Out-of-Plane Effects in Ocean Acoustics

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LONG-TERM GOALS

The focus of my current research is to develop improved models of signal and noise propagation in complex, three-dimensional environments.

OBJECTIVES

In recent years tremendous progress has been made in modeling both the ocean environment and its effects on sound. Global models of the 4D (space-time) oceanography are produced both regularly and frequently. They are also readily available through FNMOC Reachback Support. In fact, rather than just a deterministic forecast, the oceanographic models routinely provide ensemble forecasts representing a 'fuzzy' ocean, i.e., a distribution of possible realizations.

It is interesting that the sound models that propagate through such fields have really not kept up. Three-dimensional propagation modeling has, of course, been a research topic of interest for many decades. However, it has never really become a mainstream activity, partly because it used to be too time-consuming, partly because the environmental information was not available.

The community has now clearly recognized that the time is right to take a step up in the modeling capability and do fully three-dimensional modeling using ensemble forecasts of the ocean structure. The goal of this research is to do exactly that, leveraging the BELLHOP3D Gaussian beam tracing code. Further enhancements will be made to BELLHOP3D; however, a particular focus will be the assessment of 3D effects in various upcoming experiments. In the last year we have focused on underwater acoustic communications as the application of interest.

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APPROACH

I will be investigating other 3D approaches; however, BELLHOP3D is the main tool for this work. BELLHOP3D is an extension of the widely used BELLHOP model which operates in either a 2D or Nx2D mode (where 3D fields are constructed from multiple bearings). Separately we have been working with FOR3D (3D parabolic equation model), which will be used to provide independent benchmark solutions. This year we have also been collaborating with Ahmad Abawi and Frederic Sturm to obtain alternate solutions using the finite-element method and another 3D PE model.

WORK COMPLETED

I am continuing with efforts to benchmark BELLHOP3D against numerical and analytic solutions. I have a number of test cases I've been using so far (*halfspace, Munk profile, rotated Munk profile, penetrable wedge, seamount, truncated wedge, perfect wedge, ...*). These exercise different parts of the code, including different beam options (hat-shaped or Gaussian) and Nx2D vs. 3D options.

The *Munk profile* verifies that BELLHOP3D matches BELLHOP2D, which has been checked against many other solutions. The *wedge problem* has an analytic solution and tests a sloping bathymetry. The *penetrable wedge* has a quasi-analytic solution from Michael Buckingham. The seamount problem tests a bottom with gradients in both latitude and longitude.

Most of these test cases are now looking perfect; however, I have not been satisfied with the *seamount* results. This case is unique because it has gradients of the bottom slope in both latitude and longitude and is trying to approximate a smoothly curved surface with a faceted bottom. Beam reflection from a curved bottom is complicated — particularly in 3D — partly because the beam curvature changes on reflection.

There was an error in BELLHOP that a user detected for the case when bottom slopes were high. This was fixed in both BELLHOP and BELLHOP3D and resolved a discrepancy in one of the benchmark cases. I was also able to confirm that the faceted approximation to the seamount was causing a lot of the problems. BELLHOP handles this using a particularly curvilinear approximation that is now described in our book. However, I have not extended that to the 3D case. That is what I am currently working on. As mentioned above, the curvilinear boundary produces jumps in the beam curvature. This requires finding the local quadratic approximate to the surface and rotating the beam into the appropriate coordinate system.

Separately, I have been collaborating with Ahmad Abawi who is using boundary integral and FEM methods to provide some independent solutions. This in fact has verified precisely our solutions for the wedge. (The earlier quasi-analytic solution has turned out not be accurate, which could also be an implementation issue.) I have started testing with another problem related to BASSEX and the Kermit-Roosevelt seamounts for which previous authors have done FOR3D and 3D coupled mode solutions.

My other effort to solidly test everything involved co-organizing a special session on '3D Modeling and Benchmarking' with Frederic Sturm for the ECUA/UAM in Rhodes, Greece (June 2014).

Additional thrusts of this work are to a) examine 3D effects for *noise* modeling and b) develop more sophisticated approaches to modeling ocean dynamics.

RESULTS

As mentioned above, we have designed a variety of test cases to exercise various aspects of the 3D algorithm. We present selected examples here. The first case is the rotated Munk profile. This is a canonical deep water profile that produces a convergence zone pattern in the transmission loss (TL) when seen in a sideview (range-depth). There are many well-developed models that provide essentially exact solutions for this problem, so the true solution is readily obtained. The BELLHOP3D result matches the standard 2D BELLHOP result and provides a highly accurate solution.

Our interest here is to verify the new logic in BELLHOP3D that handles the refraction in the lat/lon direction. We simply rotate the Munk profile on its side and re-run the code. The resulting sound speed is not at all physical; however, the match of the TL seen now in plan view is essentially perfect.

In the second example we consider a penetrable wedge, which is a standard test case that has been studied for many years with well understood propagation physics. Modes traveling up towards the apex of the wedge are refracted along hyperbolic tracks. These tracks may also be understood in terms of the ray equivalent of the mode. The TL plot again shows nearly perfect agreement with the reference solution.

