DEVELOPMENT OF A SIMPLIFIED RAY PATH MODEL FOR ESTIMATING THE RANGE AND DEPTH OF VOCALISING MARINE MAMMALS

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1. ABSTRACT

A simplified ray path model has been developed to simulate various source, receiver geometries. The difference in the arrival time of the multi-path signals (surface and seabed reflections) were calculated and compared with those measured on recorded data obtained during sea trials. A number of assumption have been made in initial models including a constant sound velocity-depth profile and the treatment of the surface and seabed as a simple reflecting surfaces. Initial results have shown a number of examples with a reasonable correlation between estimated position of a submerged cetacean and the associated surface observations. Examples of multiple (positioning) solutions were however found, these are in the main thought to be due to imprecision in the knowledge of the hydrophone and water depth and inaccuracies in the initial timing measurements. The use of correlation techniques and stand-alone depth measurement devices is therefore proposed for future measurements and analysis using this technique. It is felt that within constraints, this technique provides valuable additional information regarding cetacean behaviour in the wild and can be used on recorded data sets to validate observer records. The addition of more complex time measurement techniques and better ray path modelling will hopefully provide a useful analysis tool in the study of cetaceans.

2. INTRODUCTION

As part of the European Commission's DGXIV CETASEL project a study of small cetaceans was made on the edge of the continental shelf between SW Eire, Biscay and Northern Spain. The project was aimed in particular towards the study of the behaviour of small cetaceans in the vicinity of pelagic trawls. A pelagic trawl was operated by Dutch fisheries research vessel (FRV Tridens), along the edge of the continental shelf in water depths in excess of 100m. Study techniques included the use of a surface observers, various passive acoustic listening devices and the use of a remotely operated vehicle (ROV) equipped with scanning sonar and low light TV cameras.

A multiple hydrophone system has been developed to track echolocating cetaceans. Comparison of the arrival times of high frequency echolocation '*clicks*' on a number of spatially separated hydrophones were made allowing the estimation of the positioning of a cetacean in relation to the hydrophone array. The array itself was formed using two oil filled hydrophone streamers attached to top of the pelagic trawl at distances up to 800m behind the ship fig .1. Signal processing of received '*click*' data was carried out using electronics within the streamers on up to 5 hydrophone channels. The data was then coded and modulated before sending to the surface via a 1.8 km long coaxial Netsonde cable. Post analysis of the difference in arrival time for signals on different hydrophone channels was carried out over a data set spanning over 14 weeks of sea trials. This has allowed calculation of the signal's source's position in terms of three-dimensional space, Connelly [1].

Additional lower frequency (4-20 kHz) recordings were made on a fifth hydrophone placed outside the plane of the streamers. A single (Benthos AQ4) hydrophone element contained within a oil filled pod was used. Signals were pre-amplified and processed into '*click*' and lower frequency '*whistle'* or '*vocalisation'* signals. Both low and high frequency data was then sent to the surface via the Netsonde cable.

