# Comparison of WaveQ3D to shallow water experimental data from the Florida Straits

OCE 673 Advanced Acoustic Propagation, University of Rhode Island  
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# Background

Several papers have recently focused on the presence of strong 3-D propagation effects in experimental data on the continental shelf in the Florida Straits area. The South Florida Ocean Measurement Center is a permanent underwater laboratory located on the continental shelf just south of Ft. Lauderdale [1]. The experiments in the area include not only acoustics, but supporting environmental including in-situ CTD ocean profiles, high resolution bathymetry measurements, and core sample of the ocean bottom.

During a 1999 experiment to estimate sediment properties from an acoustic inversion at this site, researchers concluded that their experiment was strongly influenced by secondary signals that originated from horizontal refraction effects [2]. In this experiment, M-sequence coded signals were transmitted with a source level of 198 dB//μPa, and frequencies from 100 to 3200 Hz, over a range of 10 km to a sparsely populated vertical array. Signal propagation was parallel to the coast along the slope at a water depth of 155 m. The sound velocity profile was strongly downwardly refracting. A simulation study based on a 3-D parabolic equation model (3DWAPE) and a 3-D ray model (MOC3D) later concluded that these secondary signals could be directly attributed to horizontal refraction from cross-slope specular reflections inshore of the straight line path between source and receiver [3].

The Calibration Operations (CALOPS) experiment for the Shallow Water Array Performance (SWAP) program found similar effects in this area in the late summer (September 7–15) of 2007 and in the winter (February 19–25) of 2008 [4]. The CALOPS experiment used a horizontal line array (HLA) of 120 elements, with ½ wavelength spacing at 450 Hz (1.75 m), resting on the bottom, perpendicular to the 250 m isobaths. A towed 171 dB//μPa source used a combination of 60 second long CW pulses, with frequencies of 24, 52.5, 106, 206, and 415 Hz and a 30-s multi-band set of five linear frequency modulated (LFM) pulses in the frequency bands 20–50, 50–100, 120–180, 200–300, and 320–420 Hz. The ship followed tracks parallel to the 120, 250, and 450 m isobaths out to a range of 80 km. The source was also towed up-shelf from deep to shallow water at range of approximately 30 km from the source.

The CALOPS experiment recorded acoustic paths that were as much as 30 degrees away from the true bearing between source and receiver. In many cases, the in-shore refracted path was as much as 20 dB stronger than the true bearing path. Subsequent modeling studies also concluded that the out-of-plane paths were the result of horizontal refraction cause by multiple specular reflections from the sloped bottom [5] [6]. Both of these studies used an adiabatic mode parabolic equation (AMPE) to compare the transmission loss, angle of arrival, and time of arrival to Summer 2007 experimental results along the 250 m isobath, with a source depth of 100 m (Run 1N). The Heaney et. al. study [5] focused on the CW results at 206 and 415 Hz, where the signal to noise was the greatest. The Ballard study [6] focused on the CW results at 52.5 Hz, where bottom penetration plays a larger role.

In this study, the CALOPS experimental results that were previously studied by Heaney, Ballard, et. al. will be used to test the accuracy of the Wavefront Queue 3-D (WaveQ3D) model [7]. The WaveQ3D model implements Hybrid Gaussian beams [8]in a fully 3-D ocean environment that is based on latitude, longitude, and altitude. The approach is designed to provide a significant speed advantage to real-time, active sonar, simulation/stimulation systems in littoral environments. The expectation is that WaveQ3D model will provide accurate transmission loss values above 150 Hz. But at lower frequencies, we expect the effects of unsupported bottom penetration to cause deviations from the experimental data. In subsequent studies, we hope to expand this analysis to all of the Run 1N CW frequencies and to the VLA receivers from the 1999 experiment.

