2aUW3. The effects of internal tides on acoustic phase and amplitude statistics in the Philippine Sea

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Moored oceanographic sensors and satellite altimetry has revealed energetic diurnal and semi-diurnal internal tides in the Western Philippine Sea. Because the internal tides have a complex spatio-temporal pattern and large vertical displacements, these waves have the potential for causing strong acoustic variability. This talk will present a tidal analysis of signal fluctuations from the PhilSea09 experiment in which broadband signals with a center frequency of 275Hz and a bandwidth of 50 Hz were transmitted at the sound channel axis to a large aperture vertical array 185-km distant. Signal phase and amplitude statistics along distinct branches of the observed wavefronts will be analyzed and compared to ray-based model predictions using internal tide information obtained from moored oceanographic instruments at the source and receiver. Key issues are the acoustic effects of the internal tide nonlinearity, temporal stability, high mode structure, and complex horizontal interference patterns.

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INTRODUCTION

In this paper we present preliminary results from an experiment conducted in the spring of 2009 in the western Philippine Sea, in which a moored source at the sound channel axis transmitted broadband pulses with a center frequency of 275 Hz to a moored large aperture vertical receiving array at 185-km range (Fig. 1). In this experiment both the transmitting (T1) and receiving (DVLA) moorings were equipped with oceanographic sensors that measured temperature, salinity, and horizontal current and this data has been extensively analyzed by Colosi et al. 2013, revealing strong internal tide fluctuations.

The focus of this study is the impact of these energetic internal tides on acoustic fluctuations. Unlike many other deep water locations throughout the world, it has been found that Philippine internal tides and the ever present Garrett-Munk (GM) type random internal waves have nearly the same sound speed variance (Colosi et al. 2013). Hence it is expected that internal tides will play a critical role in dictating the acoustic propagation conditions in this location. Further, other aspects of the Philippine sea internal tides makes them particularly interesting. First, these waves are not simple sinusoids, but they are asymmetric showing steepening from nonlinear hydrodynamic effects (Colosi et al. 2013). Strong nonlinear effects have been critical in the analysis of shallow water internal tides and acoustic variability (Apel, et al. 2000), and thus these observations give an interesting glimpse into the more mild effects of nonlinearity in deep water. Second the internal tide in this region is seen to have a rich modal structure, in which the fluctuations show a modal energy distribution that decays roughly as one over the mode number squared (Colosi et al. 2013). This aspect of the internal tide is also unusual, as many regions of the world show internal tides that are entirely dominated by mode 1 (Dushaw et al. 2011; Dushaw, 2006; Dushaw et al. 1995). Phase statistics, which are primarily influenced by large scale structure will not be impacted by the higher modes, but other acoustic observables are expected to be strongly impacted (e.g. intensity, coherence ). Thirdly, while internal tide generation in the basin is expected to be dominated by conversion processes in the Luzon Strait, and the Marianna Island arc, there are likely other generation sites within and around the rugged topography of the basin; this complex system of source regions will likely make the internal tide field a complex interference pattern both spatially and temporally. In fact analysis of observations at the DVLA and T1 moorings have already revealed clear spatial variations in the internal tide (Colosi et al. 2013).

The aforementioned issues concerning internal tides and acoustics variability are compelling and will require extensive analysis that will go far beyond what is possible to describe in this manuscript. Thus the scope of the present manuscript is quite modest. Here we will focus only on the acoustic observations and we will analyze only one observable, namely travel time or phase fluctuations along specific acoustic paths at one receiver depth. More extensive analysis will be described at the International Congress on Acoustics (ICA).
oral presentation, and in subsequent publications.

