noise ratio (SNR) hinders call detection and whale tracking from PAM hydrophone arrays as well as communication with conspecifics. SNR and propagation conditions determine the detection and localization functions of PAM systems that could be implemented to estimate whale local density time series [e.g., Clark and Fristrup (1997); Phillips *et al.* (2006); Simard *et al.* (2006b); Stafford *et al.* (2007)].

Given the propagation conditions in the monitored basin, which could be estimated with a ground-truthed numerical model, and the measured noise probability density function (PDF) in the vocalization band, the performance of a hydrophone array configuration in detecting and localizing whales can be assessed. This is the objective of the present paper for a special summer feeding habitat of North Atlantic baleen whales, located in an environment that is strongly affected by shipping noise.

The baleen whale feeding ground of the Saguenay–St. Lawrence Marine Park is located in a ~100-km-long segment of the Lower St. Lawrence Estuary at the head of the 300-m-deep Laurentian Channel (Fig. 1) [Simard and Lavoie (1999)]. This area is also a portion of the St. Lawrence Seaway, a major continental seaway of North America where cargo transits to and from the Atlantic and Great Lakes. About 6000 merchant ships annually transit through the area, with up to 5 ships/h on busy summer days. During summer, an important whale watching activity from a fleet of a few hundred–passenger ships and large zodiacs is taking place in the area [Michaud *et al.* (1997); Tecsult Environment Inc. (2000); Hoyt (2001)]. Recent observations indicate that the

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[b)]Author to whom correspondence should be addressed. Electronic addresses: yvan.simard@dfo-mpo.gc.ca and yvan_simard@uqar.qc.ca.
[c)]Electronic mail: nathalie.roy@dfo-mpo.qc.ca
[d)]Electronic mail: Cedric.Gervaise@ensieta.fr.

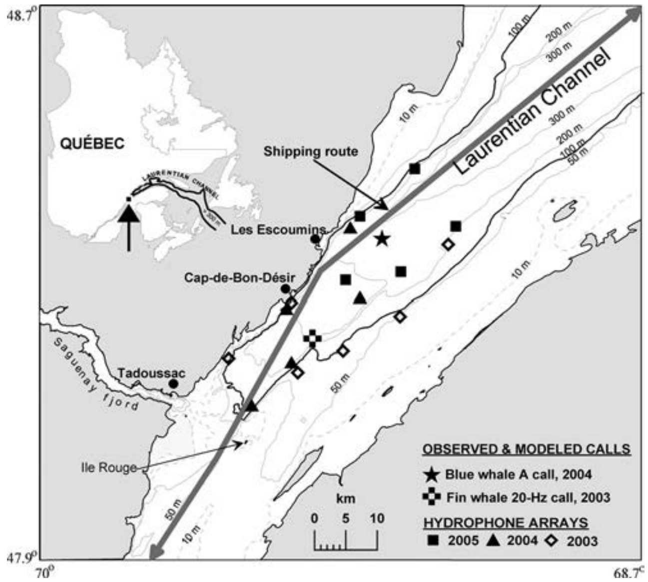

FIG. 1. Map of the study area with bathymetry, shipping route axis, positions of recording hydrophone arrays in 2003–2005 summers and of the calling blue and fin whales used for ORCA validation.

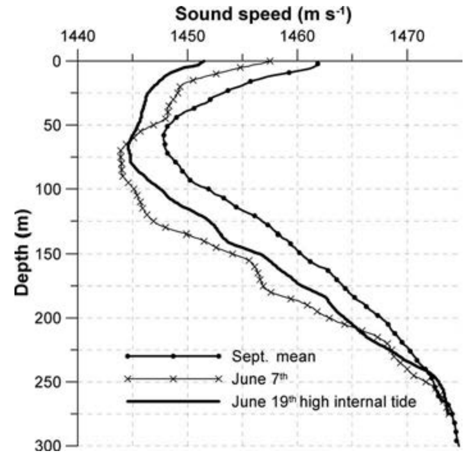

FIG. 2. Sound speed profiles in the area in summer of 2003 from Fisheries and Oceans Canada oceanographic data.

noise in the 10 Hz–1 kHz band often exceeds power spectrum density (PSD) levels for heavy traffic in ocean [Wenz (1962)], up to half of the time at some locations (unpublished data). This heavy shipping noise overlaps with the low-frequency vocalizations produced by baleen whales, notably blue [Berchok *et al.* (2006); Mellinger and Clark (2003)] and fin whales [Watkins *et al.* (1987)] feeding in the area. Call SNRs in the area mostly depend on distance between ships and whales, their respective source levels (SLs) at the corresponding frequencies, and propagation conditions [Simard *et al.* (2006a)].