# Environment Characterization

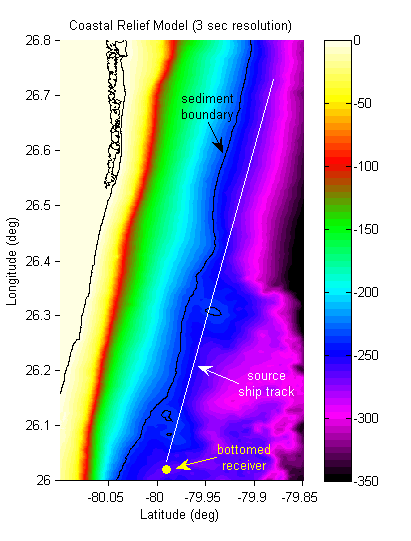
The bathymetry for this analysis was modeled using the U.S. Coastal Relief Model (CRM) [9]. This database provides gridded bathymetry, at 3 arc-second resolution, for the U.S. East and West Coasts, the northern coast of the Gulf of Mexico, Puerto Rico, and Hawaii, reaching out to the continental slope. Custom grids are freely available through the Geophysical Data System (GEODAS) Search and Data Retrieval web site [10]. In a follow-on effort, we hope to get access to higher resolution collected by the 2007 CALOPS experiment.

Figure 1 – Bathymetry and ship track

This study used a plane wave reflection coefficient to characterize bottom loss. The geophysical properties for this model (Table 1) were taken from Ballard’s analysis of measurements around this site [6]. Below the 236 m isobaths, the bottom is bare limestone because loose sediments have been scoured off by the Florida Current. At shallower depths, carbonate sand sediments layers cover the bottom. Although Ballard’s analysis includes some area of sediment pooling in the limestone area, this refinement will be saved for a follow-on effort. The large shear speeds in the limestone result in higher bottom loss, compared to the sand, at grazing angles below 20 degrees. Although the carbonate sands may have shear speeds as high as 200 m/s, this has little effect on the low angle bottom loss.

Table 1 – Geophysical Bottom Properties

|  |  |  |
| --- | --- | --- |
| Property | Limestone | Sand |
| Compression wave speed (m/s) | 3000 | 1676 |
| Compression attenuation (dB/λ) | 0.10 | 0.01 |
| Shear wave speed (m/s) | 1430 | 0 |
| Shear attenuation (dB/λ) | 0.20 | 0 |
| Density (g/cm3) | 2.40 | 1.70 |

