The effect of internal waves on underwater sound propagation

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ABSTRACT
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 sound velocity profile (SVP). Traditionally, the SVP is measured by deploying an XBT (expendable bathythermograph) and converting the temperature profile to an SVP at the location of the ship. Sonar performance is then predicted based on this SVP. However, the ocean is a dynamic environment, and sound propagation conditions can change with both position and time. This study investigated the effect of the variation in the sound velocity profile (SVP) in a dynamic oceanographic region: the Kimberley shelf, where phenomena such as internal waves are present. Temperature and salinity data collected in the Kimberley region, as part of the Integrated Marine Observing System's National Mooring Network, were used to produce SVPs at a sampling interval of 1 minute. These SVPs were then used in a range dependent sound propagation model (RAM Geo). This paper presents the results of this modelling.

1 INTRODUCTION

Under normal circumstances, estimates of how acoustic energy will behave in a given environment are made with information available at the time. This may include real-time measurements of the local sound velocity pro-file plus any relevant records and, in particular, the experience of those who are responsible for the interpretation of the sonar environment.

Internal waves that move within the bulk of the ocean are ubiquitous. They depend on buoyancy as a restoring force and because of the vertical structure of the water column, more internal wave modes tend to exist close to the thermocline, just below the surface mixed layer. There is no convenient way of estimating local internal wave characteristics from a single platform, so internal waves are normally ignored when making sonar assessments. Internal waves that manifest themselves near the thermocline will cause changes to the local sound velocity profile. It is this feature that we wish to explore in this work.

Internal waves have periods from a few minutes to a day or more and their horizontal wavelengths range between about 10 metres and 10 km. These parameters scale closely to the variations associated with operational periods. A very important aspect of operating in the vicinity of known internal wave sites is the potential danger to a submarine if it becomes exposed to the vertical velocities known to accompany solitons, which are often produced by internal wave activity. There have been a number of events where submarines have been subjected to unwanted vertical movement and it has been assumed that internal wave activity was responsible. It makes sense therefore to try and understand not only if and how internal waves affect the sonar process, but also where they are and when to avoid them. .

The work presented here has been undertaken using what resources were readily available. There are a few different technologies that could be used for internal wave observations, but it will be necessary to understand what the benefits of these observations might be before committing to any experimental program.

The SVP obtained from an XBT dropped at one location becomes progressively less suitable as you move away from the time or location of the drop, or when considering propagation through regions with strong spatial changes in SVP. 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; Sagers and Wilson, 2017).

The aim of this study was to examine the effect on sound propagation of the variation in SVP in dynamic oceanographic regions of the Australian coast, where phenomena such as internal waves are present. This paper considers only 2D acoustic propagation in the direction of the strongest horizontal changes in SVP, (e.g. normal to the crests of internal waves. Future work will investigate effects of cross-track sound speed gradients and will require fully three dimensional propagation modelling.