In this paper, the importance of masking for detecting and localizing blue and fin whales signature calls is assessed from the summer noise level PDF in the call bands from a multiyear monitoring time series of the study area, and modeling of call propagation with a normal mode propagation model, validated with *in situ* observations. Call masking is first assessed for a single hydrophone under the seaway mean- and low-noise levels (representing quieter environments) as function of source depth and range, for the summer range of oceanographic conditions. The effects on spatial detection and two-dimensional (2D) localization from the autonomous hydrophone PAM array configuration used in 2003 are then estimated for a possible range of source depths for the different calls.

II. MATERIAL AND METHODS

Three hydrophone arrays were deployed in the study area during summers of 2003–2005 (Table I, Fig. 1). All hydrophones were HTI 95-min with a nominal receiving sensitivity in the low-frequency band (<2 kHz) of −164 dB re 1 V/μPa, which was confirmed by calibration at the Defense Research and Development Canada (Dartmouth, NS, Canada), acoustic calibration facility. The 16 bit acquisition systems were AURAL autonomous hydrophone systems (Multi-Electronique Inc, Rimouski, Qc, Canada) programmed to sample continuously over the 1 kHz band. They were deployed as oceanographic moorings with special care to minimize possible noise sources, with the hydrophones at intermediate depths in the water column close to the summer sound channel axis [Fig. 2, Table I, Simard and Roy (2008)]. In 2003, two hydrophones from a cabled coastal array deployed along a cape completed the seven-hydrophone array [Fig. 1, Cap-de-Bon-Désir, Table I, Simard and Roy (2008)]. The arrays were synchronized with a combination of means: starting and stopping the AURALs with a pulse per second impulse from a global positioning system (GPS) receiver, simultaneous recording of same acoustic signals, time drift cross-checks with the coastal array, and linear time interpolations assuming constant drift.

TABLE I. Hydrophone arrays' deployment characteristics and number of 5 min power spectral densities systematically sampled along the time series for the noise PDF.

Year	Start date	Duration (d)	Hydrophone mean depths (m)	Number of hydrophones	Array aperture (km)	Total recording (h)	Noise PSDs (No.)
2003	09/03	26	43–54	5	40	3120	
	08/19	43	93–144	2		2064	
2004	08/14	72	126–179	5	32.5	8640	1378
2005	05/03	72	113–170	4	21	6912	1043
	05/03	17	120	1		408	61

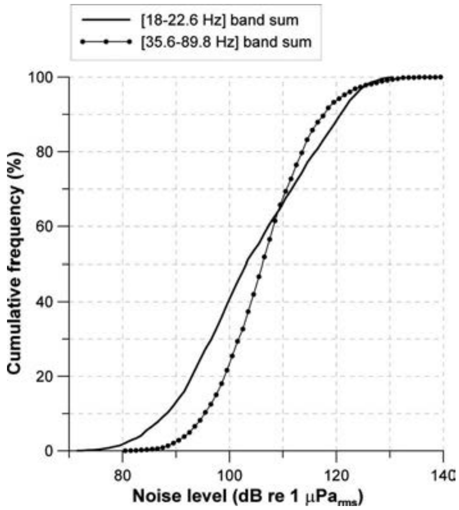

FIG. 3. Cumulative probability of summer noise levels in blue and fin whale signature calls' bands in the study area from 2482 systematic periods of 5 min recordings at ten stations. The low-noise conditions correspond to the first 25% below ~100 dB re 1 μPa_{rms}

The acoustic time series at the stations (Table I) were first examined for the presence of flow noise in the recordings, by monitoring the sound pressure level in an indicative low-frequency narrow band. Valid recording periods were those where this indicator level was below a threshold determined by cross-checks on the spectrograms of the signals for the absence of flow noise. The series of valid periods were then randomly subsampled to extract a 5 min recording for each 6 h consecutive periods to compute the noise level for ANSI third-octave bands that were summed over the call bands to get the noise levels. The summer noise level PDFs integrated over the infrasound (18–22.6 Hz) and audible *D*-call (35.6–89.8 Hz) bands were estimated for 2482 periods of 5 min extracted from the 15 960 h of recording during summers of 2004 and 2005 from the hydrophones deployed at ten stations in the study area (Figs. 1 and 3).

ORCA normal mode propagation model [Westwood *et al.* (1996)] was used to propagate representative blue whale A, B, and *D*-call and the 20 Hz pulse of fin whales [e.g., Berchok *et al.* (2006); Watkins *et al.* (1987)]. It was configured for the average seafloor conditions in the study area at the head of the 300-m-deep Laurentian channel (Table II) [Loring and Nota (1973); Massé (2001); Table 1.3 in Jensen *et al.* (2000)], and the September 2003 sound speed profile from Fisheries and Oceans Canada oceanographic data (http://www.osl.gc.ca/sgdo) (Fig. 2). Two additional sound speed profiles from June were used to assess the effect of the environmental variability in response to summer warming and the local internal tide. Four simplified profiles covering the expected envelope of summer variability and a 75 m internal tide were also used to explore the effect of variability in propagation medium.

