Internship Report

Year: 2
Semester: 4

Acoustic tracking of sperm whales and killer whales in a context of fisheries interaction.

Last Name: RICHARD
First name: Gaëtan

Previous and current internships: (Please indicate your current internship in bold)

Master Biosciences	Semester	Internship supervisor	Host team, laboratory	Country
1st year	S2	Dr. Jean-Luc Jung	BioGeMME	France
2nd year	S3	Dr. Olga Filatova	SMRU	Scotland
	S4	**Dr. Julien Bonnel**	**AP – ENSTA Brest**	**France**

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Abstract

Interactions between marine mammals and fisheries are real issues both ecological and economical. For instance, killer whales and sperm whales around Crozet Archipelago and Kerguelen Islands have learned to remove fish from longlines causing high economical loss and modifying survival rates. Our study fitted into this context as a preliminary step to better understand cetacean depredation behaviour. A way to assess cetacean behaviour is to monitor their acoustic activity. Indeed, cetacean use echolocation clicks while foraging, thus these sounds enable animal localisation by passive acoustic monitoring. By implementing an acoustic tracking algorithm, our purpose was to predict the setting of 4-hydrophone array so that tracking capacity was optimal, while respecting constraints on the length of the cables and the maximal depth of the recorder. We associated the hydrophones in two pairs, and demonstrated that the deeper the first pair was and the longer the distance between the pairs was, the better the precision of localisation was. These results will allow optimal deployments of hydrophones among longlines, so that depredating cetaceans could be localized accurately, and thus the depredation issue better understood.

Introduction

Interactions between marine top predators and fisheries are global phenomena, and in most of the cases are sources of conflicts (Northridge and Hofman, 1999). For instance, some marine mammals have learned how to remove fish from lines or nets, such as sperm whales, *Physeter microcephalus*, and killer whales, *Orcinus* orca (Donoghue et al., 2002; Gillman et al., 2006; Hamer et al., 2012; Kock et al., 2006). This activity of depredation (Donoghue et al., 2002) could lead to significant financial cost for fisheries (Read, 2008) and to biological cost for marine mammals, such as higher risks of mortality and modification of energy balances (Northridge and Hofman, 1999).

Our study focused on the context of depredation off the Crozet (46°25'S, 51°40'E) and Kerguelen (49°20'S, 70°20'E) Islands, Southern Indian Ocean. In these waters, killer whales and sperm whales depredate on longline fisheries targeting a high commercial valuable fish, the Patagonian toothfish, *Dissostichus eleginoides*. Indeed, a recent study estimates a financial loss around €60M in 10 years due to the depredation of killer whales and sperm whales in the Crozet and Kerguelen Exclusive Economic Zones, EEZ hereafter (Gasco, 2013).

Patagonian toothfish is a demersal fish presenting a large bathymetric distribution during their life. Indeed, they spawn in deep water, and after hatching, larvae become pelagic and remain in upper water layers (<500m) until their juvenile stage when they become benthopelagic. Juveniles migrate into deeper water while growing (Collins et al., 2010). Thus, in order to avoid catches of juveniles, demersal longlines are deployed deeper than 500m and up to 2500m (Tixier et al., 2010, 2014). It is known that sperm whales can reach such depth and that they can naturally feed on toothfish (Yukhov, 1982), whereas it is unknown whether toothfish is a natural component of killer whales diet. Indeed, Crozet killer whales feed on penguins, seals, baleen whales and fish (Guinet, 1992), and a recent study revealed that killer whales could occasionally reach depth up to 900m (Pitman et *al*. pers. comm.), so they might also have natural access to toothfish. However, it is still unknown how sperm whales and killer whales interact with the longline fisheries within the EEZ.