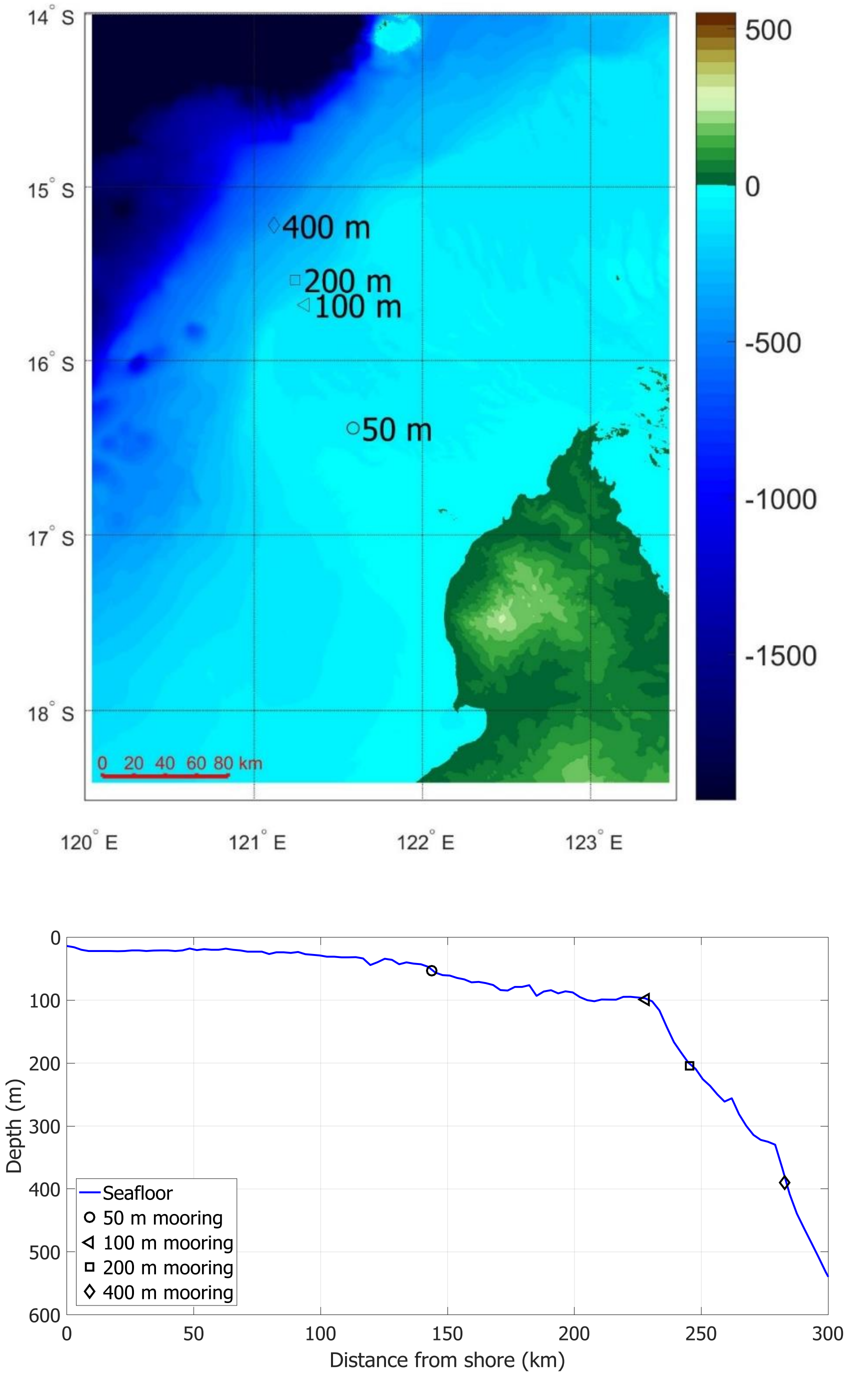

Figure 1: Bathymetry of the case study area: (top) a map showing the locations of the Kimberley moorings; (bottom) the across shelf depth profile.

To carry out this initial study, high sample rate sound velocity profile data were required. One source of data that fulfilled the study's requirements was temperature and salinity data, which can be used to calculate sound velocity, collected as part of the National Mooring Network (NMN) within the Integrated Marine Observing System (IMOS) program (http://imos.org.au/facilities/nationalmooringnetwork/). The NMN shelf array mooring off the Kimberley coast was identified as an appropriate case study, as it is known as a dynamic oceanographic region (Jackson et al, 2004). The location of the IMOS moorings off the Kimberley coast can be seen in Figure 1 (top). There were moorings at the 50, 100, 200 and 400 m contours. The across-shelf depth profile running through the mooring locations can be seen in Figure 1 (bottom). Data from the 200 m mooring were primarily used for this study as it was felt this was in a location where internal wave activity would be most likely to be detected.

2 METHODS

2.1 Sound velocity data

Temperature, salinity and pressure data collected by IMOS's NMN in the Kimberley at the 200 m mooring were downloaded as NetCDF files from the IMOS Ocean Portal (http://imos.aodn.org.au). Initial analysis found an appropriate time series between 2nd and 3rd April 2013. Temperature and pressure data had been collected at the following nominal depths (m): 31, 39, 49, 59, 69, 79, 89, 99, 109, 119, 134, 159, 184, 204 m; and salinity data at 31, 49, 89 and 184 m. The sampling interval for all variables was 1 minute. Data were resampled so all depth bins were on the same time scale. For each profile, the salinity was linearly interpolated to the depth bins where salinity was not measured, and then for each depth bin the sound velocity was calculated from the temperature, salinity and pressure using the formula in Millero and Li (1994). The result is shown in Figure 2. During this period, sound velocity ranged from 1508 to 1548 m/s, with typically a downwardly refracting profile. Some of the temporal variations in sound velocity shown in Figure 2, were associated with the movement of water by tidal forces. In particular, during high tide there were rapid oscillations in sound velocity (Figure 3), which are characteristic of soliton internal waves.