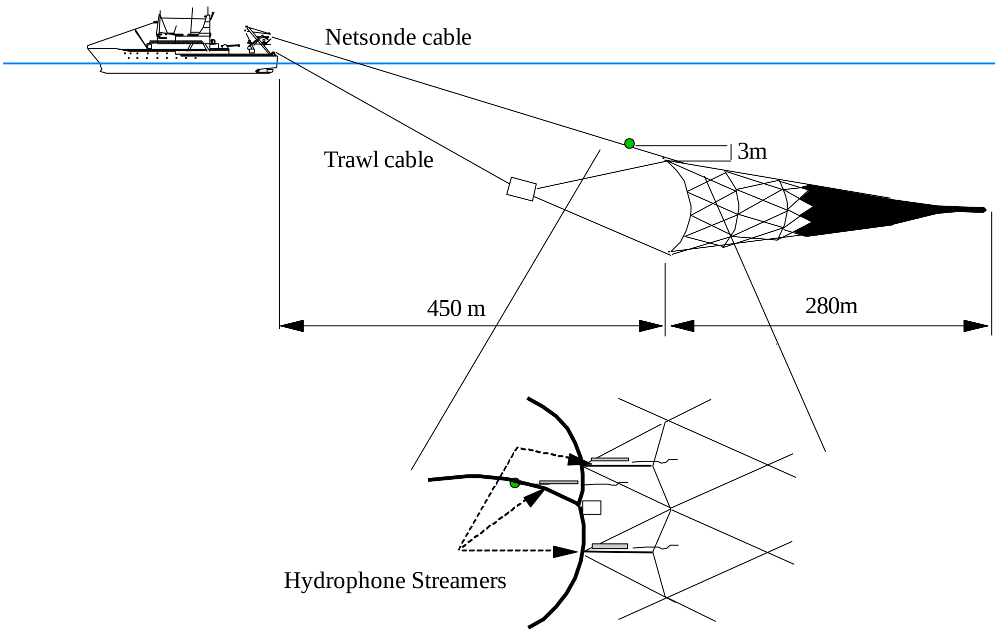

Figure .1. Hydrophone and tracking array positioning on a pelagic trawl

During several encounters of cetaceans during a trial held in October 1996 both '*click*' and '*whistle'* signals were observed from animals in the vicinity of the ship. A number of examples of lower frequency (less than 20 kHz) *'whistles'* signals including multi-path (seabed and surface reflections) signals were observed. With knowledge of the hydrophone position and water depth, comparison of the arrival time of the direct and multi-path components of a signal has allowed the estimation of both range and depth of signal source from the receiver.

Although intended to supplement and validate the visual observer's records of events this off-line tool has proven useful in extracting valuable data in conditions where visual observation was range limited by sea state or during the night.

3. MULTI-PATH SIGNALS

Acoustic signals arriving at a receiver are joined by acoustic radiation outside the main path of the direct signal after reflection at either the surface or the seabed. Multi-path phenomena of this type are characteristic of acoustic propagation underwater. The study of the problem of image interference in man made acoustic systems due to multi-path echoes, dates back to the early developments in underwater telemetry and communication systems, Caruthers[2]. The increased path length's resulting in a delayed arrival time and interference with the direct signal.

Many authors have also studied reflection and scattering effects at both the surface and seabed. A perfectly smooth sea-surface would form a near perfect reflector, more realistic situations however resulting in reflection losses of around 3dB at frequencies of 25 – 30kHz, Urick and Saxton [3] and Liebermann [4]. The degree of scattering at the surface in relation to reflection can be described in terms of *the Rayleigh parameter* $R = kH\sin\theta$ where k is the wave number ($2\pi/\lambda$), H the rms '*wave height*' and θ is the grazing angle, Urick [5]. For R << 1 the surface acts as primarily as a reflector and R >> 1 as a scatter. The degree of coherent reflection on an identical reflection and incident angle is therefore increased at lower frequencies and under smother conditions. In the case of a 10 kHz signal and a 1m wave height both scattering and reflection take place, sufficient acoustic radiation may however be reflected at a similar incident to reflected angle to allow the detection of simple reflected muti-path signals.

Reflection, scattering and transmission losses must be considered in the case of incident sound radiation arriving at the seabed. The predictions of reflection losses are however more complex than the surface due to a greater variety of seabed materials and multi-layering of the seabed itself. Additional reflected signal level may lost due to transmission of sound into the seabed. This radiation may then be re-reflected from a sub-bottom layer of differing material. The study of sound propagation at and in the seabed has also had considerable attention, Cron and Schumacher [6], Mackenzie [7], Eyring, Christenson and Raitt [8].

Refraction effects due to variations in sound velocity with depth may also cause a bending of the propagation path seen by an acoustic signal. In the case of source and receiver placed close to the seabed in deep water, ranges may are limited to several km. Variations in sound velocity with depth and the travelling of curved paths results in a variation in propagation times for signals travelling different routes, Cestone [9]. The application of *Snells law* to refraction effects, Mackenzie [10], when applied to sound propagation in water of varying sound velocities has become one the most important features of ray path models. Models for sound velocity prediction in terms of temperature, salinity and pressure have been developed over several years, reviewed Mackenzie [11] and later refined by Ross [12].

Although exact prediction of sound behaviour at the surface and seabed is complex, the treatment of both the surface and seabed as perfect reflectors was felt valid in certain circumstances and formed the basis of the initial ray path models developed within this study. Additional effects such as phase shifting, frequency smearing (due to the frequency of the wave movement, Roderik and Cron [13]) and refraction were initially ignored for this application as the resultant variations in received signal were not believed to be significant when applied to the existing data set.

4. METHOD

The higher frequency component (typically > 100 kHz) of echolocation signals observed in bottlenose dolphins (*Tursiops truncatus*) exhibit a high degree of directivity. Typical -3dB beam-widths in the order of 10^0 have been measured, in both the horizontal and vertical plane, Au [14], at these higher frequencies. Lower frequency *vocalisation* signals, typically less than 25 kHz, are often observed during interactions with cetaceans. These signals exhibit a much lower directivity to that observed by the peak energy band of the main echolocation signal. The probability therefore for the simultaneous generation of multi-path echoes from the surface and seabed is increased.