It is thus necessary to find a way to assess whales' behaviour while interacting with the longlines in order to be able to address the depredation issue, by determining if this behaviour is taking place when hauling out the line and/or when the line is fishing. Monitoring whales' behaviour is hardly accessible because of logistical constraints. However, passive acoustics can provide a good alternative to direct observations and data-loggers. Indeed, toothed whales, such as killer whales and sperm whales, produce echolocation clicks while foraging (Barrett-Lennard et al., 1996; Miller et al., 2004; Zimmer, 2011) in repeated trains and with a high broadband intensity. These sounds can be detected by hydrophones several kilometres away from the clicking animal.

Thus, clicks allow fine temporal and spatial scales localization by acoustic tracking (Gassmann et al., 2013; Roy et al., 2010; Thode, 2005; Zimmer, 2011).

The purpose of our study was to define the best hydrophones setting, constrained by the number of hydrophones (4), the length of the cables and the depth of the recorder, to localize killer whales and sperm whales in the depredation context. Thus, we developed a two-dimensional acoustic tracking algorithm, using a ray-tracing propagation model environment-dependant. Then, by simulating hypothetical clicks at different range and depth from the receivers, we statistically tested the efficiency of different hydrophones settings.

Material and method

We implemented our acoustic tracking algorithm following a commonly used model-based ranging method (Baggeroer et al., 1993; Mathias et al., 2013; Tiemann et al., 2006; Zimmer, 2011), which was divided into three steps: (i) modelling multipath arrivals within a research grid at a fine spatial scale, using a ray-tracing propagation model; (ii) measurement of the multipath arrival pattern for each click on each receiver; (iii) comparison of the measured arrival pattern with the predicted ones among the grid. The researched source localisation was finally determined by the localisation on the grid of the hypothetical source with the pattern matching most closely the measured one. To be more selective our algorithm associated the estimations of time delays and of the arrival angles.

In our study we developed the acoustic tracker without real data, so we simulated the "measured" data.

Setting of the environment

Underwater sound propagation is highly dependent of the speed of sound which is also dependent of oceanic environment parameters. We used temperature and salinity data from the World Ocean Database (NOAA) within the EEZ. Thus, for a given GPS point we had temperature, T (Celsius), and salinity, S (PSU), as functions of depth, z (m), and then we used the following formula to obtain the sound speed profile, c in m.s^{-1} (Clay and Medwin, 1977, see Fig.1):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S-35) + 0.016z, \quad (1)$$