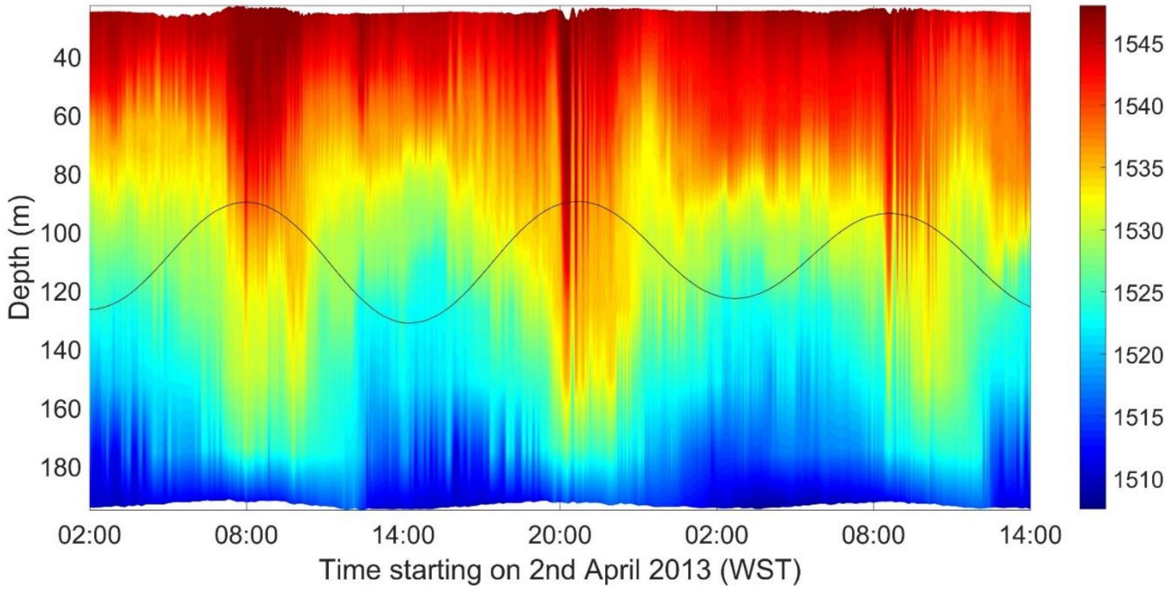

Figure 2: Sound velocity profiles (colour plot) and relative predicted tide (black line) between 2nd and 3rd April 2013 calculated from the CTD data collected on the 200 m IMOS mooring off the Kimberley coast, Western Australia.

2.2 Sound propagation modelling

The sound propagation model RAMGEO was used to calculate transmission loss (TL) as a function of range and depth out to a maximum range of 15 km. RAMGeo is a well-tested parabolic equation model suitable for range dependent sound speed profiles and fluid seabeds written by Michael Collins from the US Naval Research laboratory (Collins, 1995; Jensen, 2011). Parameters used in the modelling are shown in Table 1. A 7 kHz source at 10 m depth in 204 m of water was modelled over a "sand" half-space seabed based on the seafloor geo-acoustic properties described by Jensen (2011). Shear waves were not considered in this study, and the seafloor was modelled as being flat. The sound velocity at the sea surface was set to the same as the shallowest measurements (31 m). To consider the impact on submarine detection, TL was incoherently spatially averaged (in the pressure squared domain) in range by +/- 25 m and in depth by +/- 5 m.

