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The effect of internal waves on sound propagation parallel to the internal wave crests

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ABSTRACT

This study investigated the likely effects of nonlinear, short period, internal waves, typical of those that occur on Australia's Northwest Shelf, on the propagation of underwater sound. Measured oceanographic data from the Integrated Marine Observing System was used as a basis for fully three-dimensional acoustic propagation modelling. The effect of the passage of a group of nonlinear internal waves on acoustic propagation in a direction parallel to the internal wave crests at a frequency of 7 kHz was examined. The results indicated that changes in incoherent transmission loss at a range of 15 km, during periods of high internal wave activity, could be as much as 30 dB over ten minutes, and have a standard deviation of 9.2 dB over an hour. This was approximately double the standard deviation over a 1-hour period of relatively low internal wave activity. However, the modelling involved some simplifications that may impact on the accuracy of these results, which are discussed.

1 INTRODUCTION

Knowledge of the undersea environment is critical in estimating ship and submarine performance, estimating own-ship susceptibility, and for tactical planning. A major factor determining the detection range of an active sonar system is the underwater sound field environment. This may include real-time measurements of the local sound velocity profile plus any relevant records and, in particular, the experience of those who are responsible for the interpretation of the sonar environment. However, the ocean is a dynamic environment, and the sound field can change with both position and time. This is especially true for locations that experience internal waves and other oceanographic phenomena, such as the North West of Australia (Jackson and Apel, 2004). Previous studies have shown that internal waves can significantly affect the propagation of underwater sound, the magnitude and type of effect are dependent on a range of factors such as frequency, water depth, seabed properties, and the direction of propagation relative to the wave crests (Flatte and Tappert, 1975; Zhou *et al.*, 1991; Mohsen et. al., 2005; Apel et. al., 2007; Sagers and Wilson, 2017).

This study is a continuation of an investigation into the effect of the variation in sound field in dynamic oceanographic regions, where phenomena such as internal waves are present, on sound propagation. In the previous study by Parnum et al. (2017), only 2D acoustic propagation in the direction of the strongest horizontal changes in SVP (e.g. normal to the crests of internal waves) was considered. In this study, the effects of cross-track sound speed gradients, where horizontal refraction effects play a dominant role, are investigated. The propagation model used for this work was Bellhop3D: a fully three dimensional beam tracing propagation model written by Michael B Porter (Porter, 2016). Bellhop 3D is a generalisation of the well-known Bellhop model (also written by Dr Porter), to include both vertical and horizontal refraction effects and also to include out of plane seabed reflections. See Jensen et. al. (2011) for the theoretical basis of both these models and Porter (2016) for details of Bellhop3D. Being a beam tracing model, Bellhop3D is well-suited to the frequency of interest for this study (7 kHz), however like any acoustic propagation model it is important that its input parameters are carefully chosen in order to obtain accurate results.

2 METHODS

2.1 Sound field data

The sound speed data used in this study was the same as that used for the previous study, by Parnum et al (2017), that looked at acoustic propagation normal to the internal wave crests. It is based on data collected by the 200 m mooring of the Integrated Marine Observing System's National Mooring Network mooring array off the Kimberley coast (IMOS, 2017). See Parnum et. al. (2017) for further details.

For the purposes of this project, it was necessary to convert the sound velocity time-series into three-dimensional spatial sound speed fields appropriate to specific times. The coordinate system used for the current project was defined for compatibility with Bellhop3D as follows:

> X: horizontal coordinate in the direction from the acoustic source to the receiver, with X = 0 at the acoustic source.
>
> Y: horizontal coordinate perpendicular to X and increasing in the direction of internal wave propagation, with Y = 0 at the acoustic source.
>
> Z: Vertical coordinate, increasing downward with Z = 0 at the sea surface.

As in the previous project, it was assumed that the internal wave field was propagating past the mooring with a group speed of 0.8 m/s and that the propagation was non-dispersive, so that there was no change to the internal wave shape. This assumption was used to convert the 1-minute temporal samples to equivalent 48 m spatial samples in the Y direction. Measured data were interpolated onto a 2 m spacing in the Z direction, and then interpolated to a 3 m spacing in the Y direction using Matlab's piecewise cubic hermite polynomial (pchip) interpolation method. This gives a smooth interpolation without the artefacts that often result from cubic spline interpolation.

The resulting Y-Z sound field was then replicated in the X direction out to a maximum X coordinate of 16000 m. The fact the sound speed was independent of X allowed this to be done with a coarse spacing of 1000 m without loss of modelling accuracy.