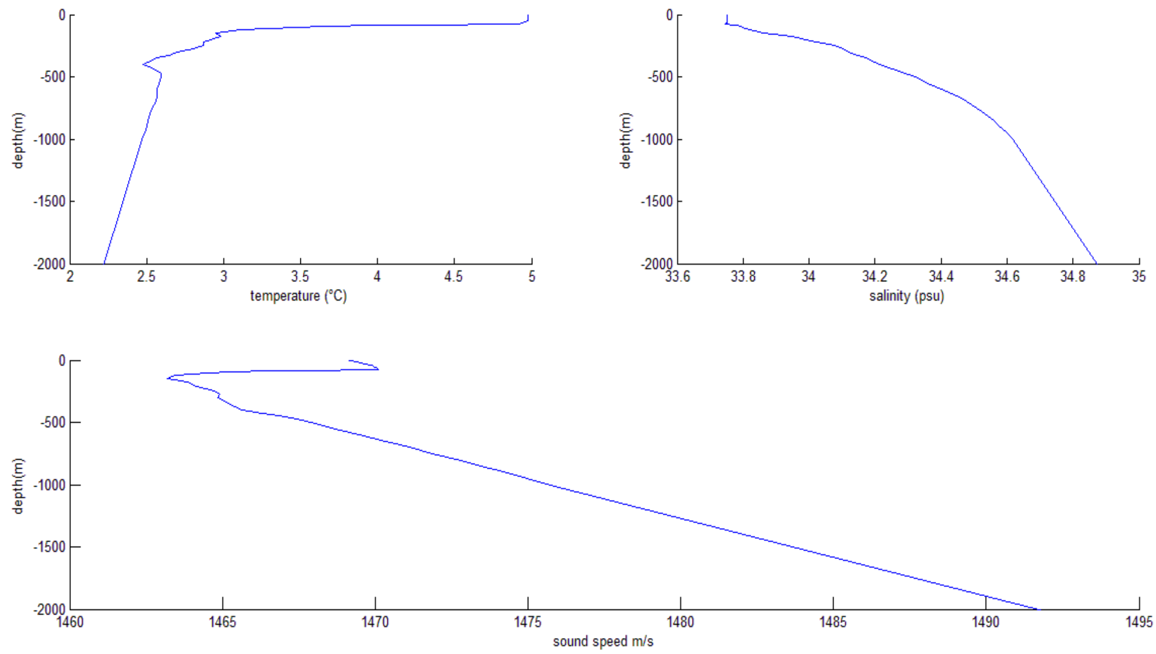

Figure 1. Temperature (top left) and salinity profiles (top right) used to calculate the sound speed profile (bottom) for this study.

The sound profile is required to model the sound propagation within a two-dimensional research area. We ran the Gaussian beam-tracing acoustic propagation model, BELLHOP (Porter and Bucker, 1987), through the software Matlab, in order to simulate hypothetical sources among a research grid, received by the hydrophones (Mathias et al., 2013; Tiemann et al., 2006). This modelled research grid served as a reference to localise sounds recorded, since for each point BELLHOP outputs the arrival times and angles of simulated rays.

Fisheries within the EEZ use longlines measuring in average 8000m and generally deployed between 500 and 2000m depth (Guinet et al., 2014; Tixier et al., 2010, 2014). Consequently, we defined a research grid of 10000m in range and 2000m in depth (Fig.2.a.), with a resolution of 20x10m (range x depth). We did not modelled difference of bottom depth as our model was independent of bottom reflected rays. For each simulated source on the grid, 50000 rays were launched between -89° and +89° from the horizontal. BELLHOP outputted arrival time and arrival angle (which do not depend on the source frequency) on each receiver and bounce numbers on the surface or on the bottom for every ray of each source among the grid. The receivers were modelled on the vertical axis at the beginning of the grid.

The recording device is a vertical array composed of 4 hydrophones linked to a centrally located receiver by 100m-long cables. Our tracking algorithm was based on two models, a time-delays estimation, commonly used with widely spaced hydrophones, and a beam-forming method (estimation of arrivals angles), requiring closely spaced hydrophones (Gassmann et al., 2013; Mathias et al., 2013; Zimmer, 2011). Thus, we associated the hydrophones in two pairs, within which hydrophones were separated by 10m (Mathias et al., 2013) and with variable distance between the pairs (Fig.2.b.). As our purpose was to find the best setting, we tested 4 different distances between the pairs, limited by cables (60, 90, 160, 190m), at 5 different immersion depths for the first pair, restricted by the recorder's pressure resistance (150, 250, 350, 450 and 550 m depth), so we tested 20 different settings.