The validity of the model was first examined by propagating actual blue and fin whales infrasounds, localized with the hydrophone arrays deployed in 2003 and 2004 by using hyperbolic and isodiachron algorithms [Spiesberger and Fristrup (1990); Spiesberger and Whalberg (2002); Spiesberger (2004)] (Fig. 1), and estimating propagation losses by ORCA. These latter were added to the measured received levels on the arrays (in decibels re 1 μPa_{rms} for the call duration corresponding to 90% of total energy) to estimate the SLs. The resulting SLs (167–194 dB re1 μPa_{rms} at 1 m) for possible source depths of 20–50 m generally agreed with published estimates [McDonald *et al.* (2001); Charif *et al.* (2002); Oleson *et al.* (2007); Širović *et al.* (2007)], except for low estimates at a few stations where sloping bathymetry differs from the model and sound speed profiles may be affected by tidal upwelling (cf. Discussion).

The SLs used for the simulations were 190 and 160 dB re 1 μPa_{rms} at 1 m for infrasounds [McDonald *et al.* (2001); Charif *et al.* (2002); Oleson *et al.* (2007); Širović *et al.* (2007)] and audible *D*-call [Berchok *et al.* (2006)], respectively. The simulated calls were downsweep chirps, from 22.5 to 17.8 Hz lasting for 1 s for representing infrasound calls, especially the 20 Hz pulse of fin whales (but also blue whale infrasounds, which obey to same propagation conditions), and from 85 to 35 Hz lasting for 2 s for the blue whale *D*-call. Simulations were run for calling depths from 1 to 50 m, the possible range of depths where air-driven calls can likely be produced [Aroyan *et al.* (2000)] and were observed *in situ* [Oleson *et al.* (2007)]. The calling depths used for assessing the performance of the hydrophone array to detect and localize whales in the feeding ground were 25

TABLE II. Parameters used for Laurentian channel silt bottom description for ORCA normal mode propagation model.

Variable	Layer 1	Layer 2	Bed rock
Gradient	Linear	Linear	
Thickness (m)	1	200	
Compressional wave speed top of layer ($m\,s^{-1}$)	1473	1575	1700
Compressional wave speed bottom of layer ($m\,s^{-1}$)	1575	1575	
Shear wave speed top of layer ($m\,s^{-1}$)	0	80	0
Shear wave speed bottom of layer ($m\,s^{-1}$)	80	80	
Density top of layer ($kg\,l^{-1}$)	1.0	1.7	1.8
Density bottom of layer ($kg\,l^{-1}$)	1.7	1.7	
Compressional wave attenuation top of layer ($dB\,\lambda^{-1}$)	−0.1	−1.0	−0.5
Compressional wave attenuation bottom of layer ($dB\,\lambda^{-1}$)	−1.0	−1.0	
Shear wave attenuation top of layer ($dB\,\lambda^{-1}$)	0	−1.5	0
Shear wave attenuation bottom of layer ($dB\,\lambda^{-1}$)	−1.5	−1.5	

and 50 m, which cover the likely bounds of calling depth range.

Cumulative PDFs of noise levels in the calling bands were used to assess call masking by attributing a probability of detection/masking to the modeled call levels as function of range and depth. These functions were then used to map the detection and localization expectancy for the array deployed in 2003 (Fig. 1) for source depths of 25 and 50 m and receiver depth of 100 m. Masking probability was assessed for SNRs of 0 dB for mean summer noise level conditions and for low-noise conditions corresponding to the first quartile of the noise PDFs. Such masking corresponds to a detector (whale or signal processor) that would integrate the noise at frequencies in the vicinity of the specific call frequency band for the call duration. These conditions best match the 20 Hz pulse of fin whales or the A and B calls of blue whales, for which the narrow bandwidth and/or short duration prevents any detection gain through signal processing.

For the larger bandwidth blue whale *D*-call downsweep, which lasts a few seconds, it can be shown that a 10 dB processing gain can be obtained from an optimal time-frequency detector [e.g., Mellinger and Clark (2000)]. This possibility is therefore considered in assessing the expected detection and localization of *D*-call from the hydrophone array. The detection probability of the array at a given location is defined as the maximum probability level obtained for that point among all hydrophones of the array. 2D localization requires detection on a minimum of four hydrophones [cf. Spiesberger (2001)]. The localization probability expected at a given location is the fourth highest rank of the detection probability for that location from all hydrophones.