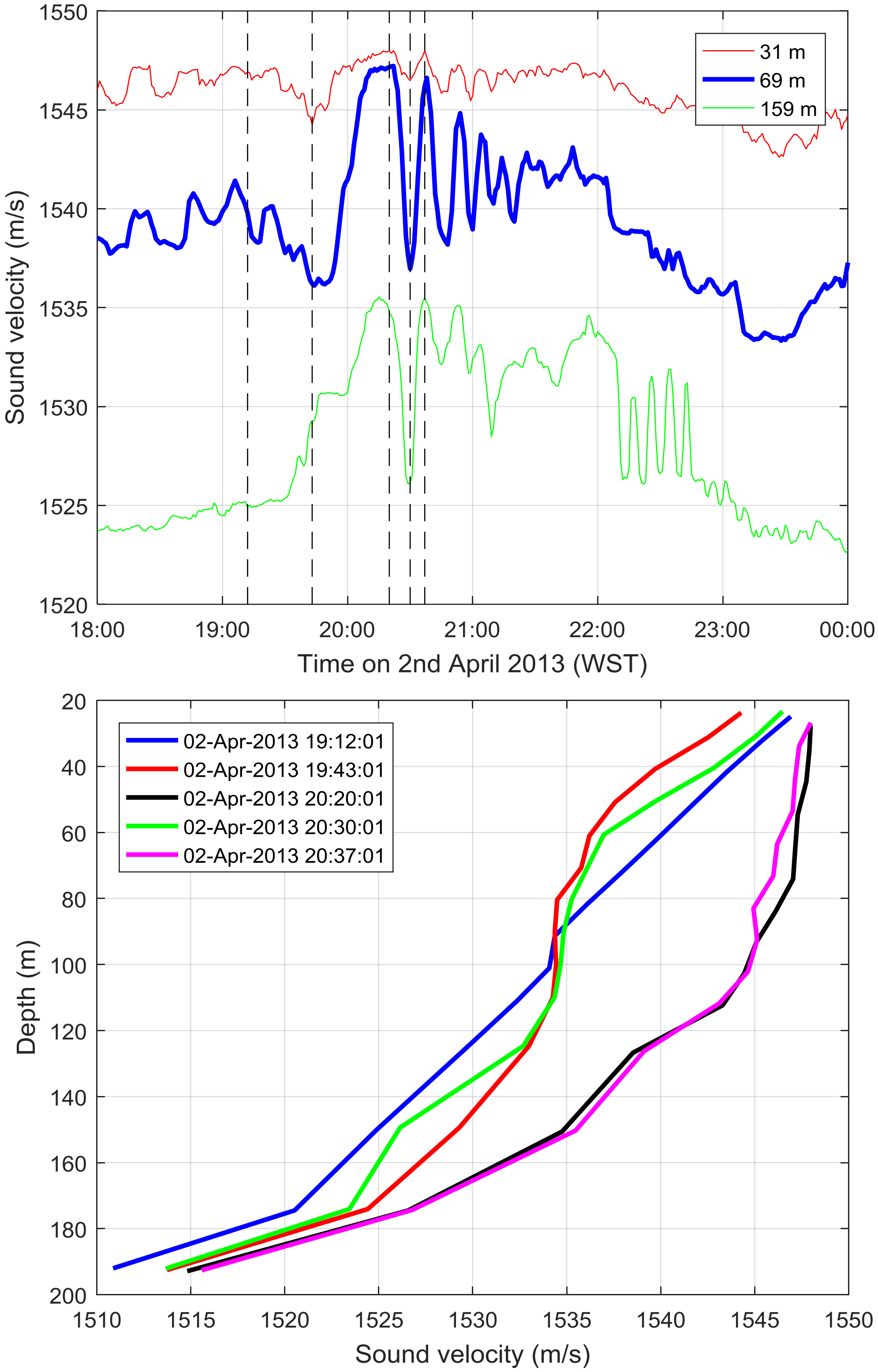

Figure 3: Sound velocity vs time at selected depths (top), with vertical black dashed lines showing the times of SVP profiles (bottom), during 2nd April 2013. Data is from the 200 m mooring.