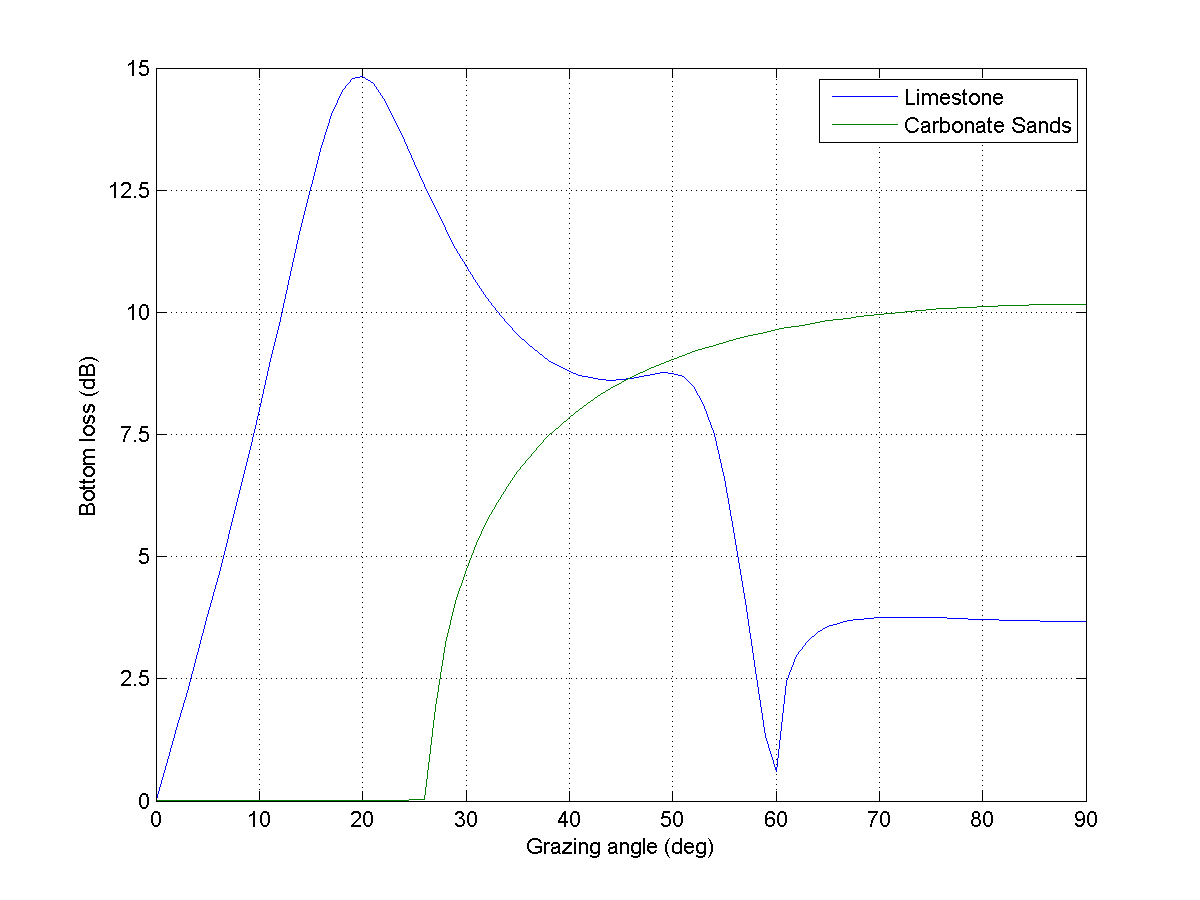


Figure 2 – Bottom loss model for limestone and sand bottoms[[1]](#footnote-1)

The refractive properties of the ocean (Table 1) were modeled using Heaney’s analysis of measurements around this site [4]. Heaney’s analysis suggests that a single sound velocity profile (Figure 3) can be used as an initial estimate of the ocean conditions in the whole area. For this analysis, a piecewise cubic Hermite interpolating polynomial (PCHIP) was used to create a continuous profile from this data. Unfortunately, the profiles from Heaney’s analysis only go down to 250 m; but, this is the only portion critical for up-slope analysis. Using Ballard’s analysis [6], we assume that the profiles are approximately isovelocity below 250 m. In a follow-up effort, we plan to create a 3-sound velocity profile that includes the CTD in-situ measurements discussed in Ballard’s work.

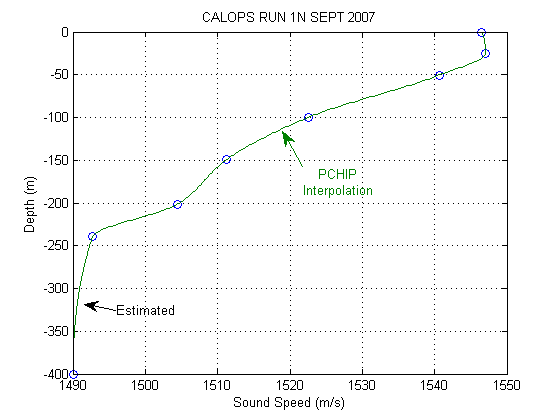


Figure 3 – Sound speed profile for CALOPS Run 1N September 2007

# WaveQ3D Modeling

To model this scenario in WaveQ3D, wavefronts were propagated from the receiver locations to a series of target locations along the source’s track. As shown in Table 2, launch angles for the wavefronts were limited to values that were likely to impact the transmission loss at the target locations. The frequencies at which to perform the transmission loss were matched to the center frequencies of the transmitted signals.

Table 2 – WaveQ3D Configuration

|  |  |
| --- | --- |
| Parameter | Values |
| Receiver Location | 26.0217N 79.99054W on the bottom |
| Source Ranges | 3 km to 80 km in 1 km increments |
| Source Bearing | 8° true |
| Source Depths | 100 m |
| Frequencies | 24, 52.5, 106, 206, 415 Hz |
| Travel Time | 0 s to 80 s in 0.025 sec increments |
| Launch D/E | -40° to +40° in 2° increments |
| Launch AZ | -40° true to +20° true in 2° increments |

Figure 4 illustrates the impact of out-of-plane reflections from the bottom on the direction of the ray paths. This figure was created by overlaying the ray paths, for a horizontal slice through the wavefront, at an elevation angle of +2° (up). Paths across the slope, like the one along the source track at 8°, travel at along an azimuthal direction that is very close to their launch angle. However, other paths experience a horizontal refraction that bends the rays into curve paths that shift the propagation direction away from the coastline.