2.2 Bellhop 3D parameters

Except where otherwise indicated, the parameters listed in Table 1 were used for the majority of the modelling described here.

Table 1. Bellhop3D modelling parameters. These parameters were used for the modelling except where otherwise noted.

Parameter	Value
Frequency	7 kHz
Source position (Z positive down)	X = 0 m, Y = 0 m, Z = 10 m
Water depth	204 m
Maximum receiver range	15 km
Beam type	B (Gaussian beams)
Run type for transmission loss calculations	I (Incoherent transmission loss)
Run mode	Full 3D
Calculation box size (X, Y, Z)	(16000 m, 1500 m , 250 m)
Seabed compressional sound speed (m/s)	1770
Seabed density	1894 $kg.m^{-3}$
Seabed compressional wave attenuation	0.8 dB/wavelength
Receiver bearings from source	0° (direction of positive X axis)
Elevation beam fan for transmission loss calculations	-40°:0.2°:40°
Bearing beam fan for transmission loss calculations	-5°:0.05°:5°

Sensitivity tests were carried out in order to determine the optimum beam launch angle spans and spacings for the horizontal (bearing) and vertical (elevation) directions. It was found that a +/- 5° bearing span, a +/- 40° elevation span, and a 0.2° elevation spacing were sufficient to achieve convergence in all cases. However, the required bearing spacing depended on the properties of the sound speed field, with a 0.2°spacing being sufficient in neutral and focussing situations, but transmission loss (TL) still increasing with decreasing bearing step size down to 0.05° in defocussing situations. It was deemed impractical to reduce the bearing angle step further than 0.05° because of the resulting excessive computation time. Furthermore, there seemed limited value to do so, because the modelled TL in defocussing situations was already high enough, it was likely to be limited by the underlying accuracy of the modelling method. Therefore, a bearing step of 0.05° was used to produce the results presented below.

Semicoherent and incoherent TL test runs produced essentially identical results. It was arbitrarily decided to use the incoherent TL for the majority of the results presented here. It was neither feasible nor desirable to carry out coherent TL calculations at this frequency.

3 RESULTS

3.1 Temporal variations in TL for a period of high internal wave activity

As an illustration of the magnitude of the effects of the internal waves, Figure 1 shows modelled TL versus range plots at 1 minute intervals for a 20 minute period of high internal wave activity. These results were calculated using some non-standard parameters, as indicated in the caption, but serve to demonstrate that in most cases the internal waves have increasingly larger effects on the TL at ranges beyond 5 km, but in some instances can have significant effects at ranges as short as 1 km.

The magnitudes of the resulting TL changes are illustrated in Figure 2, which shows the incoherent TL at 15 km range for three receiver depths as a function of time over a 1-hour period of high internal wave. These results were computed using the standard parameters shown in Table 1. In this case, the internal waves result in changes in TL (at 15 km) of more than 30 dB over time intervals of approximately 10 minutes.

The largest TL values correspond to times when an internal wave trough lies along the transmission path, resulting in sound speeds that reduce rapidly either side of the transmission path (Figure 3, left), and therefore refract the sound away from the receiver (Figure 4). Conversely, the smallest TL values correspond to times when an internal wave crest lies along the transmission path, resulting in a horizontal-plane sound speed that increases rapidly either side of the transmission path ((Figure 3, right), and refracts the diverging sound back towards the receiver, resulting in a strong focussing effect (Figure 5).

3.2 Transmission loss variations for periods of high and low internal wave activity

The TL variations shown in Figure 2 and discussed above were for a 1-hour, high internal wave activity period from 20:09:00 to 21:09:00 WST on 2nd April, 2013. These were compared to modelled TL variations for a 1-hour period of low internal wave activity from 02:00:00 to 03:00:00 WST on 3rd April, 2013 (Figure 6). Table 2 and Table 3 give the mean and standard deviation of the TL for each of these periods for receiver ranges of 5 km, 10 km and 15 km, and depths of 35 m, 95 m, and 195 m.

For both high and low internal wave activity periods, there was a systematic increase in mean TL with increasing receiver depth, but the standard deviation of the TL was found to be essentially independent of receiver depth. The standard deviation of the TL increased with increasing range in all cases. At 15 km range, the TL standard deviation during the high-activity period is approximately double that during the low activity period.