Table 1: Parameters used in the RAMGEO Modelling

Parameter	Value
Frequency, (kHz)	7
Source depth, (m)	10
Water depth, (m)	204
Water density, (kg/m^3)	1024
Seabed density, (kg/m^3)	1894
Seabed p-wave speed, (m/s)	1770
Seabed p-wave attenuation, (dB/λ)	0.8

To simulate the effect of the temporal changes in the SVP on propagation between a fixed source and receiver, a series of TL calculations was carried out, each with an SVP at the source corresponding to the measured SVP at that time. For comparison purposes, calculations were done using both range independent sound speed profiles, and range dependent sound speed profiles. For each range dependent model run, 313 SVPs were used (1 per 48 m of range), which were obtained by converting the SVP data from a time dependence to a range dependence assuming an internal wave propagation speed of 0.8 m/s. This value was obtained from previous studies (Sagers and Wilson, 2017), and compared well to a calculation based on the location of peaks in the correlation between temperatures at the 100 m and 200 m moorings. For the example shown in Figure 2, these correlation peaks corresponded to propagation speeds that varied between 0.72 and 0.86 m/s.

3 RESULTS

Figure 4 plots the modelled TL between a fixed source and receivers at two different depths at a range of 15 km. TL is plotted as a function of time for both the range independent and range dependent SVP cases. The dB differences between these range dependent and range independent results are plotted in Figure 5.

All of the TL curves in Figure 4 show short-term fluctuations of several dB which is a result of the random nature of constructive and destructive interference that occurs when fluctuations in the acoustic travel times along the various multi-paths contributing to the received signal exceed the signal period. Theory predicts that in this situation the TL fluctuations should be log-Rayleigh distributed with a standard deviation of 5.6 dB (Lurton, 2009), however in this case the standard deviation has been reduced somewhat by the spatial averaging that was carried out at the receivers.

The differences between the range independent and range dependent transmission loss values for the shallow receiver have a mean of -1.5 dB and a standard deviation of 1.2 dB, whereas for the deep receiver the mean difference is 0.6 dB and the standard deviation is 1.2 dB. From Figure 5 it is apparent that while random TL fluctuations account for a substantial part of this variability, there are also longer term trends with amplitudes of a few dB that are likely to be related to the location of the various sound speed profile features along the transmit path.

The mean differences indicate that, on average, the range independent modelling underestimates the TL to the shallow receiver and overestimates the TL to the deep receiver. A likely explanation for this is that the rapid changes in sound speed profile with range included in the range dependent modelling tend to reduce the effectiveness of surface duct propagation, resulting in a greater proportion of the acoustic energy escaping to the lower part of the water column. This effect can be seen in Figure 6 which compares transmission loss vs range and depth plots for the range independent and range dependent cases at 19:00:00 on 2nd Apr-2013 (WST) (347 minutes on the horizontal scales of Figure 4 and Figure 5). A more effective surface duct can be seen in the top 40 m of the water column in the range independent case than in the range dependent case, although seabed reflections obscure this effect to some extent. The corresponding sound speed profiles are shown in Figure 7.

