# YOU CAN'T GET THERE FROM HERE: SHALLOW WATER SOUND PROPAGATION AND WHALE LOCALIZATION

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## SUMMARY

Sound propagation in summer conditions in the Bay of Fundy is modelled here for the case of a shallow source (a whale at 10 m depth) communicating with a bottomed receiver (an ocean bottom hydrophone at 163.1 m depth). It is shown that the signal strength along the direct path at long ranges (5–8 km) is extremely weak, for three reasons: (1) destructive interference of the shallow source and its image in the sea surface, (2) destructive interference between paths arriving at the bottom and their bottom-reflected counterparts, and (3) upward refraction by the positive sound speed gradient at the seabed. The first significant signals arriving at long ranges are paths that reflect from the surface and the bottom several times, the number of times increasing with range. Consequently, localization algorithms based on the assumption of direct straight-line paths are prone to bias and error. It is suggested that a simple straight-line, average-speed model could be made to work if the algorithm were to admit the hypothesis that the paths could be reflected paths, which could be accommodated simply by using the method of images.

## SOMMAIRE

On décrit dans ce document la modélisation de la propagation du son dans des conditions estivales dans la baie de Fundy dans le cas d'une source à faible profondeur (une baleine à une profondeur de 10 m) communiquant avec un récepteur sur le fond (un hydrophone sur le fond océanique par une profondeur de 163,1 m). Il est démontré que la puissance du signal à longue portée (5 à 8 km) suivant la trajectoire de propagation directe est extrêmement faible et ce pour trois raisons : 1) interférence destructive entre la source peu profonde et son image à la surface de la mer, 2) interférence destructive entre les trajectoires arrivant au fond et leur réflexion sur le fond et 3) réfraction vers le haut attribuable au gradient positif de vitesse du son au fond marin. Les premiers signaux significatifs arrivant à de longues portées sont ceux dont la trajectoire est réfléchie plusieurs fois à la surface et au fond, le nombre de réflexions augmentant en fonction de la portée. En conséquence, les algorithmes de localisation basés sur l'hypothèse voulant que les trajectoires de propagation directe en ligne droite sont sujets à des biais et des erreurs. Il est suggéré qu'un modèle simple basé sur la propagation en ligne droite à vitesse moyenne pourrait fournir de bons résultats si l'algorithme était modifié de manière à tenir compte de l'hypothèse voulant que les trajectoires puissent être celles de rayons réfléchis, ce qui pourrait se faire simplement par la méthode des images.

## 1. INTRODUCTION

It is evident that successful acoustical localization of whales depends heavily on the fidelity of the sound propagation model used, at least with respect to travel times, but possibly also with respect to waveform shape, in cases where correlation techniques are used. Typical "hyperbolic" underwater position fixing often assumes direct straight-line paths with a constant sound speed. This model can be adequate at short range (several water depths), but may break down in some environments at longer ranges owing to a combination of several physical acoustic effects. (A definition of hyperbolic position fixing: For two receivers of known location, if one knows the difference between arrival times of a pulse from a source of unknown location, the locus of possible source positions forms a hyberbolic surface, if the signal speed is constant. In order to reduce the positional ambiguity, arrival time differences from multiple pairs of receivers are needed: the near-intersection of the hyperbolic surfaces fixes the source position, within some error bound.)

The environment in question is a portion of the Bay of Fundy, a shallow water region of average depth 164 m over a seabed composed of a surficial layer of LaHave clay (1–10 m thick) over a basement of Scotian Shelf drift, or till. In