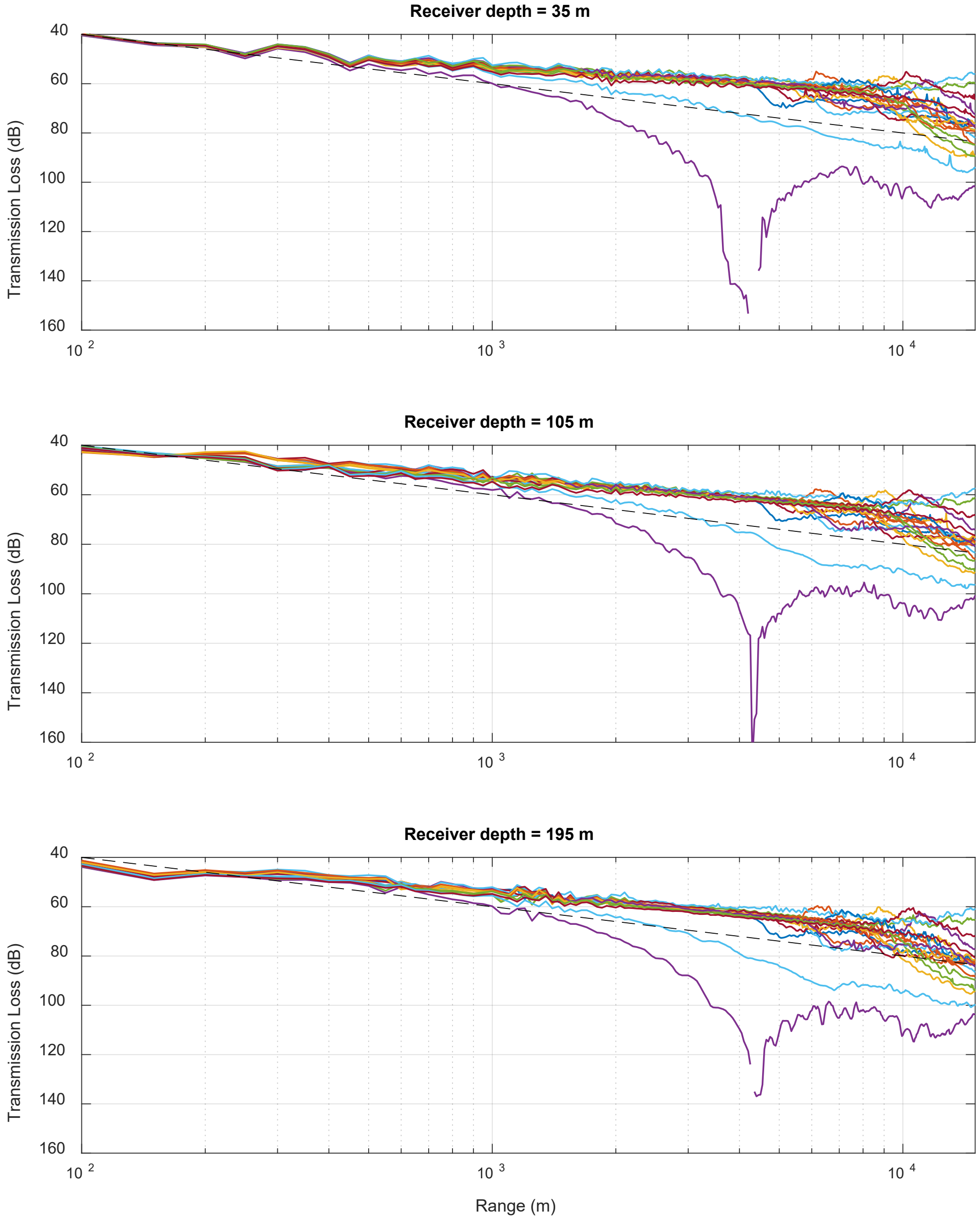

Figure 1: Semi-coherent transmission loss versus range at 1 minute intervals over a 20 minute period of internal wave activity at receiver depths of: 35 m (top), 105 m (middle) and 195 m (bottom). The black dashed line is 20 $\log_{10}$ (Range). Elevation angle range was +/- 80° and bearing angle range was +/- 20°. Beam spacing was 0.1° for both.