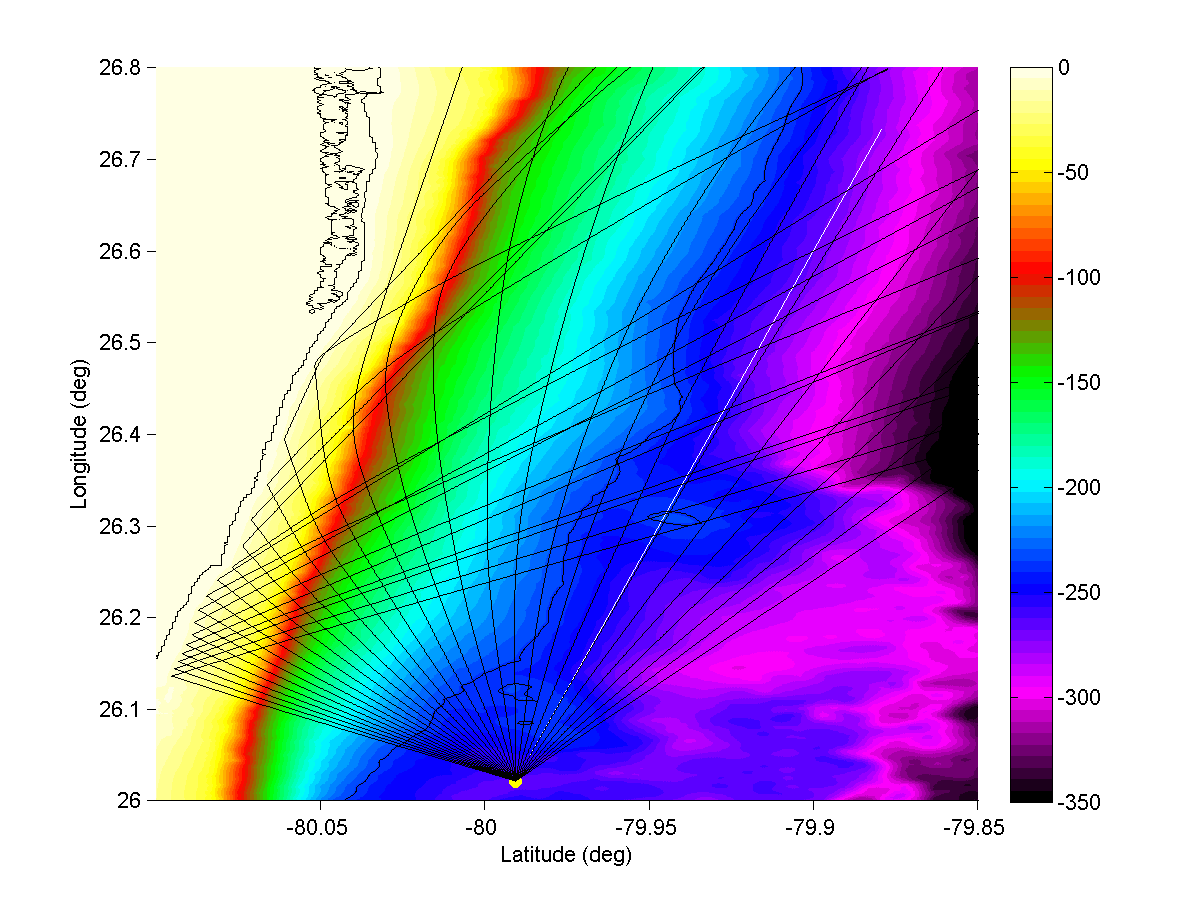


Figure 4 – WaveQ3D Horizontal Refraction Effects

Figure 6 illustrates the interplay between the sound speed profile and the sloping bottom on the ray paths. This figure was created by plotting ray depths, as a function of travel time, for a vertical slice through the wavefront, at an azimuthal angle of -30° (north-west), and elevation angles from 0° to 16° (up). The downward refracting profile tends to trap ray paths along the bottom. When the launch angle is nearly parallel to the bottom, the ray path follows the bottom contours and experiences the largest number of bottom reflections. Higher launch elevations increase their maximum height off the bottom and experience fewer reflections.