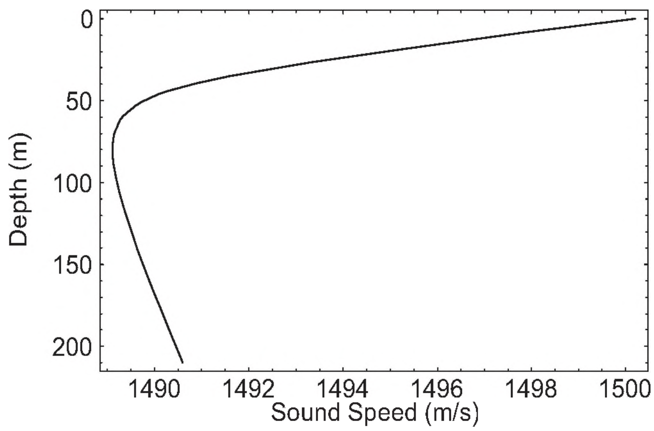


**Figure 1**. *A simplified sound speed profile for the Bay of Fundy in summer. Note the upward-refracting gradient at the bottom, the location of the receivers.*

summer there is a strong downward-refracting sound speed profile near the sea surface and a weak upward-refracting profile at the seabed, which can be approximated by a smoothed bilinear profile with a minimum at about 75 m depth, as shown in Figure 1.

The Northern Right Whale typically vocalizes near the surface, not while diving, so we assume a shallow source depth of 10 m for modelling purposes. For the experiments described elsewhere in these Proceedings, the receivers are ocean bottom hydrophones (OBHs) mounted 0.9 m above the seafloor, so we use a receiver depth of 163.1 m for modelling purposes. The elements of the array of receivers used for whale localization are widely separated, several kilometers apart, and it is expected that a whale could be localized both inside and outside this array pattern, perhaps up to a few tens of kilometres away. To give some idea of the angles involved, the direct line-of-sight path from whale to OBH is only about 4 degrees below the horizontal plane at 2 km range, and about 1 degree at 8 km range.

Considering the environment and the geometry, there are three fundamental limits on the assumption that direct-straight line paths are adequate for localization algorithms:

1. The proximity of the source to the surface results in an effective source beam pattern that creates enhancements and nulls at specific angles, owing to constructive and destructive interference between a directly radiated path and its reflection in the surface, which has inverted phase. There is always a null in the horizontal direction, which reduces the effective source strength at long range. This well-known phenomenon is called "Lloyd's mirror" [Jensen *et al.* 1994].

2. The placement of the receiver at the seabed introduces a similar effect: for every path to the receiver through the water, there is an associated path that reflects from the seabed just before combining with its mate. In effect, arrivals along these two paths arrive simultaneously, but the bottom-reflected path has suffered an amplitude loss and a phase shift. This effect would be the same for a receiver within a small fraction of a wavelength of the seabed. At near-horizontal angles, for realistic seabeds, the reflection is almost perfect in amplitude with a reversal in phase. The combination of these arrivals results in poor sensitivity of an OBH at low grazing angles.

3. The positive sound speed gradient near the seabed tends to refract sound upwards away from the bottom, decreasing overall signal amplitude there; in extreme cases, there may exist a shadow zone for some source depths (deeper than 41 m in this case), preventing acoustic rays from reaching the OBH directly.

In this short paper we will briefly explain the origin of these effects. We then examine their combination using an underwater acoustic model that correctly combines the relevant physical factors. Finally, we suggest a possible work-around for those who are constrained to use localization algorithms that assume direct straight-line propagation of rays.

## 2. EFFECT OF NEAR-SURFACE SOURCE

The change in effective level (in decibels) of an omnidirectional source near a perfectly reflecting (but phase-inverting) sea surface is given by the Lloyd's mirror expression

$$\Delta L_S = 20\log_{10}\left[1-\exp\left[i4\pi\left(fz/c\right)\sin\theta\right]\right] \text{ dB}, \qquad (1)$$

in which $f$ is the frequency, $z$ is the source depth, $c$ is the sound speed, and $\theta$ is the angle of propagation relative to