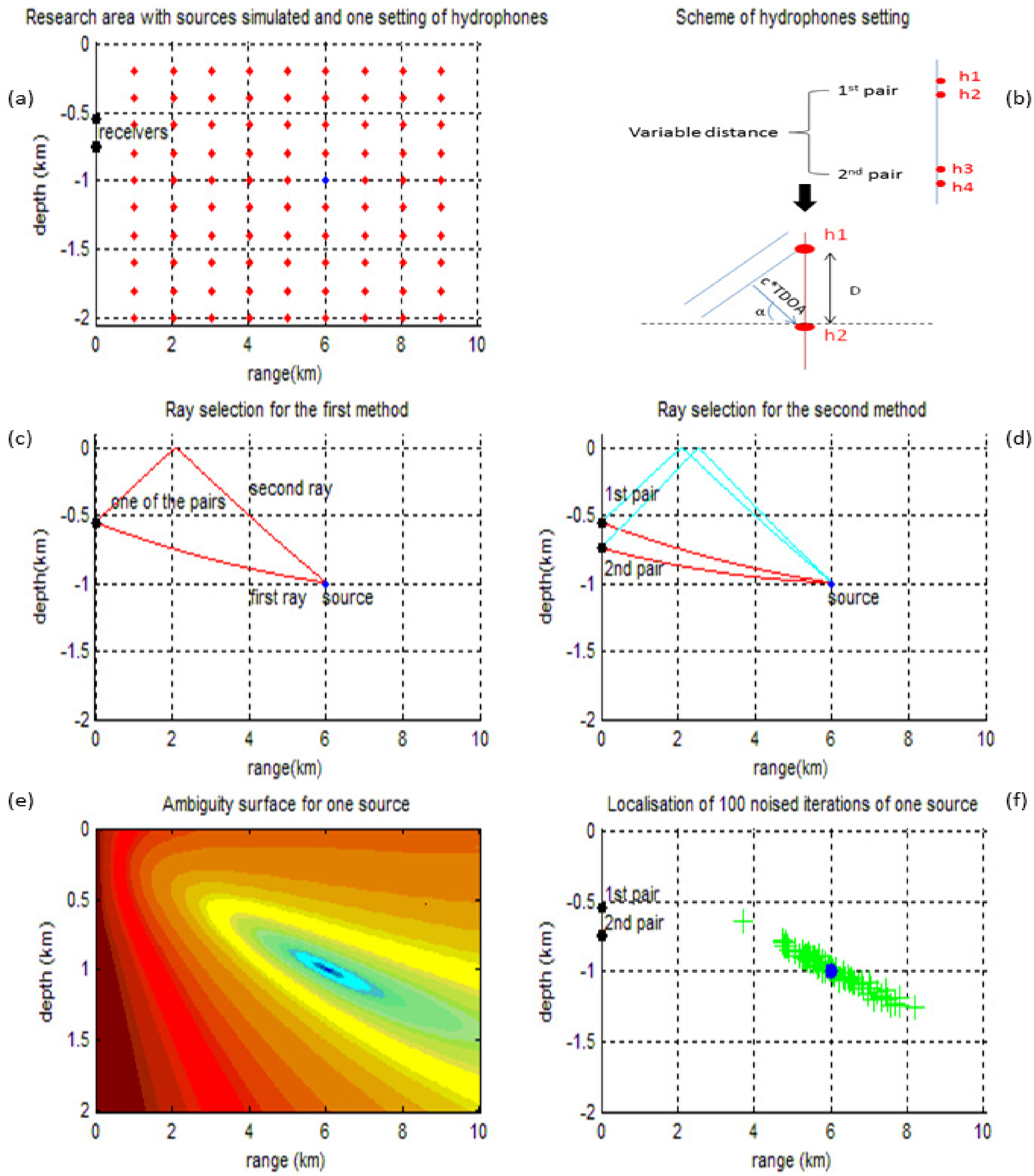

Figure 2. Method summary. The setting defined the beginning in range of the research grid, within which we simulated 90 sources (a). The hydrophones were associated in 2 pairs, with D=10m in order to estimate rays' arrival angles (b). We varied the distance between pairs and the setting's depth (a, b). To compute the ambiguity surface, we used the comparison of arrival patterns between the first and the second arrival rays in one receiver (c, in red) and the comparison of arrival patterns of the first arrival rays between two receivers (d, in red). By combining both methods, we calculated one ambiguity surface for each source (e), the coldest colours represent the lowest *Lwms* values, *i.e.* the most likely position of one researched source. To test the settings efficiency, we randomly simulated 100 noisy signals per each source position, the 100 noisy signals lead to 100 estimated sources' position in green (f), and can be compared with the true source position, in blue.