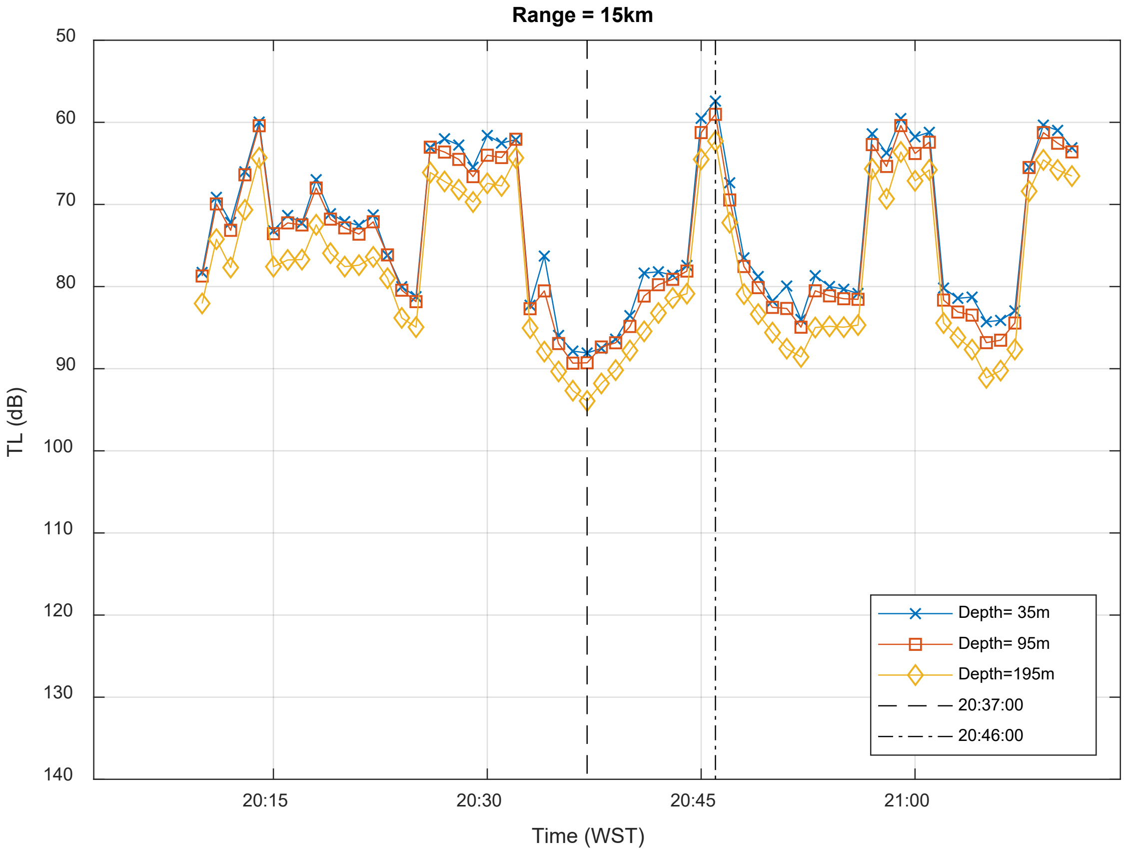

Figure 2: Incoherent transmission loss at 15 km range versus time for receiver depths of 35, 105 and 195 m over a 1 hour period of high internal wave activity.