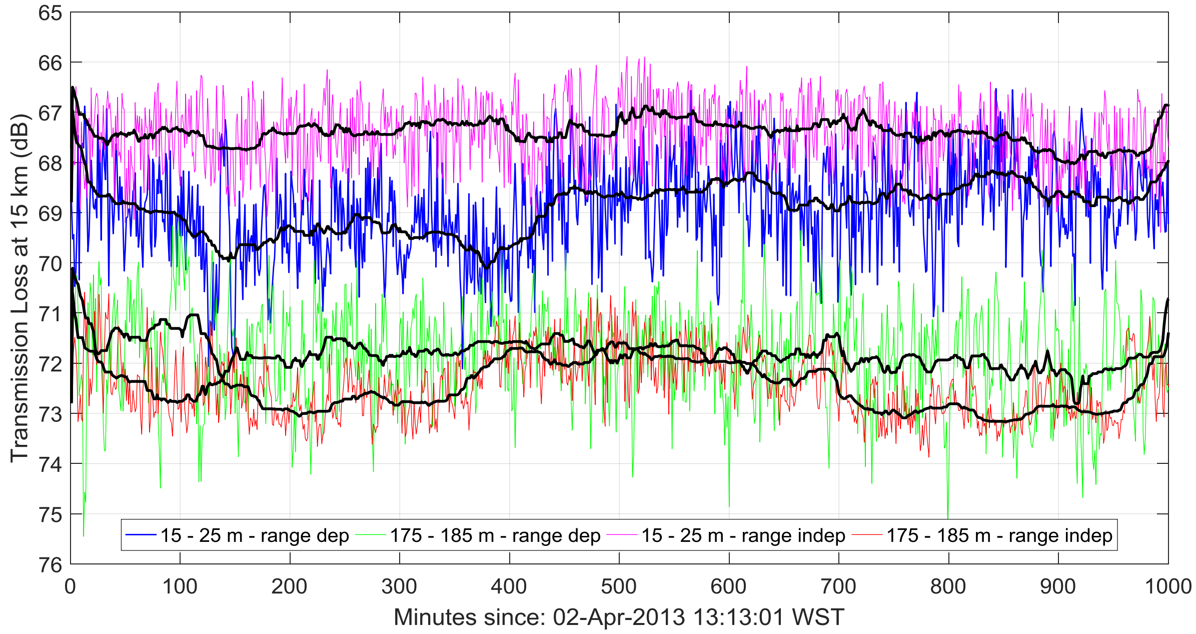

Figure 4: Modelled transmission loss at a range of 15 km as a function of time for receivers near the sea surface and the seafloor. The blue and green curves shows the results obtained using the appropriate range dependent SVP at each time, whereas the magenta and red curves show the results obtained using range independent modelling based on the SVP at the source at each time. The black lines are 50 minute median filter versions.

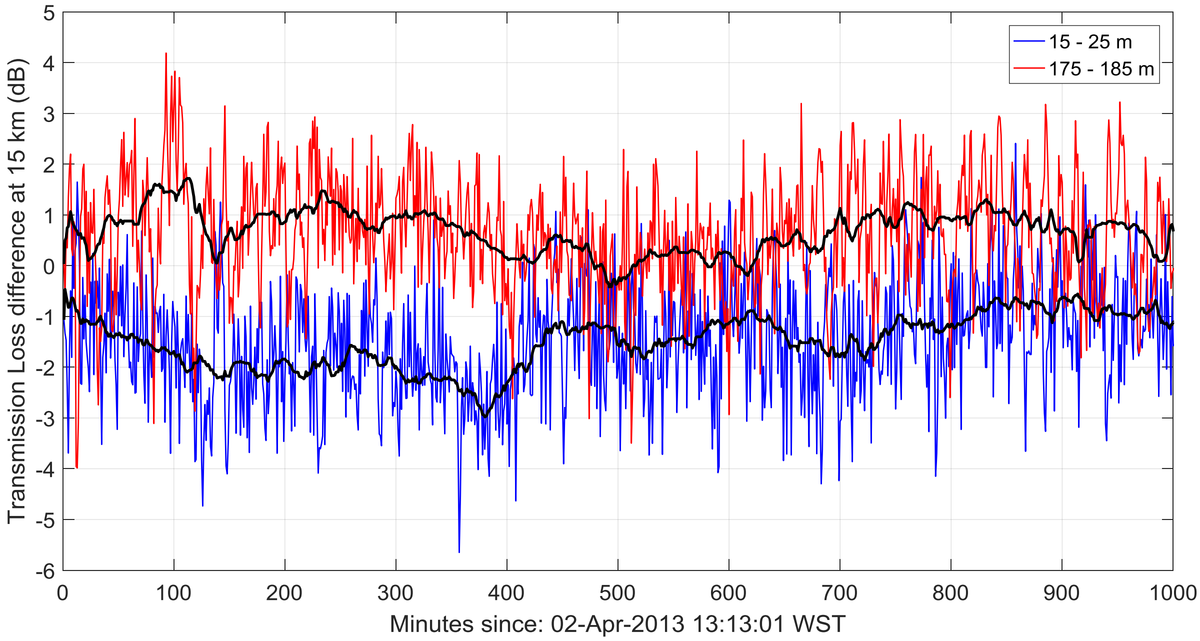

Figure 5: The difference in the modelled transmission loss obtained using the range dependent SVP minus the results obtained using range independent modelling based on the SVP at the source at each time. The black lines are 50 minute median filter versions.