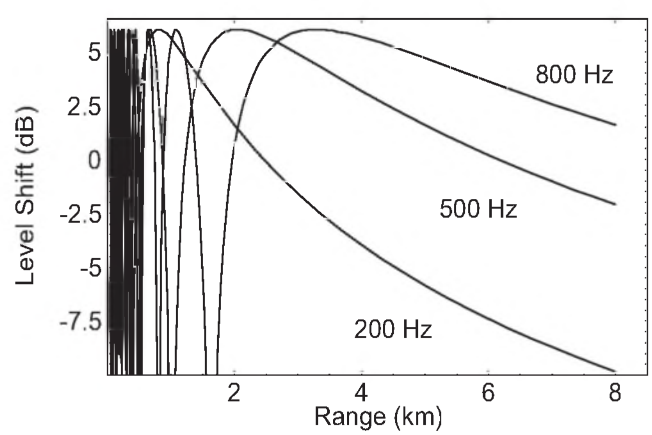


**Figure 2.** *Effect of locating the source 10 m from the surface, for a receiver at 162.1 m depth, at several frequencies, in an isospeed environment.*

the horizontal plane. Even for an unbounded isospeed environment, this has consequences as source-receiver range increases. Figure 2 shows the effect for a shallow source communicating with a deep receiver at three frequencies. (The effects of the reflecting bottom, multipath propagation, and spherical spreading are not yet included.) The effect is complex at short ranges, with both dropouts and enhancements in signal level, highly frequency-dependent. More importantly, at long ranges, there is a significant decrease of level, particularly at low frequencies, owing to the presence of the horizontal null.

## 3. EFFECT OF BOTTOMED RECEIVERS

The change in effective response (in decibels) of an omnidirectional bottomed receiver is given by the expression

$$\Delta L_R = 20\log_{10}\left[1 + R(\theta)\right] \text{ dB}, \qquad (2)$$

in which $R(\theta)$ is the complex plane-wave reflection coefficient of the seabed at grazing angle $\theta$. (This expression results simply from adding the contribution from a ray path and its bottom-reflected mate at the seabed; there is no phase delay between them other than that introduced by the reflection.) Again, for an unbounded isospeed environment, this has consequences as source-receiver range increases. Figure 3 shows the effect for a bottomed receiver receiving signals from an elevated source for the two bottom types, as a function of range. (The effects of surface reflection, multipath propagation, and spherical spreading are not yet included.) Note that the response is enhanced at short range, owing to reflected in-phase energy; however, at long range the out-of-phase reflected energy partially cancels the direct arrival. The magnitude of the effect is sensitive to the acoustic properties of the seabed.

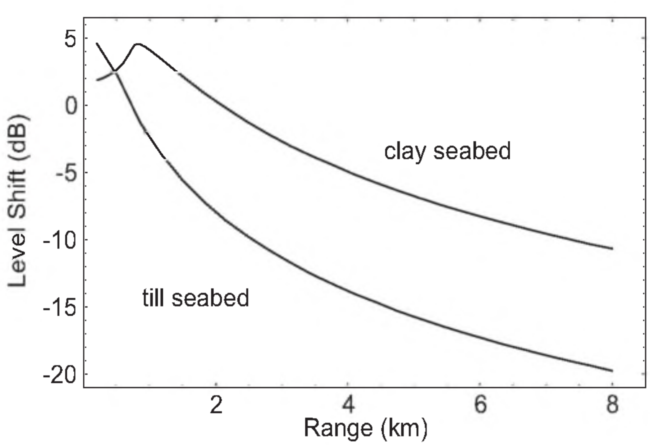


**Figure 3.** *Effect of locating receiver on the bottom, receiving signals from a source elevated 153.1 m, for two seabed types in an isospeed environment.*

The calculation of $R(\theta)$ for a semi-infinite homogeneous elastic seabed is standard and can be found in [Jensen *et al.* 1994], although they do not show the angular dependence of the phase shift. Table 1 gives the values of the seabed parameters we used: density, compressional wave speed, compressional attenuation, shear wave speed, and shear attenuation. (These parameters are not unique: one can observe the same acoustic effect with seabeds having different acoustic parameters.)