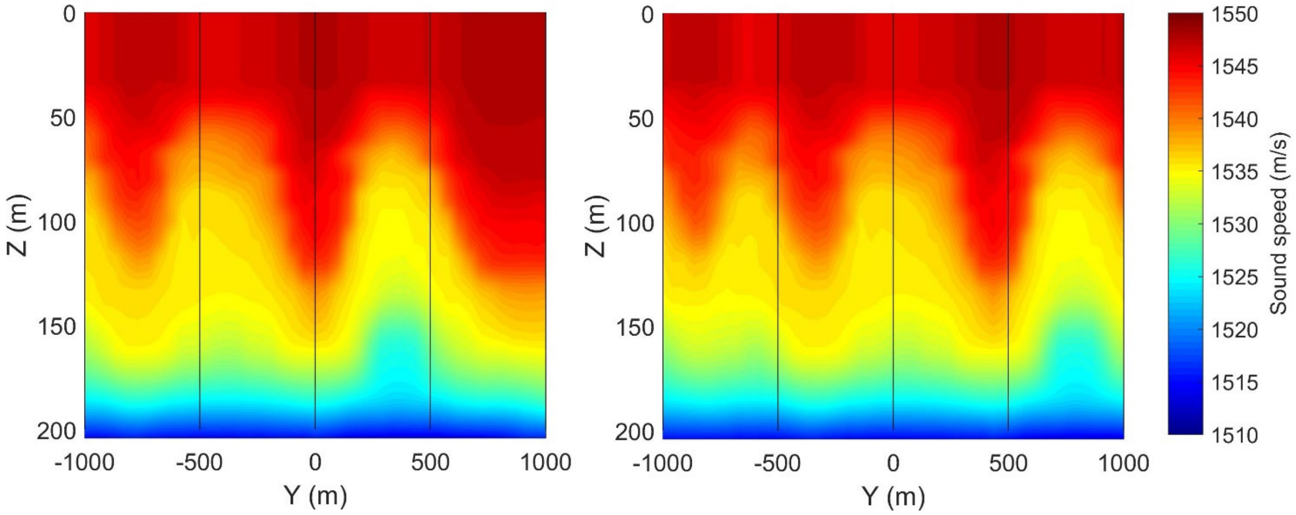

Figure 3. Sound speed as a function of depth and distance perpendicular to propagation at times corresponding to: (left) maximum defocussing (20:37:00 WST on 2nd April, 2013); and, (right) maximum focussing (20:46:00 WST on 2nd April, 2013).

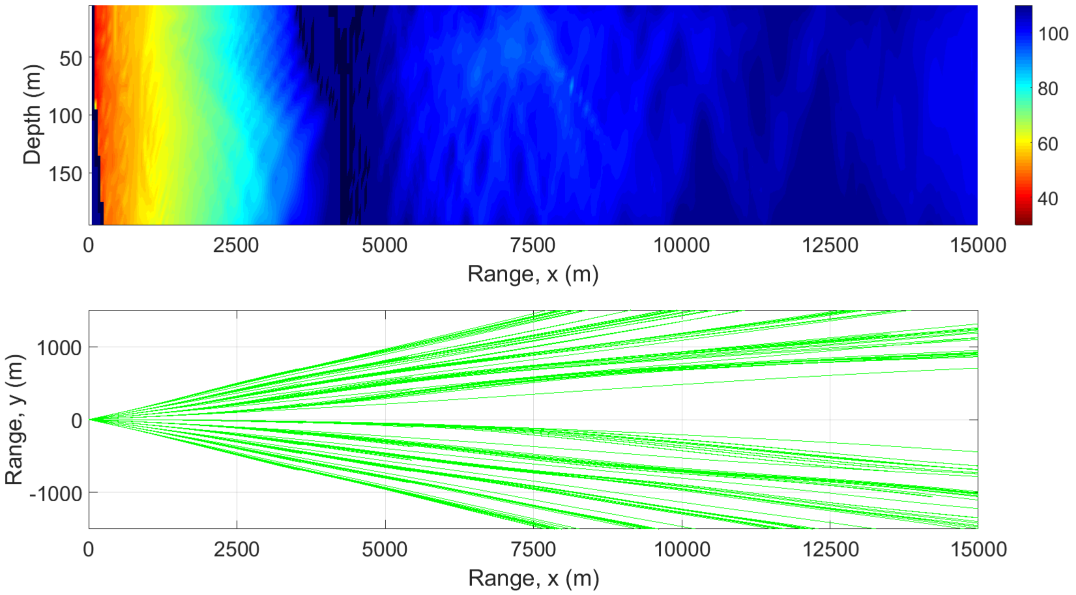

Figure 4: Semi-coherent TL vs Range vs Depth (top), top view of ray trace (bottom) for time of maximum defocussing (20:37:00 WST on 2nd April, 2013). Other mmodelling parameters were as per Table 1.