Post analysis of possible multi-path signals obtained during the October 1996 trial was carried out in both time and frequency domains. A rolling map Fast Fourier Transforms (FFT) was used, fig .2., and peak signal levels for both the direct and each multi-path for a given '*whistle*' were observed. A single frequency was then selected for the best signal to noise ratio for both the direct and multi-path signals. Arrival time differences of these peaks at a specific frequency could then be measured.

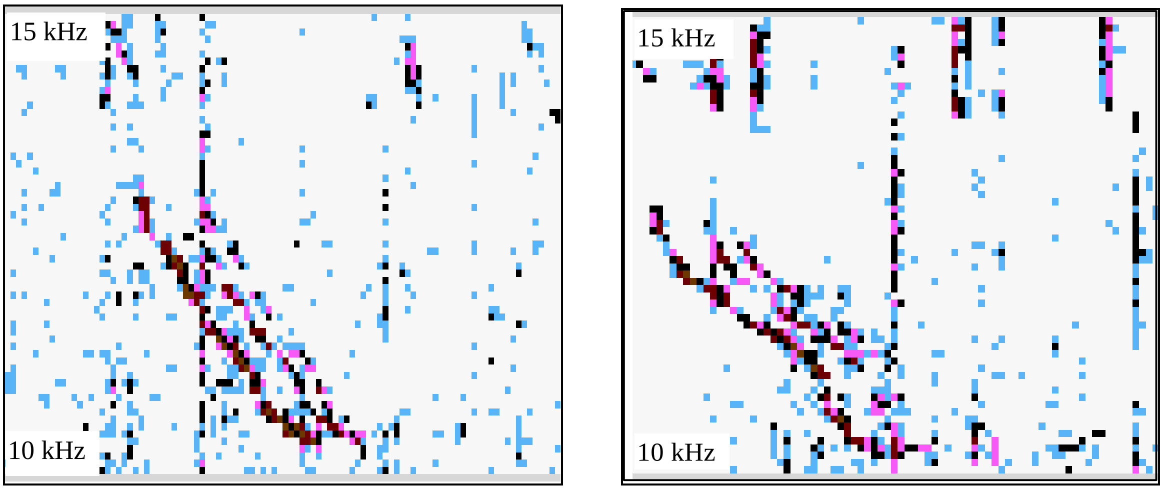

Figure .2. Rolling map FFT of vocalisation signals of cetaceans including multi-path signals.

Simple ray path models were developed in software for known depths and hydrophone positions assuming reflections of the signal at the surface and seabed. The peak signal observed for the multi-paths were assumed to have identical angles of incidence and reflection and a constant sound velocity profile with depths. Comparison of the measured and modelled arrival time's differences was then possible.

Figure .3a.Surface and seabed multi-path simulation   Figure .3b. Second surface and seabed multi-path

Although used initially while exploring the methodology manual adjustment of the geometry to match measured timings was too time consuming and prone to error. Scanning software was therefore developed, fig .3a. to evaluate all permutations of the geometry to a discrete step resolution. All possible geometry's within defined ranges were therefore checked and prioritised for the closest matches to the observed timings. Several examples were also seen which included additional multi-paths (i.e. surface - bottom and bottom – surface reflections). These were also modelled, Fig .3b. and arrival time differences computed.

Within a simple geometry, a mathematical solution for positions can also be found. Knowledge of water depth (*H*) hydrophone depth (*A*) and multi-path propagation differences (D and F) allows the derivation of angle θ_1 and range to the source (*C*), fig .4.