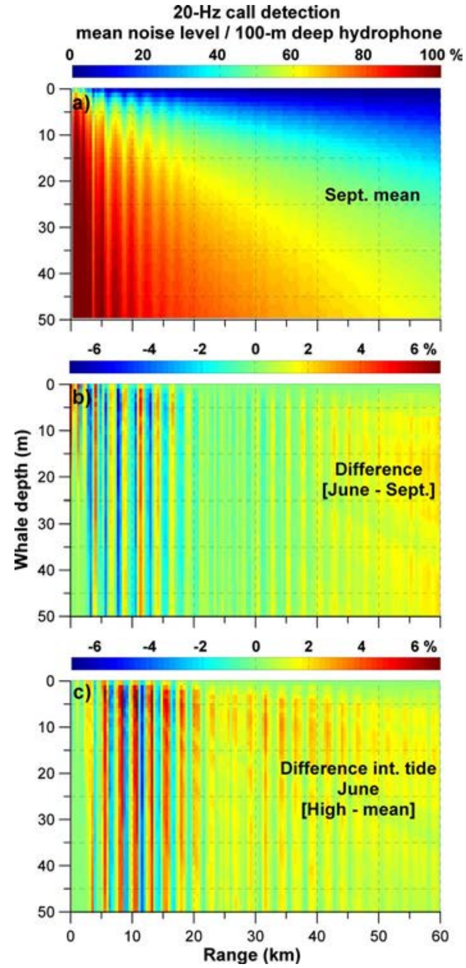

FIG. 4. (Color online) Percentage of calls expected to be detected by a 100-m-deep receiver as function of whale calling depth and range, for infrasounds for the September mean sound speed profile of Fig. 2. (a) The difference with the June 7 sound speed profile (b) and the variation due to the high internal tide in June (c).

III. RESULTS

A. Single hydrophone configuration

In the upper water column where the whale is expected to call, the probability to detect a call under mean noise conditions increases as the source depth moves toward the ~60-m-deep sound channel axis (Fig. 2) in response to the downward refraction (Fig. 4). The probability of detecting a whale calling in the upper 20 m is less than 50% for infrasounds at distances larger than 60 km [Fig. 4(a)] and almost nil for *D*-calling blue whales at ranges larger than 5 km for a 100-m-deep hydrophone [Fig. 5(a)]. Constructive and destructive modal interferences generate up to $\sim \pm 5$ dB fluctuations around the decreasing trend in received levels as function of range in the first 20 km, which translates in $\sim \pm 5\%$ fluctuations in expected detections (Fig. 6). These fluctuations are minimal in the sound channel at depths of ~100–130 m, from the modeled total loss as function of depth and range for sources ranging from 20 to 40 m and the range of oceanographic conditions (not shown). The detectability of *D*-call is improved under low-noise conditions but remains less than 50% at ranges larger than 12 km [Fig. 5(b)]. A 10 dB processing gain significantly improves their detectability [Figs. 5(c) and 5(d)], but it still remains lower than that of infrasounds.

The different sound speed profiles at the beginning of the whale season in June, yet only superficially affected by summer warming (Fig. 2), produce a 20 Hz call detection pattern that is very similar to that of September ($\pm 7\%$), except for the positions of the zones of modal interference, which change in range by ± 1 km [Fig. 4(b)]. Similarly, the semidiurnal change of sound speed profile due to the internal tide (e.g., Fig. 2) also generates slight local changes ($\pm 8\%$) in call detection in response to similar range shifts in modal interference [Fig. 4(c)]. The June conditions appear to be slightly more favorable to *D*-call detection [Figs. 5(e) and 5(f)]. These conditions also slightly shift the band pattern of detection with range.

B. Sparse array configuration

Infrasound spatial detection expectancy for the possible range of source depths under mean noise conditions is higher than 70% within the simulated array inner space [Figs. 7(a) and 7(c)]. The maps show annuli patterns around the hydrophones resulting from the above mentioned modal interferences. The localization expectancy within the array varies from 55% to 93% and presents a mosaic blueprint generated by the hydrophone detection patterns and the array configuration [Figs. 7(b) and 7(d)]. The detectability maps of the