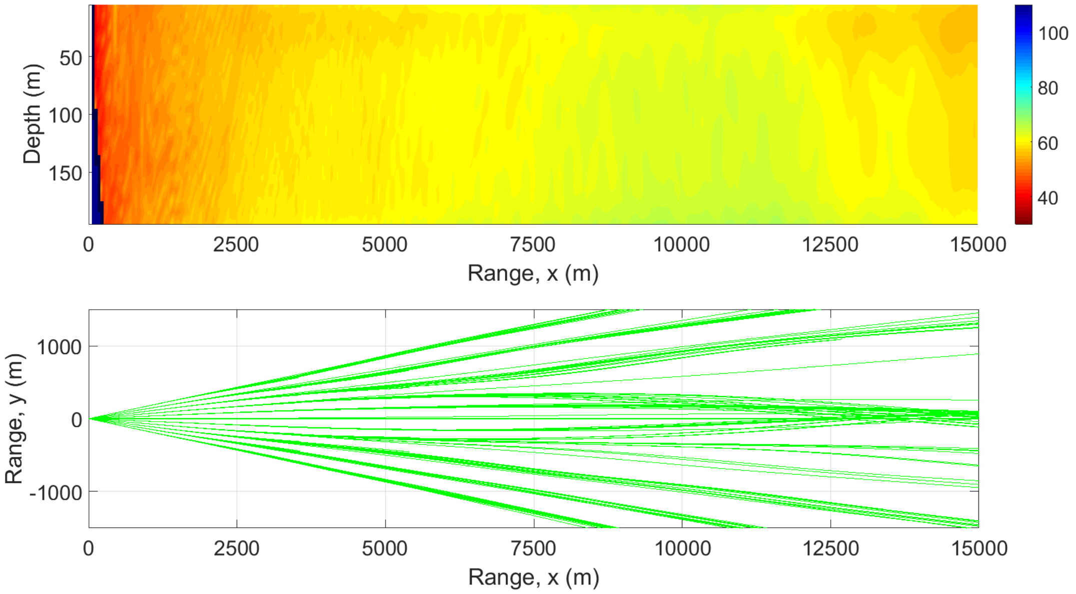

Figure 5: Semi-coherent TL vs Range vs Depth (top), top view of ray trace (bottom), for time of maximum focussing (20:46:00 WST on 2nd April, 2013). Other modelling parameters were as per Table 1.

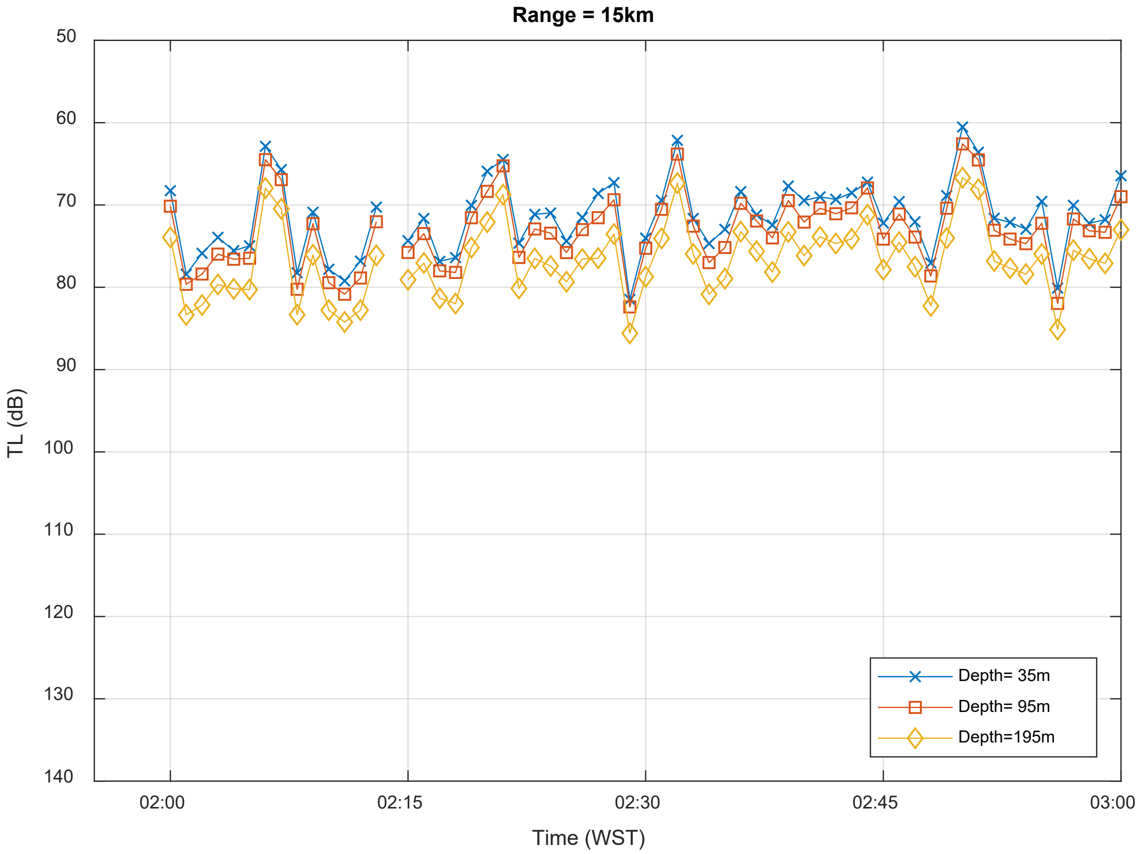

Figure 6: Incoherent transmission loss at 15 km range as a function of time for a 1-hour period of low internal wave activity.

Table 2. Mean and (standard deviation) of modelled incoherent TL in dB for the stated receiver ranges and depths for a 1-hour period of high internal wave activity (20:09:00 to 21:09:00 WST on 2nd April, 2013).