RESULTS

The focus of this manuscript will be on internal tide induced travel time (or phase) fluctuations along specific ray paths. Here the physical picture is that the internal tide sound speed fluctuation $\delta c$ induces an advance or delay of the acoustic energy along the ray path thus leading to a travel time fluctuation. To first order the ray path itself is not altered by the sound speed fluctuation and thus the travel time variation can be written as an integral over the unperturbed ray path ($\Gamma$) giving,

$$\delta T_\Gamma(t) = -\int_\Gamma \frac{\delta c(\vec{r},t)}{c^2(z)} ds$$

Figure 2 shows 9 ray paths that were identified from the data for a receiver depth of 1100-m. Each ray path is given an identifier (ID), where the absolute value of the ID gives the number of ray turning points, and the sign of the ID denotes whether the ray has an initial downward (-) or upward (+) trajectory. Note that some of the rays are in-fact reflecting off the ocean surface. For each of these ray paths a travel time time series is observed. Figure 2 shows the time series for ray ID +9, where we have attempted to remove low-frequency mesoscale fluctuations by subtracting a low order polynomial fit. Note that the temporal sampling of the travel times is not uniform. Acoustic transmissions generally occurred every 3 hours, but there were three periods of greatly increased sampling where the interval was 5 minutes (this rapid sampling was intended to examine signal temporal coherence). For each of the ray path travel time, time series a tidal fit was performed using 8 diurnal (O1, K1, P1, Q1, J1, NO1, ALP1, and OO1) and 7 semidiurnal (M2, S2, N2, K2, L2, MU2, ETA2) frequencies; this fit is also shown in Fig. 2. Note that the tidal fit accounts for 86% of the total travel time variance. The residual travel time fluctuation (bottom right panel of Fig 2.) has a root-mean square (rms) value of 5.5 ms and this residual is due to residual low-frequency mesoscale fluctuations, random GM-like internal wave fluctuations, and some travel time tracking errors.

Table 1 shows the travel time statistics for all nine resolved ray paths. In all cases the tidal fits account for a significant fraction of the total variability. Here the implication is that this tidal variability is due to internal tides, not the astronomical or barotropic tides, since the barotropic tides have very little internal vertical displacement and their horizontal currents are only a few cm/s. Interestingly, rays 8 and 9 which both have ID -6 and which differ due to a surface reflection, have significantly less travel time fluctuation than the other rays. In particular the difference between these two rays and rays 6 and 7 which have ID +6 and which differ due to a surface selection, is remarkable since their spatial sampling properties (e.g. ray

![Figure 2](image-url)
paths) are very similar. The observed travel time residuals are consistent with estimates of the effects of GM-like internal waves based on path integral theory, which predict a variance of 4 to 16 ms$^2$.

**Table 1**: Travel time statistics for the nine rays shown in Fig. 2. The first row gives the variance of the raw travel times, while the second row gives the variance of the de-tided time series.

<table>
<thead>
<tr>
<th>Ray</th>
<th>Ray 2</th>
<th>Ray 3</th>
<th>Ray 4</th>
<th>Ray 5</th>
<th>Ray 6</th>
<th>Ray 7</th>
<th>Ray 8</th>
<th>Ray 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID +7</td>
<td>ID -7</td>
<td>ID +8</td>
<td>ID -8</td>
<td>ID +9</td>
<td>ID +6</td>
<td>ID +6</td>
<td>ID -6</td>
<td>ID -6</td>
</tr>
<tr>
<td>Total Variance (ms$^2$)</td>
<td>197</td>
<td>121</td>
<td>205</td>
<td>126</td>
<td>218</td>
<td>154</td>
<td>188</td>
<td>56</td>
</tr>
<tr>
<td>Residual Variance (ms$^2$)</td>
<td>29</td>
<td>23</td>
<td>28</td>
<td>29</td>
<td>30</td>
<td>47</td>
<td>40</td>
<td>28</td>
</tr>
</tbody>
</table>

**Conclusions**

The analysis that has been presented suggests that internal tides will have a dominant role in influencing acoustic phase fluctuations in the Philippine Sea. Future work to examine other acoustic observables, as well as data from the entire receiving array will bring this picture of the effects of internal tides on Philippine sea acoustic propagation into better focus. In addition future work will examine the degree to which the environmental observations of internal tides can be reconciled with the acoustic variability thus addressing such issues as non linearity, high mode structure, and complex spatial and temporal patterns.

**Acknowledgments**

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**References**