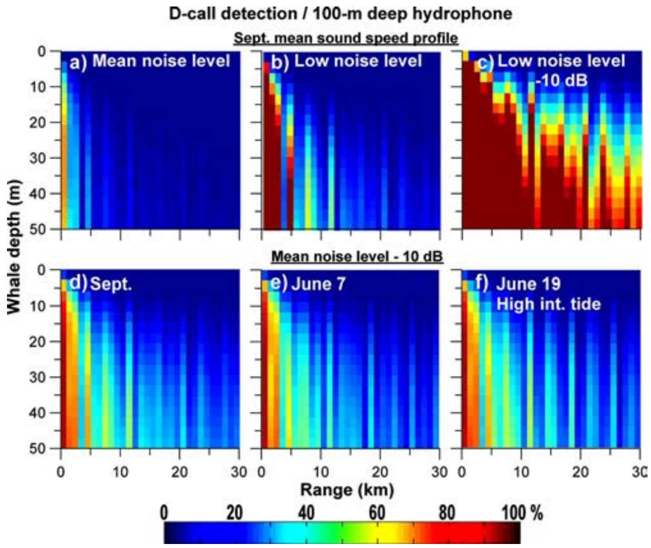

FIG. 5. (Color online) Percentage of calls expected to be detected by a 100-m-deep receiver as function of whale calling depth and range, for audible *D*-call for mean and low noise with the September mean sound speed profile [(a)–(c)] and with a 10 dB processing gain for the three sound speed profiles of Fig. 2: September mean (d), June (e), and June high internal tide (f).

higher-frequency *D*-call with a 10 dB gain processor are more variable and include areas where only 10%–20% of the calls are expected to be detected [Figs. 8(a) and 8(d)]. The maps of localization expectancy mirror this lower detectability with values varying from 5% to 55% for the mean noise conditions [Figs. 8(b) and 8(e)]. This is considerably improved under low-noise conditions, where values range from 20% to 100% [Figs. 8(c) and 8(f)].

C. Discussion

Noise level PDFs used in this study come from multi-year sampling effort distributed over the whole study area in summer, for depths corresponding to that used in the modeling. The 15 960 h of recordings this sampling effort represents make us confident that the PDF estimates are robust and representative of the average summer conditions at the head of the Laurentian channel in the St. Lawrence estuary. Flow noise at the hydrophone and strumming from the mooring are often a problem in estimating noise levels in low-frequency bands such as the whale call bands considered here. Much of these possible interferences were eliminated when selecting the time periods for estimating PSDs. For PAM implementation, however, these flow related interferences would hinder whale detection during a part of the tidal cycle, varying in length with the fortnight cycle. The three-dimensional pattern of tidal currents predicted by an operational circulation model [e.g., Lavoie *et al.*, (2000); Saucier and Chassé (2000)] could help optimizing hydrophone locations to minimize such interferences. For example, locating the hydrophones on the Laurentian channel slopes at a depth of ~50 m, as in 2003, may seem *a priori* favorable but stronger tidal currents in this area make this choice less advantageous than deeper depths in the basin just below the sound channel, as used in the modeled array.

Sound channel characteristics should also be simultaneously considered in configuring the optimal array. The 100–130 m receiver depths used in 2004 and 2005 and for the simulations appear as the optimal layer to put the hydrophones to detect 20–40 m calling whales. In this layer where the sound is steadily channeled in summer, the influence of modal interference is largely reduced compared to upper and lower depths, and the seasonal and tidal changes in oceanographic characteristics have little effects. Therefore, the detection range is increased and the detection probability as function of range is more stable. The detection radius is thus larger and the amplitude of the annulus detection pattern is reduced compared to other possible receiver depths in the water column. A receiver is also expected to be less strongly imprinted by noise from transiting ships at a depth of 100 m than at a depth of 50 m. Therefore, the duration of the masking periods would be reduced.

The results clearly show the interest of taking into account the regional noise conditions and propagation characteristics in assessing the detectability and localization expectancy of large aperture hydrophone arrays to monitor whales over a basin from their calls, especially when these overlap with the main spectral band of local noise. Although baleen whales' powerful infrasounds can be detected over distances exceeding hundreds of kilometers in deep oceans [Stafford *et al.* (1998)], at their traditional feeding ground in the Saguenay—St. Lawrence Marine Park, it appears that, beyond ~60 km, the majority of these calls are most likely masked by the seaway shipping noise. Detectability of the audible blue whale *D*-call is less because of their 30 dB lower SL and higher noise levels in this band, which is closer to shipping noise spectral peak [Wales and Heitmeyer (2002); Simard *et al.* (2006a)]. However, their larger bandwidth and time-frequency structure allows processing gain to significantly improve their detectability. This allows maintaining this call in the list of valid prospects for whale monitoring over large distances from sparsely distributed hydrophones, despite its lower SL.