		Receiver Range		
		5 km	**10 km**	**15 km**
Receiver depth	**35 m**	60.9 (2.5)	68.8 (4.9)	73.2 (9.1)
	95 m	62.5 (2.4)	70.3 (4.9)	74.4 (9.2)
	195 m	65.4 (2.6)	73.8 (5.0)	78.0 (9.4)

Table 3. Mean and (standard deviation) of modelled incoherent TL in dB for the stated receiver ranges and depths for a 1-hour period of low internal wave activity (02:00:00 to 03:00:00 WST on 3rd April, 2013).

		Receiver Range		
		5 km	**10 km**	**15 km**
Receiver depth	**35 m**	60.1 (1.7)	66.2 (2.8)	71.5 (4.5)
	95 m	62.2 (1.8)	68.3 (2.8)	73.1 (4.5)
	195 m	64.7 (1.8)	71.8 (2.8)	76.8 (4.4)

3.3 Effect of sampling resolution of sound field on transmission loss calculations

An attempt was made to investigate the time scale over which changes in TL occur. This was done by smoothly interpolating the spatial sound velocity field to a time interval of 7.5 seconds (which is 1/8 of the IMOS data sampling interval), for 2-minute periods either side of the times of maximum defocussing and maximum focussing. Figure 7 shows the results. There is an anomalous point just after 20:37, and possibly around 20:36, but apart from that the results were consistent with the 1-minute interval data shown previously (also plotted in Figure 7). In most cases, the 7.5-second interval results lie close to the straight lines joining the 1-minute interval data points, indicating that interpolating to a finer sample interval has not provided any new information about the rate at which the TL would change in practice, and that reaching any conclusions in this regard would require sound velocity data sampled at a higher rate.

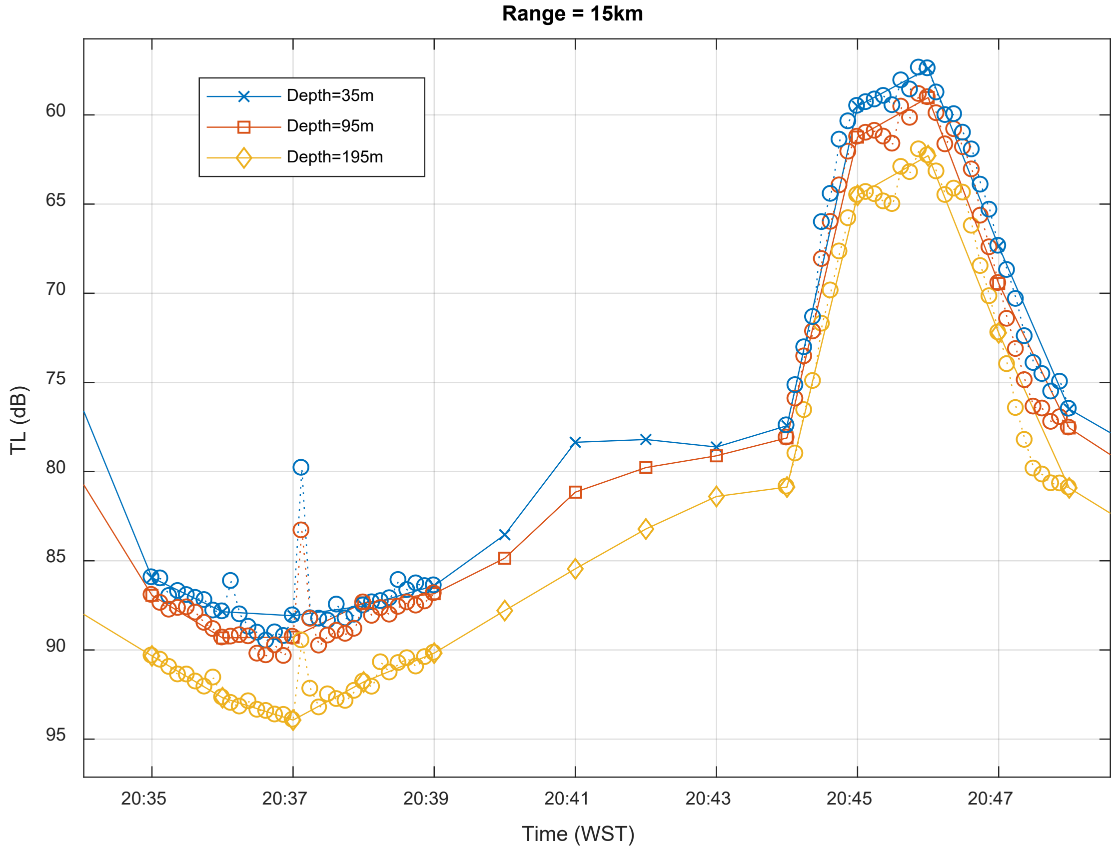

Figure 7: Incoherent transmission loss at 15 km range as a function of time at 7.5 second intervals around the times of maximum and minimum transmission loss during the high internal wave activity period (circles). Crosses are the 1 minute interval data shown in the upper plot of Figure 6.