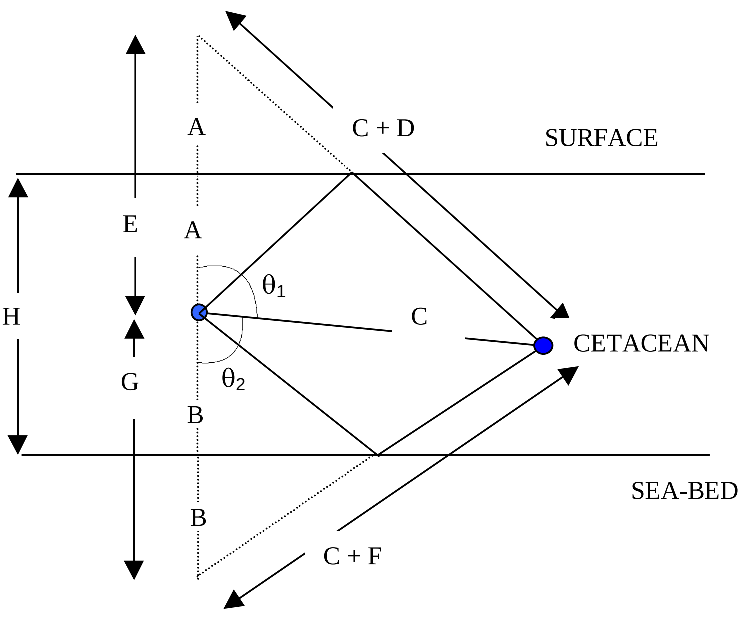

Figure .4. Geometry of simple multi-path signals.

$$\theta_1 = 180 - \theta_2$$
$$Cos\theta_1 = -Cos\theta_2$$
$$G = 2B = 2(H - A)$$
$$D = vel \times t_{rev1}$$
$$F = vel \times t_{rev2}$$

Using the Cosine rule: and

$$Cos\theta_1 = \frac{E^2 + C^2 - (C+D)^2}{2EC} \qquad Cos\theta_2 = -Cos\theta_1 = \frac{G^2 + C^2 - (C+F)^2}{2GC}$$

Equating these equations gives: and:

$$C = \frac{G^2E - F^2E + E^2G - D^2G}{2(GD + EF)} \qquad \theta_1 = Cos^{-1}\left(\frac{4A^2 - 2CD - D^2}{4AC}\right)$$

Calculation of both source range and source depth is possible. The algorithm does however require knowledge of which received echo is associated with which multi-path. Reversal of which can yield alternate solutions. Comparison is possible with solutions found using the scanning technique, covering all possible geometries. The closest matched solutions from the scanning technique were then compared to similar geometries applied to the above algorithm as validation.

5. RESULTS

A number of multi-path signals similar to those shown in fig .2. were analysed utilising the scanning technique. In most cases distinct single solution were found. Comparison with surface observation logs and known environmental factors were made. Validation of this technique is difficult at this time due to the limitation of alternate methods for positioning of the cetacean to that of surfacing observations. Consideration of factors including ship speed and maximum cetacean swimming speed did however provide several examples with a reasonable correlation between surface observations and vocalisations of animals at depth Kaschner [15].

Several examples of multiple solutions, with two '*good fits*' to measured arrival time differences were found. This is particularly problematic as the hydrophone receiver approached mid-water. In many cases multiple solutions could be eliminated through the use of a second hydrophone s placed in the vicinity of the first. Only a single matching solution for both receivers should then exist. Slight variations in water and receiver depth of just a few m's can also cause relatively large variations in solution obtained or cause the generation of multiple solutions. Improvement to the accuracy of these measurements would be required to minimise errors and the generation of ambiguous results. The use of stand alone depth measurement systems placed near the hydrophone and automatic logging of water depth at the ship will provide a much greater accuracy in positioning than that available with current data.

Errors may also have been introduced due to inaccuracies in the measurement of arrival times. Detection of a suitable part of the spectrum with sufficient signal level for the direct and multi-path signals can often be difficult. Difficulties may also arise in the coincident arrival of both multi-paths. This is a particular problem when the source and receiver approach mid-water. The use of correlation techniques is proposed to provide a higher degree of accuracy with better timing and better signal discrimination. Errors in timing can also be introduced due variations in sound velocity with depth causing bending of the propagation path and variations in the local sound wave-front velocity. The inclusion of ray path correction's within models is feasible, Mackenzie [11], if the sound velocity profile is known. The measurement of sound velocity profiles from a moving ship was however impossible with the available equipment at the time the original recordings were made. The application of standard profile models, Ross [12], will be compared with the straight-line models presented here.

6. CONCLUSIONS

Although a highly simplified approach to sound propagation underwater has been applied to the models developed, the technique has provided valuable additional data concerning cetacean behaviour in a acoustic environment with a significant multi-path component. Effects including reflection or refraction of sound due to mid-water layering have been ignored but may well become significant in the case of recordings made in deeper water. The developments of very sophisticated ray path models have taken place in the fields of underwater communications, telemetry and by the military. These models require detailed knowledge of sound velocity profiles, unavailable with this current data set. The simplified model has shown correlation with observed surface behaviour and may be useful in the study of general behaviour of cetaceans in situations where suitable signals are seen. Developments in the software modelling and improved measurement and logging should yield significant improvements in the accuracy of this technique.

7. REFERENCES

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