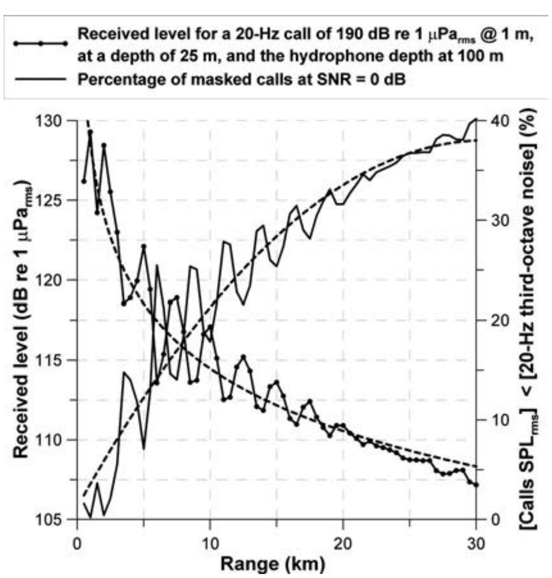

FIG. 6. 20 Hz call received level and percentage of masked calls under mean noise conditions as function of range for a 25-m-deep calling whale and a 100-m-deep receiver.

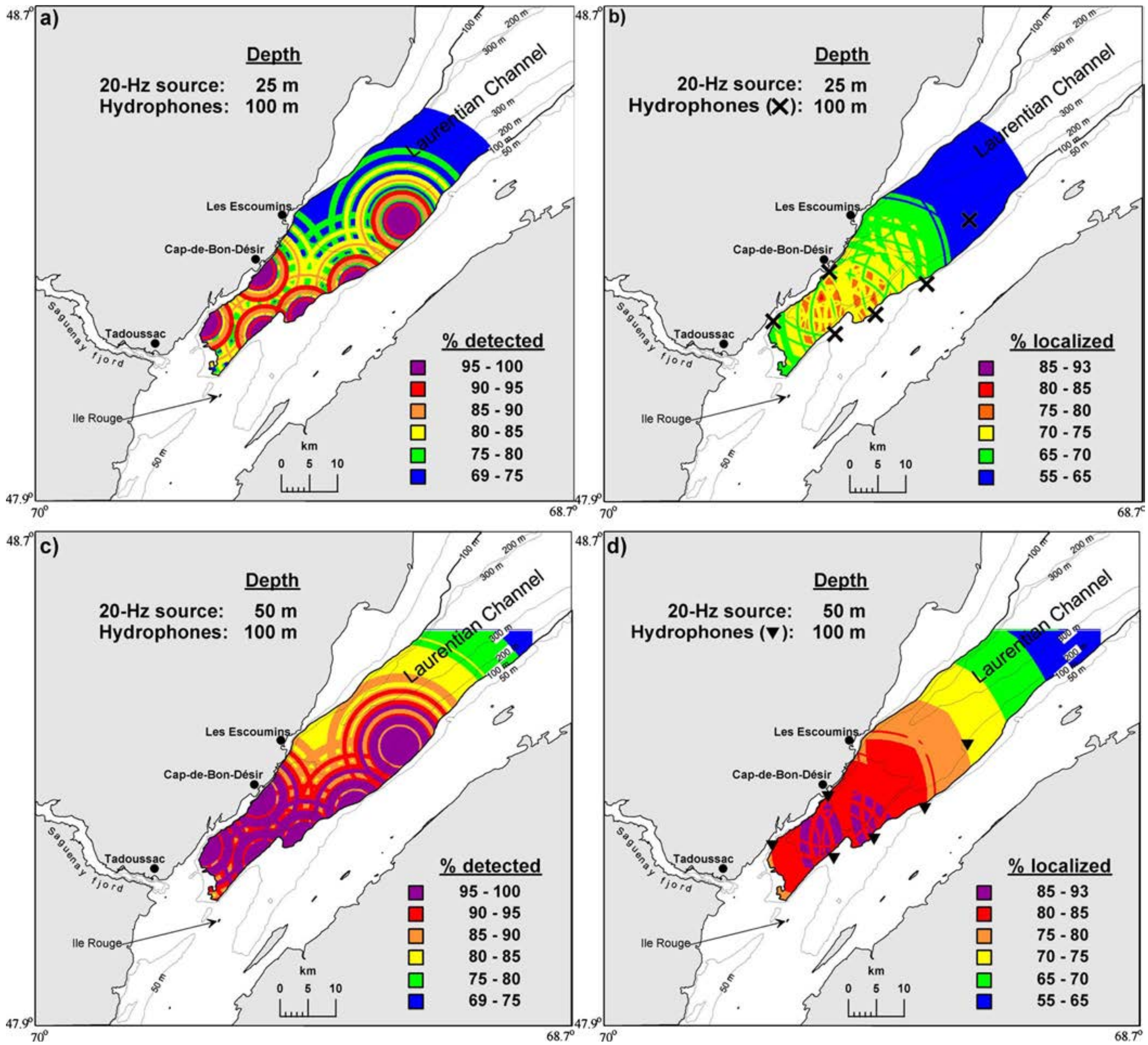

FIG. 7. (Color online) Maps of percentage of infrasound calls from 25 and 50 m calling whales expected to be detected [(a)–(c)] and localized [(b) and (d)] by a 100-m-deep hydrophone array at the 2003 array location under mean noise conditions on the seaway. Nonlinear palettes.