**Table 1: Acoustic parameters of the seabed types**

| | $\rho$ | $c_p$ | $\alpha_p$ | $c_s$ | $\alpha_s$ |
|---|---|---|---|---|---|
| | [gm/cm$^3$] | [m/s] | [dB/$\lambda$] | [m/s] | [dB/$\lambda$] |
| Clay | 1.54 | 1520 | 0.2 | 50 | 2 |
| Till | 2.1 | 1830 | 0.6 | 400 | 1 |

## 4. EFFECT OF REFRACTION BY THE SOUND SPEED PROFILE

Finally, there is the effect of the sound speed profile itself. A variable sound speed profile refracts rays and modifies the variation of signal amplitude along the rays. The presence of a positive gradient of sound speed at the bottom may create a shadow zone, depending on the source depth. One method of illustrating this is to trace a ray that leaves the receiver in the horizontal direction, and see how far it must travel to reach a given source depth. Using the simplified sound speed profile in Figure 1, we plot such a ray in Figure 4. At a given source depth, sources at ranges shorter than the maximum range may communicate with the bottomed receiver along a direct path ray that arrives at the receiver with positive angle; sources at longer ranges have no direct path, but may be able to reach the receiver through a path reflected from one or more boundaries, or refracted

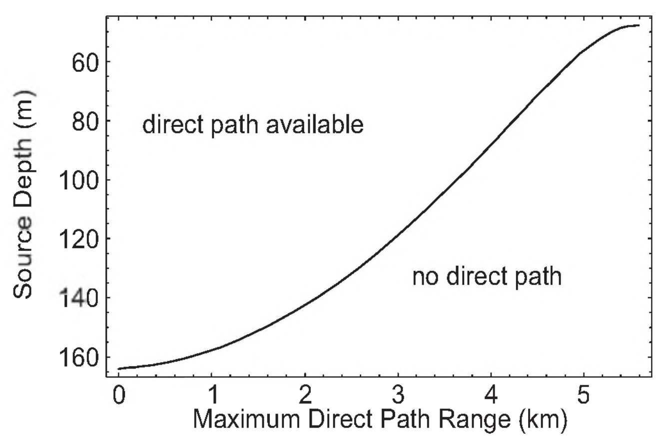


**Figure 4.** *Maximum range of a direct path between a source and a receiver bottomed at 163.1 m, for the spond speed profile in Figure 1. Sources shallower than 41 m always have a direct path available.*

back by the down-ward refracting gradient at the surface. (In a sense, this is a kind of direct path, but not for the purpose at hand.) Any of these paths will have longer travel times than a straight-line path would suggest. The full effects of refraction will be covered in the next section.

## 5. THE COMBINED EFFECT

To treat all physical effects properly, one needs to use a pulse propagation model that can handle the proximity of the source to the surface, the refractive effects of the sound speed profile, the reflective properties of the seabed, and the response of the bottom receiver. We used the OASES model [Schmidt, 1999 and 1988], which was originally developed for seismo-acoustic modelling in stratified ocean media. (OASES and other useful models can be found on the internet through SAIC's Ocean Acoustics Library, http://oalib.saic.com/). We calculated the band-limited impulse response of this channel between a shallow source and a near-bottom receiver at several ranges: 2 km, 5 km, and 8 km, shown in Figure 5. We considered the frequency band 100–800 Hz, roughly matching the Right Whale "gunshot" sounds. The seabed was made of 2 m of clay