Because the ray paths start on the bottom, negative depression/elevation launch angles will travel along almost the exact same paths as the positive angles. But, they each suffer from an addition additional bottom loss event. Given that the overall number of bottom bounces is large, we would expect this model to overestimate the total loss by approximately 3 dB if the negative angle paths were neglected.

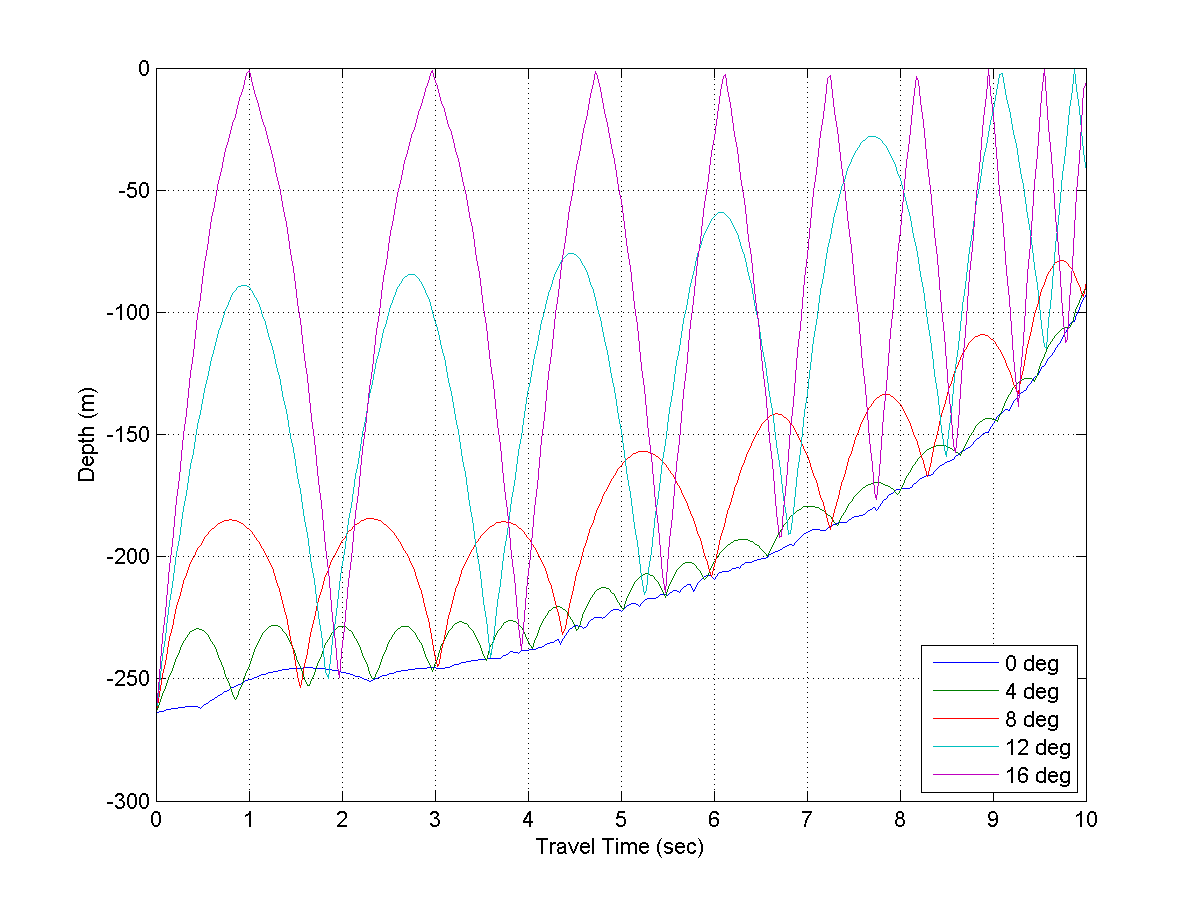


Figure 6 – WaveQ3D Vertical Refraction Effects

Figure 5 illustrates a typical result from Heany’s work (reference [5]). The blue asterisks/lines represent measurements from the acoustic path along the ship track. The transmission loss for this path falls off monotonically as a function of range, and the arrival angle are within a few degrees of the true bearing from the receiver to the source. The magneta dots/lines represent measurements from an acoustic path that follows a horizontally refracted path up the slope and then back down to the receiver. The contribution from these paths dominates the received in the ranges between 45 and 75 km. The measured arrival angles for this path are significantly skewed in the up-slope direction.