The presence of a well defined sound channel at intermediate depths in summer, due to the cold intermediate layer of North West Atlantic, provides notable gain to received levels as calling whales are approaching the channel axis. This latter may, however, be too deep to provide maximum gain based on present knowledge on calling depths of baleen whales [Aroyan *et al.* (2000); Oleson *et al.* (2007)]. Strong internal tides and higher-frequency internal waves at the head of Laurentian channel [e.g., Saucier and Chassé (2000)] generate semidiurnal vertical oscillations of the sound channel that are modulated by the fortnight tidal cycle. One can expect that call propagation and detectability would increase during flood and decrease during ebb, assuming that whales are calling between 25 and 50 m depths. However, the simulations showed that the gain may average zero but variations in detection probability by $\pm 7\%$ over ± 1 km should be expected depending on receiver depth. Whales' shallow night dives [Michaud and Giard (1998)] during the nocturnal migration of their krill prey to feed in the $\sim$20 m surface layer [Sourisseau *et al.* (2008)] could result in less propagating and less detectable shallow calls.

The kilometer-scale pattern in modeled received levels with range is a feature that would likely exist *in situ* because of the constructive interferences of the various propagating modes of the call, which are traveling at different speeds. However, the actual realizations of the interferences at a given location and time would likely be modulated by the time and range-dependent characteristics of the water masses, bottom gradients, and basin shape, which are not taken into account in the present normal mode propagation model. The simulations showed that seasonal and tidal variabilities can generate ± 1 km shift in the positions of these annulus patterns. They also showed that these modal interference patterns can introduce ± 15–20 dB local variations