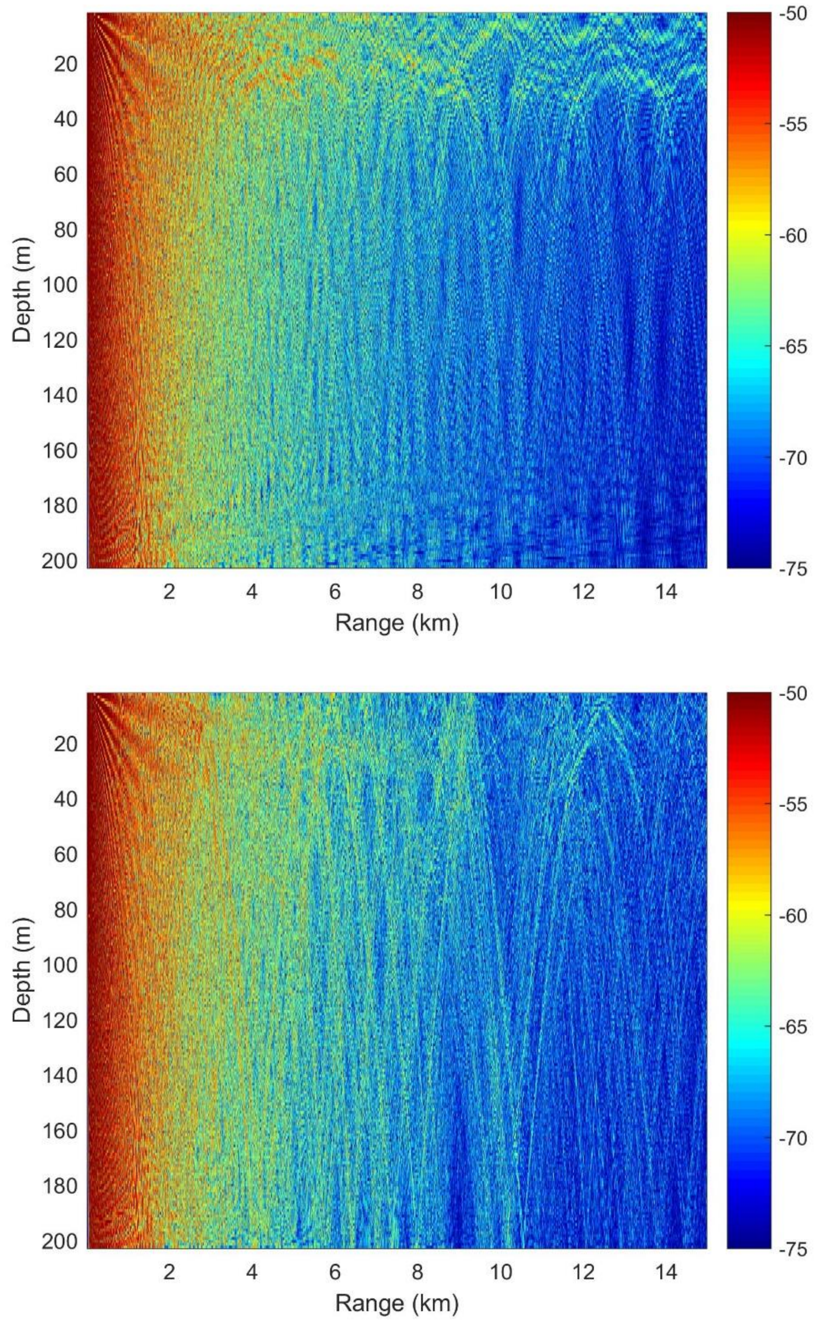

Figure 6: Transmission loss as a function of depth and range using range independent SVP (top), and range dependent SVP (bottom) at 7 pm on 2nd Apr-2013 (WST).