Efforts to model WaveQ3D transmission loss for this environment were not as successful. The WaveQ3D modeling results for this event are illustrated by the red dots in Figure 5. Beyond 10 km, WaveQ3D has trouble forming the acoustic ray paths into the eigenrays needed for transmission loss calculation. We believe that this failure stems from algorithm used to bundle the rays into groups with a common number of surface and bottom reflections. As discussed in Figure 6, the number of bottom bounces increases as function of the depression/elevation angle at launch. Without a grid of similar ray paths around the target point, WaveQ3D is unable to estimate the divergence of the wavefront.

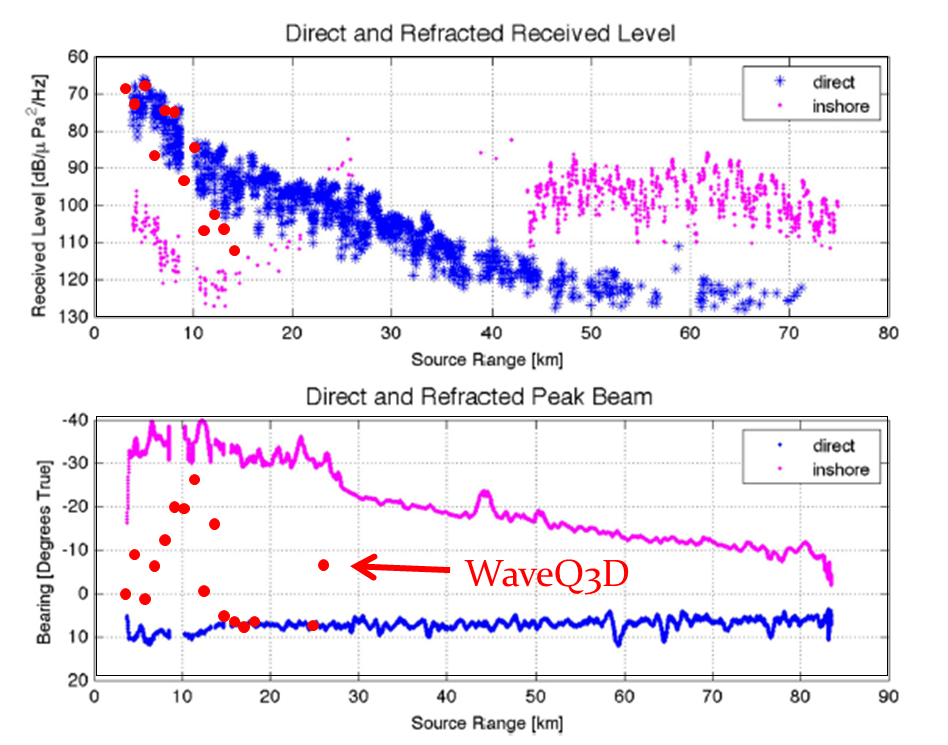


Figure 5 – Transmission Loss for Run 1N

# Conclusions

In a follow-on effort, we hope to resolve the WaveQ3D issues that were illustrated by this analysis.

* Revisit the reflection calculation to reduce numerical errors when the incident ray is nearly parallel to the interface.
* Revisit the ray bundling algorithm in search of schemes that will support eigenrays formation under these conditions.
* Investigate the use of the dynamic ray equations as an alternate scheme for forming eigenrays in this type of environment.

In addition, there are several improvements that should be made to the environmental characterization:

* Include the higher resolution collected by the 2007 CALOPS experiment;
* Includes areas of sediment pooling in the limestone area; and
* Use all of the in-situ CTD measurements instead of a single profile.

Once these issues have all been addressed, we hope to extend the analysis to include Jianga’s VLA measurements [2] in the water column.

References

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1. We discovered that there was a bottom loss plotting error in Dr. Ballard’s paper. A phone call with Dr. Ballard confirmed that Figure 3 (above) is a better representation of the bottom loss used in her calculations. [↑](#footnote-ref-1)