Measured data

We simulated 90 sources within the grid, every 1000m in range (from 1000 to 9000m) and every 200m in depth (from 200 to 2000m depth, Fig.2.a.). For each source, we ran BELLHOP to obtain the arrival time on each hydrophone. This measure was then noised to copy the possible estimation error of a real measure, estimated from Zimmer (2011). We added a random normalised value with a standard deviation of 150μs on each "measured" ray and repeated the operation 100 times per measure. To be closer to the reality, we removed bottom reflected rays (Mathias et al., 2013), and kept the two first arriving rays on receivers for each source for our tracking algorithm. Then we calculated the rays' vertical arrival angles on each pair of receivers (Eq.2). Considering that clicks propagate as a plane wave on short range (Fig.2.b.), we used the time difference of arrival (*dT*) of the same ray between two hydrophones closely spaced, D=10m, to compute the incident angle, α in radian (Gassmann et al., 2013; Mathias et al., 2013):

$$\alpha = \operatorname{asin}\left(\frac{\mathrm{c.dT}}{\mathrm{D}}\right), (2)$$

with *c* the mean sound speed ($m.s^{-1}$).

Ambiguity surface

An ambiguity surface is a two-dimensional function comparing the measured rays' pattern with modelled rays' patterns among the reference grid (Fig.2.e.). We used two different comparison models using weighted mean-square error. For each points of the grid (*r,z*), both methods estimated the mean-square error between the measured and modelled time difference of arrival between two arriving rays (*dT*), and the mean-square error between measured and modelled arrival angles (α) of these rays.

The first method used the first and second arriving rays (*i, j*) measured on one receiver (Mathias et al., 2013, see Fig.2.c.). We computed the weighted mean-square error (*Lwms*) between the measured rays (*i, j*), using all possible combination of the modelled rays (*A*, *B*) on one receiver, for each point of the grid (*r,z*):

$$Lwms_{pair\ 1\ or\ 2}(r,z) = \min_{A,B}\left[\left(\frac{dT_{A,B}(r,z)-dT_{i,j}}{\sigma_{time}}\right)^2 + \left(\frac{\alpha_A(r,z)-\alpha_i}{\sigma_{angle}}\right)^2 + \left(\frac{\alpha_B(r,z)-\alpha_j}{\sigma_{angle}}\right)^2\right], (3)$$

with σ_{time} the standard deviation of the measured arrival time differences and σ_{angle} the standard deviation of the measured angle. For each point of the grid (*r,z*), we selected the modelled arrival combination (*A*, *B*) minimizing *Lwms*. We applied the first method on each pair, so we obtained two different ambiguity surfaces.

The second method is similar to the first one, but we only considered the first arriving rays on two receivers (Fig.2.d.). We computed the *Lwms* between the first measured rays of each pair of hydrophones (*i1*, *i2*), using all possible combination of the modelled rays between the two pairs (*A1*, *A2*), for each point of the grid (*r,z*):

$$Lwms_{2pairs}(r,z) = \min_{A1,A2}\left[\left(\frac{dT_{A1,A2}(r,z)-dT_{i1,i2}}{\sigma_{time}}\right)^2 + \left(\frac{\alpha_{A1}(r,z)-\alpha_{i1}}{\sigma_{angle}}\right)^2 + \left(\frac{\alpha_{A2}(r,z)-\alpha_{i2}}{\sigma_{angle}}\right)^2\right], (4)$$

Finally, we combined the three *Lwms* obtained by the two methods to compute one *Lwms*. Thus, we considered all the comparative factors (time difference of arrival and arrival angles) available thanks the two pairs of hydrophones, and so we strengthened our selective criteria:

$$Lwms_{mix}(r,z) = Lwms_{pair1}(r,z) + Lwms_{pair2}(r,z) + Lwms_{2pairs}(r,z), (5)$$

The lowest values *Lwms* in the ambiguity surface revealed the likeliest position of the researched source (Fig.2.e.).