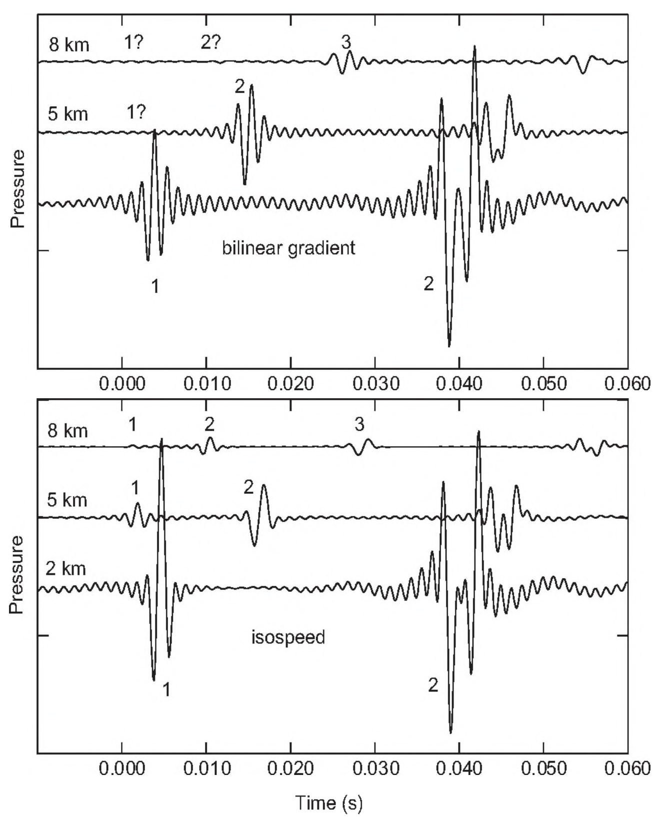


**Figure 5.** *OASES model outputs of the 100-800 Hz impulse response of the shallow water channel between a shallow source and a near-bottom receiver at three ranges, including all effects of refraction, seabed interaction, and proximity of source and receiver to boundaries. Label numbers refer to arrivals in Table 2.*

over a halfspace of till. The time axis of the plot is adjusted so that zero time at each range corresponds to a the arrival time of a pulse covering the horizontal range at the average speed in the water column, i.e. the adjusted time is $t - r/1.491$, where $t$ is time in seconds and $r$ is range in kilometres. If there were a direct arrival with significant amplitude, it would occur shortly after zero time. Two results are shown, one for the bilinear sound speed profile (upper) and one for an isospeed profile with the average speed of 1491 m/s (lower).

**Table 2: Pulse Arrival Time after r/1.491 s**

| Range r | Arrival # | KosmicRay | OASES isospeed | OASES bilinear |
|---|---|---|---|---|
| 2 km | 1 | 4 ms | 4 ms | 4 ms |
| 5 km | 1 | 2 ms | 2 ms | - |
| | 2 | 16 ms | 16 ms | 15 ms |
| 8 km | 1 | 1 ms | - | - |
| | 2 | 10 ms | 10 ms | - |
| | 3 | 28 ms | 29 ms | 26 ms |

Even for the isospeed environment, early arrivals are attenuated at long range relative to later arrivals; this is even more evident for the case of the bilinear profile, which includes refraction effects. Table 2 compares times of arrivals between the OASES results and a simple, isospeed, straight-line ray model (with multipaths) called KosmicRay, developed by the author. KosmicRay reproduces the travel times and waveforms of the isospeed OASES results, and is used to interpret the OASES calculations in ray terminology.

Figure 6 provides a schematic illustration of the relevant paths, ignoring refraction. The first OASES arrivals

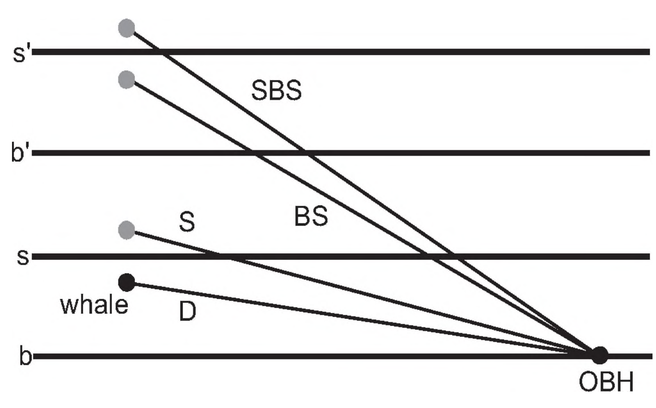


**Figure 6.** *Simplified ray path analysis of arrival structure, using the image method: on the left, s and b denote sea surface and seabed, respectively; s' and b' denote images of these planes. Within the figure, D denotes a direct path with no reflections, S denotes a surface-reflected path, BS denotes a bottom-surface-reflected path, and SBS denotes a surface-bottom-surface-reflected path*