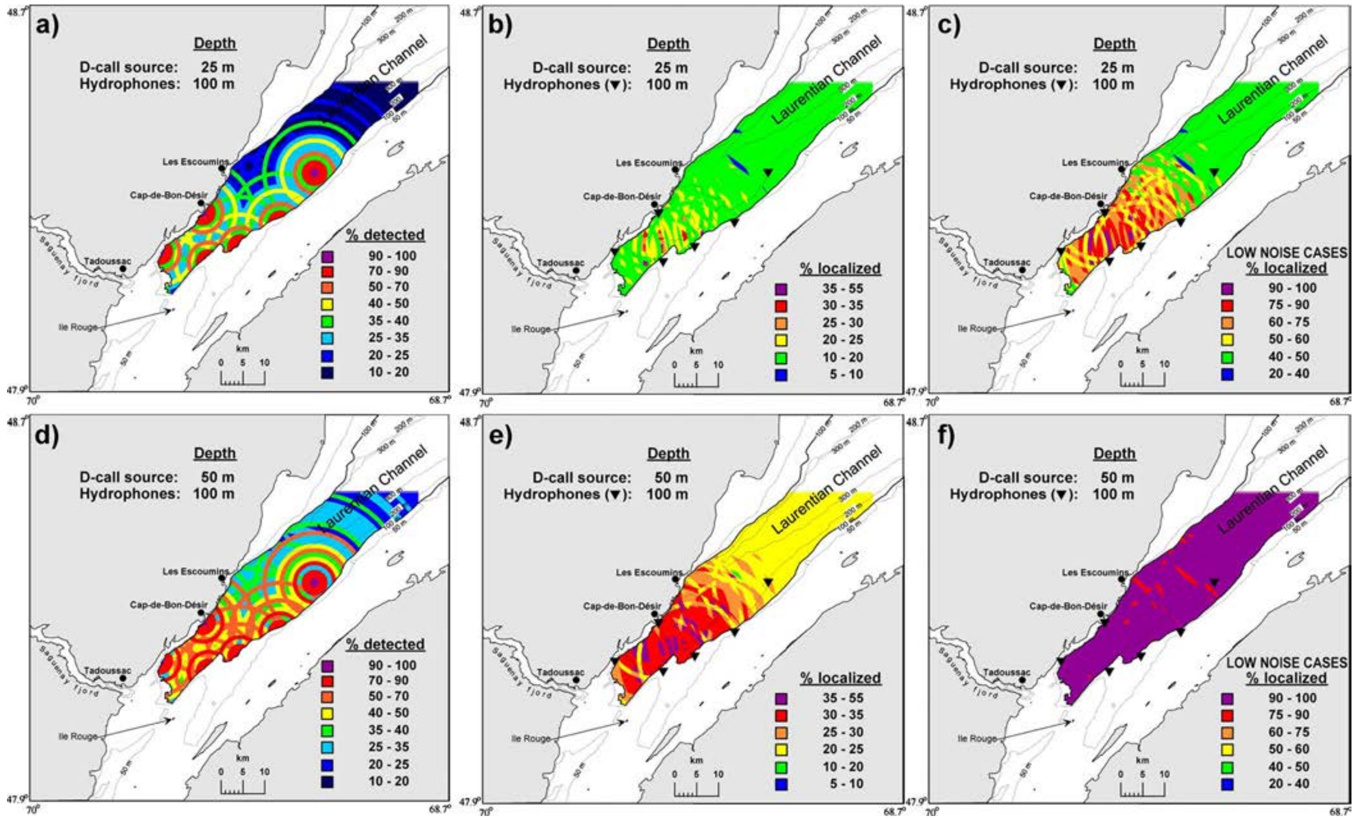

FIG. 8. (Color online) Maps of percentage of blue whale audible *D*-call from 25 and 50 m calling whales expected to be detected [(a) and (d)] and localized [(b), (c), (e), and (f)] with a 10 dB gain processor by a 100-m-deep hydrophone array at the 2003 array location under mean noise conditions [(a), (b), (d), and (e)] on the seaway and low-noise conditions occurring 25% of the time [(c) and (f)]. Nonlinear palettes.

in propagation loss and expected received levels from given sources, for both the seasonal and the tidal scales. The estimates of call SLs from the addition of propagation loss to measurements at a sparse array of distant hydrophones should show such a variability. The variability of our SLs estimates for observed fin whale 20 Hz pulses and blue whale A calls appears therefore realistic given the local characteristics of the internal tide and higher-frequency propagating internal wave [Saucier and Chassé (2000); Lavoie *et al.* (2000)]. The SL estimate range includes the published values for these calls, which is indicative of a reasonably unbiased adjustment of the propagation model to the regional conditions.

A 100-m deep PAM array of hydrophones distributed 10–15 km apart on either sides of the Laurentian channel allows at least ~70% and 55% infrasound detection and 2D localization respectively, for a whale calling at a depth of 25 m. The equivalent minima for blue whale *D*-call are about one-fourth to one-third of these percentages when a 10 dB processing gain is taken into account. To get spatial detectability and localization expectancies comparable to that of infrasounds, the detection and localization must be limited to lowest noise levels present in the area one quarter of the time. These modeling results indicate that an array of hydrophones, deployed at the optimal depth and regularly spaced about 10 km apart around the Laurentian channel, may provide a reasonably good configuration for monitoring blue and fin whales in the study area. Its detection expectancy would be >~90% and 2D localization expectancy >~75% for infrasounds in continue, and 25% of the time for blue whale *D*-call. A safe whale monitoring strategy with such a PAM would be to attach a confidence level to the whale distribution maps integrated over given time periods based on the noise levels measured at the hydrophones used for the localization. Likewise, when the hydrophones are individually used as whale detectors, call detection functions determining the detection radius of a hydrophone could be linked to the noise level in estimating the local call density for a given time period.

The sound field around a transiting ship is characterized by a three-dimensional anisotropic pattern [Arveson and Vendittis (2000); Wales and Heitmeyer (2002)] that extends over a few kilometers and affects the nearby hydrophone for a period of about 1 h at the average ship speed. Further work should explore the effect of taking this shipping noise time-space structure into account in modeling the detection and localization probability. This study was limited to the relatively flat and homogeneous Laurentian channel trench, for which the normal mode propagation model of ORCA was most appropriate and where the noise data were recorded. To extend the study to the shallower surrounding areas, the consideration of range-dependent environmental characteristics through a parabolic equation model and noise time series from these areas would be needed. Substantial efforts would then be required to properly take into account the effects of the complex bathymetry and bottom characteristics surrounding the basin, notably the steep Laurentian channel slopes where whales are often observed [Michaud *et al.*

(1997)] in response to the local aggregation of their food [Lavoie *et al.* (2000); Simard *et al.* (2002); Cotté and Simard (2005)]. The temporal variability in sound speed profile over the season and at higher frequencies should be simultaneously taken into account for accurate modeling.

Such modeling coupled with measured noise PDFs is required to determine the performance of different hydrophone array setups for detecting and localizing a proportion of whales' calls. Further work could try to evaluate the effect of the array configuration and the noise spatial pattern on the precision of the localization. The implementation of PAM to track whales in high-noise environments is truly challenging [e.g., Phillips *et al.* (2006); Buaka Muanke and Niezrecki (2007)]. The present study for the noisy Saguenay—St. Lawrence Marine Park whale feeding ground indicates that adequate protocols can be developed to optimize such PAM task even under difficult conditions.

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