Statistical analysis

The ambiguity surface computation was realised for the 90 simulated researched sources. For each source position, 100 noisy signals were generated so that localisation was reiterated 100 times per source position. The reiterations were used to estimate the mean errors of localisation in depth and range for each source as we know precisely the source localisations (Fig.2.f.). As we had 20 settings of hydrophones, we tested the errors of localisation between these configurations. We tested the accuracy of localisation for the 20 settings separately, for the distance between pairs regardless the immersion depth and, conversely, the immersion depth regardless the distance between pairs. Besides, once the best setting estimated, we tested whether sources are localised differently according to the depth of the source or/and the distance from the hydrophones.

We used ANOVA tests coupling with multiple comparison tests through Matlab (*anova1* and *multcompare*) to test the mean errors divergence.

Results

The ANOVA tests, which compared mean errors regardless sources' position on the grid, revealed significant differentiations (p<0.001) between the distance between pairs, between depths of the first hydrophone and between the 20 settings. Then, the multiple comparison tests showed that the deeper is the first pair of hydrophones and the longer is the distance between pairs, the lower are the mean errors both in depth and in range (Fig.3.). Indeed, we observed an additive effect between the distance between pairs of hydrophone and the first pair. Thus, the 20th settings, *i.e.* first pair at 550m with a distance of 190m between pairs, showed the lowest mean errors, both in range and depth regardless the sources' position, and significantly different from 18 other settings (p<0.05), after applying a Bonferroni correction (Fig.3.).