(labeled "1" in Figure 5), interpreted in terms of rays, are a combination of direct path (D) and a single surface reflection (S). Arrival "2" is a combination of BS and SBS paths, arrival "3" is a combination of BSBS and SBSBS, etc. OASES takes care of the effect of placing the sensor directly on the seabed, discussed in Section 3, so the path with the additional bottom-reflected path is not shown.

For the isospeed OASES case, the first arrival is strong at 2 km, discernable at 5 km, and not noticeable at 8 km. The second arrival is prominent in the isospeed OASES case at all ranges. For the bilinear gradient OASES case, the first arrival at 2 km is modified by the sound speed profile, but still prominent; the first arrival at 5 km and the first and second arrival at 8 km are not noticeable. Note that KosmicRay, even though it is an isospeed model, provides a good estimate of the arrival time of the first significant arrival in the gradient OASES case, but it cannot tell you in advance which arrival that will be! This is because these paths travel at relatively steep angles, so the bending of the ray paths are not significant, and they traverse the entire water column one or more times, so an average sound speed is sufficient. (For estimating travel times, it is actually more appropriate to average the "slowness" (inverse of sound speed) rather than the sound speed, but the difference is slight unless the profile has large gradients.)

## 6. CONCLUSIONS / FUTURE WORK

We have shown that several environmental and geometric factors combine to suppress direct path signal arrivals in the case of whale localization in the summer conditions in the Bay of Fundy, particularly at longer ranges (5–8 km). The consequences of this for localization have not been investigated, but those using simple straight-line rays in their localization algorithms should be alert to bias and/or error in their position estimates introduced by this assumption. Although absolute delays in arrival times of pulses have been presented here, what is relevant is relative arrival times of first significant arrivals at sensors at different ranges from the source.

The success of a simple straight-line ray model in predicting the arrival times of reflected arrivals suggests that existing algorithms could be adapted by introducing image sources to account for multipath geometry. For example, refering to Figure 6, if the water depth is $H$ and the true source depth is $z$, then placing the source at a depth of $-z$ would account for path S; source depths of $2H \pm z$ account for paths SBS and BS, and so on. The image method would naturally result in greater travel times for these paths, and the arrival time differences would reflect the changed geometry. (Note that the travel time differences between receivers actually *decrease* for multipaths, even though the path travel times increase. This is a geometric effect.) To include multipaths in position-fixing algorithms, one is faced with which multipath to choose, which is not immediately obvious unless one uses a propagation model that includes the effects described above. One way of dealing with this issue would be to compute multiple solutions associated with multiple paths, and to select the solution that provides the lowest fix error.

Another consideration to be investigated is the consequences of interference-induced modification of the effective source spectrum by reflection at the sea surface and at the seabed. This may affect detection algorithms that rely on correlation in time or in frequency, as these reflection/interference effects alter both the spectrum and the waveform of the signal.

## ACKNOWLEDGEMENTS

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## REFERENCES

Jensen, Finn B., William A. Kuperman, Michael B. Porter, and Henrik Schmidt, *Computational Ocean Acoustics*, American Institute of Physics (New York, 1994): page 16 for Lloyd's mirror, page 46 for seabed reflection.

Schmidt, Henrik, OASES Version 2.2 User Guide and Reference Manual, Henrik Schmidt (MIT, 1999) this is a file supplied with the software package

Schmidt, Henrik, SAFARI: Seismo-Acoustic Fast field Algorithm for Range-Independent Environments, SACLANTCEN REPORT SR-113, 1988.