4 DISCUSSION

The results presented above predict that nonlinear internal waves, typical of those that occur on Australia’s Northwest Shelf, can have a substantial effect on acoustic propagation in a direction parallel to the internal wave crests. The example considered here resulted in changes in incoherent transmission loss over a 15 km range of up to 30 dB in a time frame of just over 10 minutes; and, occasional changes of more than 15 dB in 1 minute. As this is incoherent TL, these fluctuations are in addition to the normal statistical fluctuations in the coherent TL due to random phases between contributing ray paths. These fluctuations result in a log-Rayleigh distributed TL, with a standard deviation of 5.6 dB (Lurton, 2009). This is in contrast to the results of the first phase of this project that indicated, for propagation perpendicular to the internal wave crests, that the same internal wave field would cause incoherent TL fluctuations of only a few dB (Parnum et. al. 2017).

The result that larger fluctuations in TL occur for acoustic propagation parallel to the internal wave crests than normal to them is expected, as similar investigations in other parts of the world have also predicted and/or observed the same effect. The reported changes in TL in this study are larger than those reported from other studies (Apel et. al. 2007, Mohsen et. al. 2005). However, those studies used frequencies of a few hundred Hz, much lower than the 7 kHz frequency used here, which may account for this difference, however it would also be prudent to consider the limitations of the modelling carried out in the current project. There are several aspects to this:

Bellhop3D is a well-tested model and has been demonstrated to give results that agree accurately with benchmarks for a number of problems (Porter, 2016). It is, however, fundamentally based on ray theory and therefore suffers (at least to some extent) from the limitations of ray models. These limitations include a lack of accuracy at very low frequencies, a tendency to overestimate the TL in shadow zones and underestimate it in caustics. The frequency of 7 kHz considered here, is well above the low frequency limit and Bellhop 3D would be expected to be accurate, providing it is run with appropriate input parameters. During this project, test runs carried out using Gaussian beams and geometric ‘hat’ beams were found to give very similar results. The latter exactly reproduce the ray theoretic result, so this test indicates that the ray theory assumptions are valid for the scenarios modelled here.

To avoid unphysical, short duration peaks of very high TL during defocussing periods it was necessary to smoothly interpolate the sound speed field to a spacing of no more than 3 m in the Y direction. Low TL peaks during focussing periods were much less sensitive to this effect. However, rather than relying on interpolation of the sound speed data, it would be much better to use sound speed data that was sampled at a higher rate than the 1 sample per minute available from the IMOS moorings, which would make the results less sensitive to the interpolation method used and also give more accurate predictions of how rapidly the TL is likely to vary during the passage of nonlinear internal waves.

The assumption that the sound velocity field due to the internal waves is invariant in the direction of propagation is also a limitation of this modelling and is unlikely to be justified in reality. Repeating the acoustic modelling with a more realistic, time-evolving three-dimensional sound velocity field would be of considerable interest.

5 CONCLUSIONS

The results of this study predict that nonlinear internal waves, typical of those found on Australia’s Northwest Shelf, are likely to result in significant fluctuations in TL for acoustic propagation directions parallel to the internal wave crests. The changes in incoherent TL at a range of 15 km during a period of high internal wave activity, were predicted to be as much as 30 dB over time intervals of approximately 10 minutes; with changes of 15 dB occasionally occurring over an interval of 1 minute. The standard deviation of the incoherent TL was predicted to be 9.2 dB (at 95 m depth) during this same period. For comparison, the modelling predicted an incoherent TL standard deviation of 4.5 dB during a 1-hour period of low internal wave activity.

The results were sensitive to the temporal and spatial sampling of the sound field, particularly in the direction across the acoustic propagation track. The results may also change if a more realistic three-dimensional internal wave field is used to determine the sound speed field. Further work is needed to explore these issues, and also to investigate how the fluctuations in the TL vary as the angle between the acoustic propagation direction and the internal wave crests changes.

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