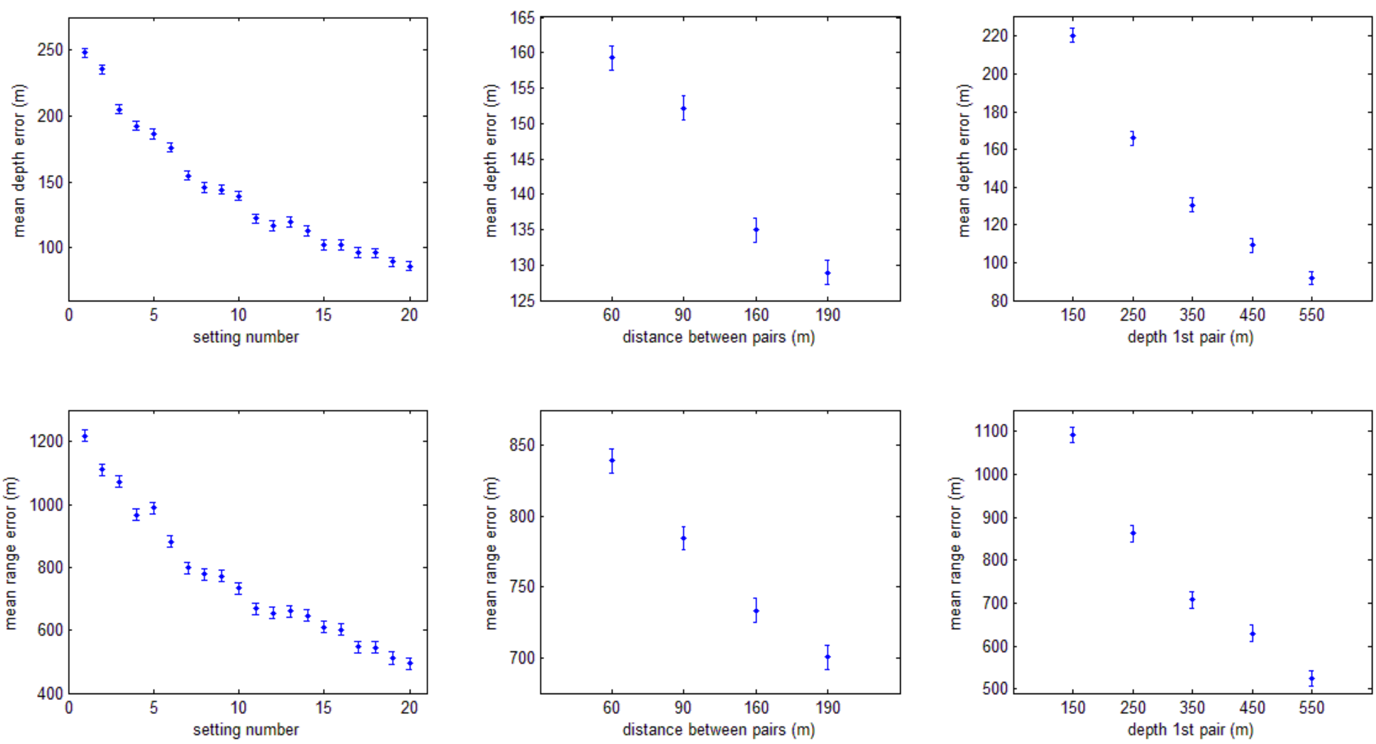

Figure 3. Mean errors of localisation, both in depth (top) and in range (bottom), as a function of the settings (left column), of the distance between pairs (middle column) and of the depth of the first pair (right column).

Once the best setting estimated, it was interesting to assess how positions of the sources could impact on the localisation precision.

When the source depth increased, regardless to its distance from hydrophones, we observed an increase of the mean depth error, from 38.4m at 400m depth to 148m at 1800m depth (Fig.4.a.), but a low variation of the mean range error. Indeed, there was no significant difference, according to the multiple comparison tests, between the mean errors (estimated around 515m) from 400m to 1800m depth (Fig.4.b.). Similarly, when the range between the sources and the hydrophones increased, we observed a slight increase of the mean depth error and a high increase of the mean range error (Fig.4.c. and d.).