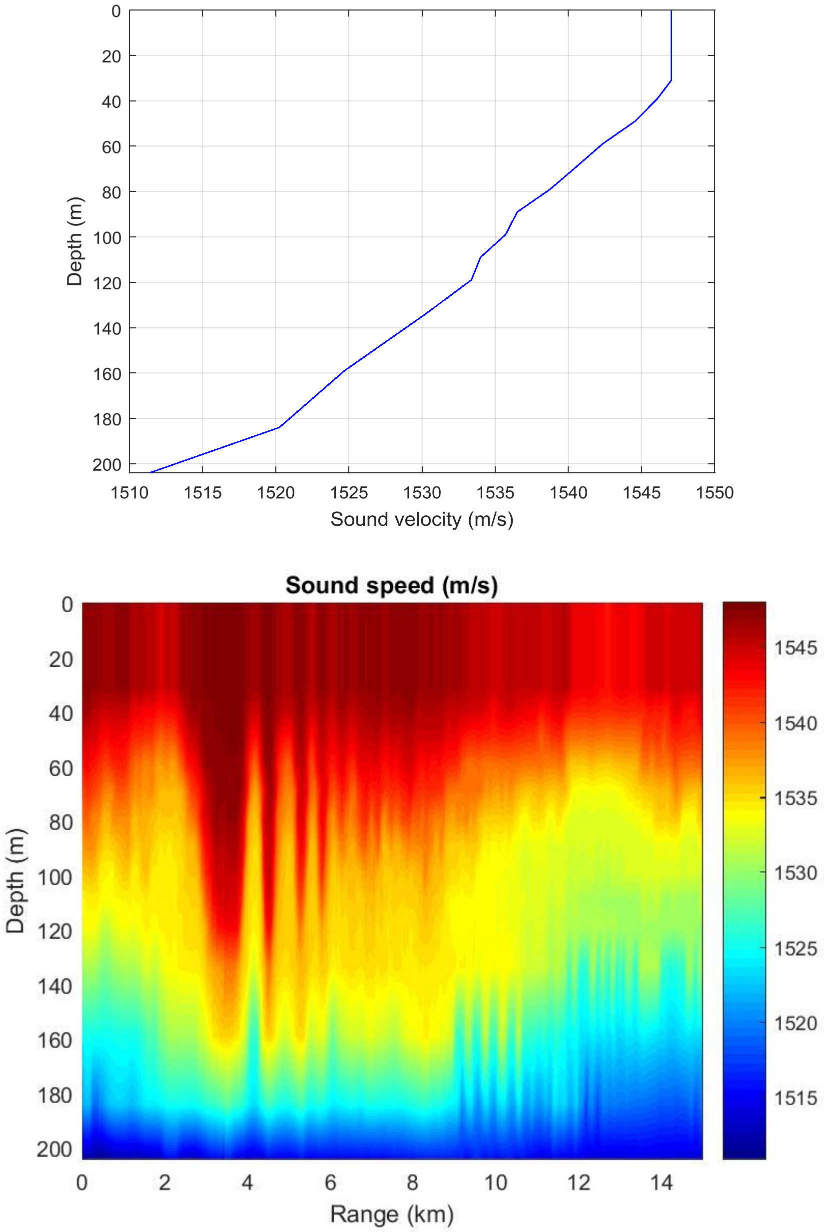

Figure 7: Sound velocity profiles (m/s) used in modelling Figure 6. Range independent (top) and range dependent (bottom).

4 CONCLUSIONS

The results presented above indicate that, despite their seemingly dramatic effect on the sound velocity profile, the effect of internal waves on acoustic propagation normal to their wave crests is likely to be only a few dB for the 15 km range, 7 kHz case considered here. More dramatic effects may be expected at lower frequencies where the surface duct is more pronounced and closer to cut-off, in deeper water where bottom reflections make less of a contribution to the sound field, and for propagation directions nearly parallel to the internal wave crests, where horizontal refraction effects can cause focussing and defocussing (Badiey *et al.*, 2005). An investigation of these effects will form the basis of future work on this project.

The fact that internal wave activity results in relatively small changes to modelled acoustic estimates for the particular case studied here cannot be regarded as definitive. There are too many factors that have not yet be incorporated. In order to model underwater acoustic behaviour in a real environment, the “true” three dimensional shape of the internal wave field near the thermocline will need to be established. This can only be estimated by an array of sensors. Three dimensional acoustic propagation modelling, a review of techniques best suited to this type of investigation and a properly instrumented experimental program must become part of the effort to understand the effects of internal waves in a real operational space.

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