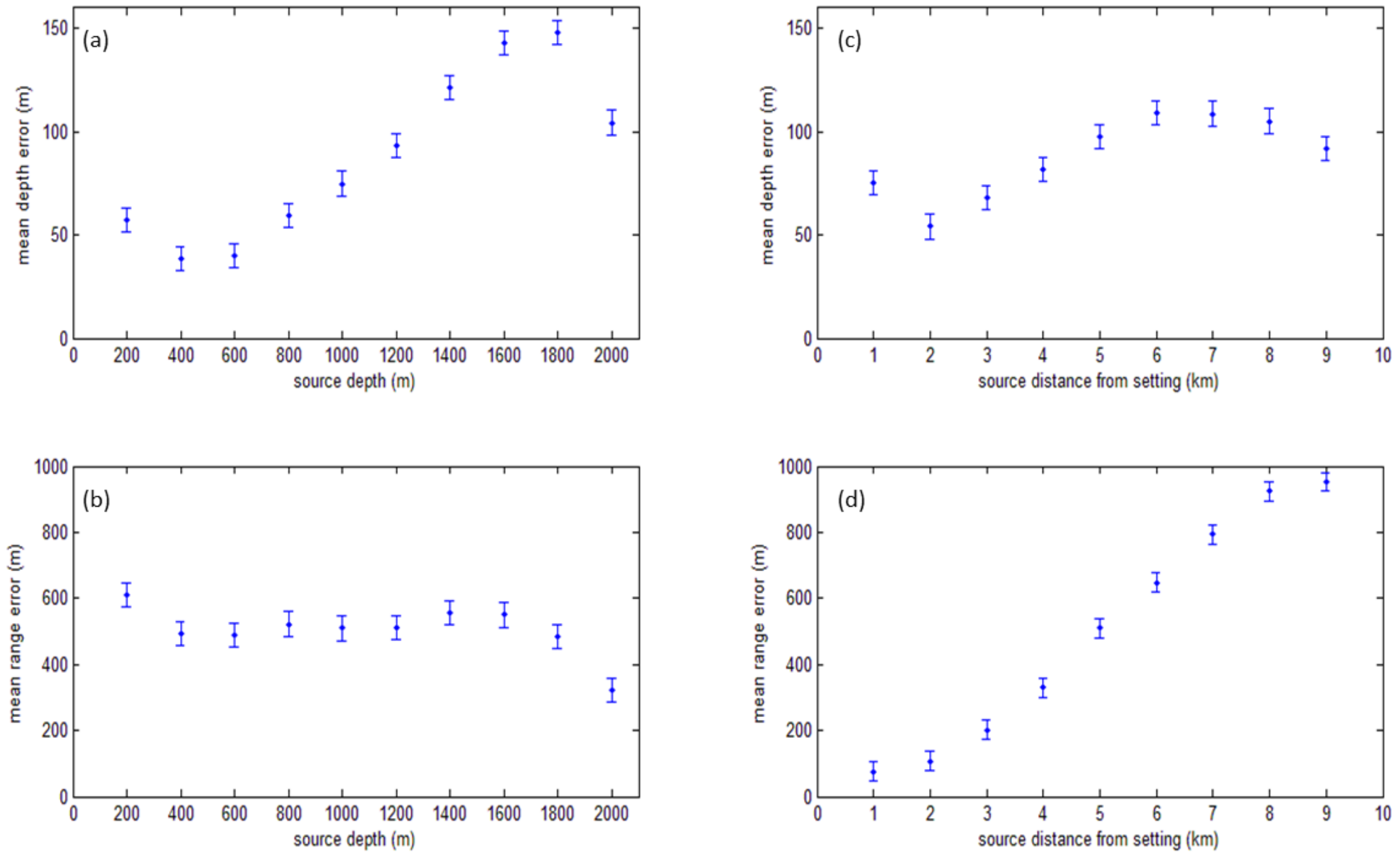

Figure 4. Mean errors of localisation with the 20th setting (1st pair at 550m with a distance between pairs of 190m), both in depth (top) and in range (bottom), as a function of the sources depths (left column) and of the horizontal distance between the sources and the setting (right column).

Discussion

This study was a preliminary work of a project which will focus on a better understanding of sperm whales and killer whales' depredation behaviour, through an acoustic approach. Indeed, no acoustic data is currently available, thus, our goal was to develop an optimised method to collect and assess acoustic data. To study depredation, a critical issue is to know at which depth animals are interacting with the longlines, so one focus of our study was to better localize cetaceans rather in depth than in range.

We based our tracking algorithm on the method exploited by Mathias et al. (2013), which revealed good localisation precisions with one pair of hydrophones for real data. As we implemented one more pair and use the two pairs to add selective criteria, we expected to also have a strong localisation resolution. Besides, we voluntarily overestimated the error of localisations by using relatively strong noises on the measure of arrival time. Indeed, we expected to have a better accuracy on the arrival time estimation with real data than with the simulated values in this study.

We revealed that to have the most accurate setting, hydrophones should be deployed as deep as allowed by the pressure constraint and with the maximum distance possible between pairs.

In our model, we considered the setting of hydrophones aligned with the longline, so range error of localization would still positioned whales on the longline. We assumed that killer whales should interact with longlines close to the surface, during hauling (Tixier et al., 2010, 2014), with a maximum possible depth at 900m, whereas sperm whales could be more likely to interact with longlines at the bottom. As a result, we should localize killer whales in depth with a maximum mean error of 75m, and sperm whales with a mean depth error of 100m, which are both enough to define whether whales interact mostly at the surface or at the bottom. It is thus essential to equip longlines with loggers recording pressure, temperature and salinity to correctly monitor the environment and set the most realistic acoustic propagation model according to local oceanographic conditions. Furthermore, by adding accelerometer among the longline and by tagging several individuals, we will be able to assess the removal of fish from cetacean and to calibrate our tracking algorithm.

Author contribution and acknowledgment

The author managed the tracking algorithm's coding, using a ray-tracing propagation, which was implemented to the algorithm with the help of Rémi Emmetière. The author also assessed the statistical analysis.

I am very grateful to Dr. J.Bonnel for allowing me to join his team and have this great experience in this very interesting research field, and I warmly thank him for his guidance during my internship. I am also grateful to R.Emmetière for his collaborative work and to B.Picard for sharing environmental data from the CEBC. I also thank Dr. C.Guinet, for his insightful comments.

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