The third example is for propagation over a seamount. This is another canonical test case and experiments at sea have also been done to compare to numerical results. In this case, the source is located to the right and rays are launched to the left where are seamount is located roughly in the middle of the plot. Here we have used an analytic representation of the seamount to avoid the 'disco ball' effect where the faceted representation of the seamount causes an irregular TL pattern. The agreement is very good except in the forward scattered direction in the shadow of the seamount where we can see some irregularity in the solution.

In the fourth and final example we consider the ‘truncated wedge’, which can be viewed as a shelf and shelf-break scenario. This example was originally considered by Sturm as a test case for his 3D PE models. The agreement between BELLHOP3D and the 3D PE solution (provided by Sturm) is nearly perfect. Small errors are probably caused by differences in the sampling of this highly detailed interference pattern.

IMPACT/APPLICATIONS

Three-dimensional effects can be important whenever there is significant variation of the environment in latitude and longitude. Seamounts, canyons, and fjords are examples where the bathymetric variation may be important. Nonlinear internal waves are examples where the oceanography may be important. The 3D effects are often most visible when seen through the prism of the signal processing chain, e.g., on a bearing-time record. The limitations of Nx2D models have been recognized for years but we are only now at the point where we have both the environmental information to feed the acoustic models and the computational power to run them.

HONORS/AWARDS/PRIZES

Pioneers Medal, *Acoustical Society of America*
(to be awarded at the Indianapolis Meeting, October 2014).

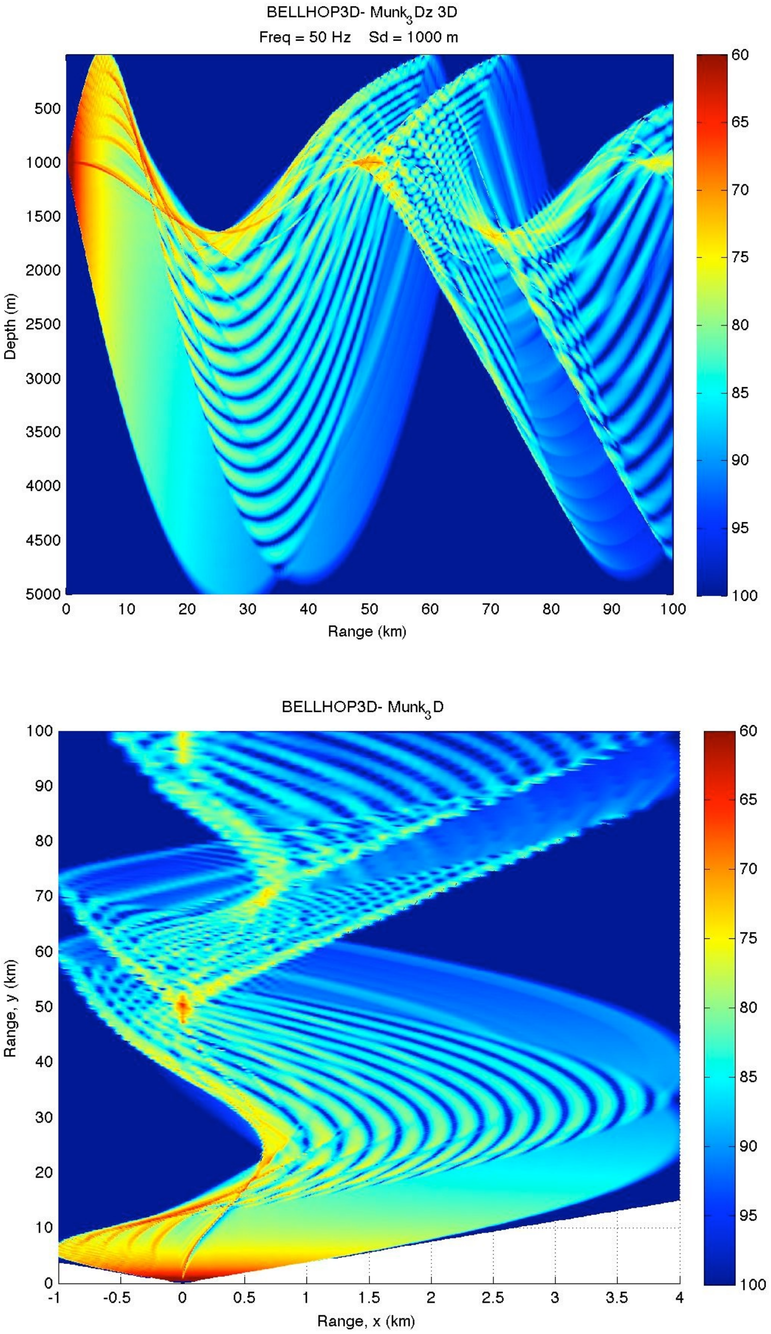

Figure 1: *Comparison of BELLHOP3D to itself. The upper panel is TL for an environment with a canonical Munk deep water profile. In the lower panel the Munk profile has been rotated on its side so that the refraction happens in the lat/lon plane. The TL is seen now in a plan view and the match confirms that the algorithm handles refraction correctly in both range-depth and lat/lon.*

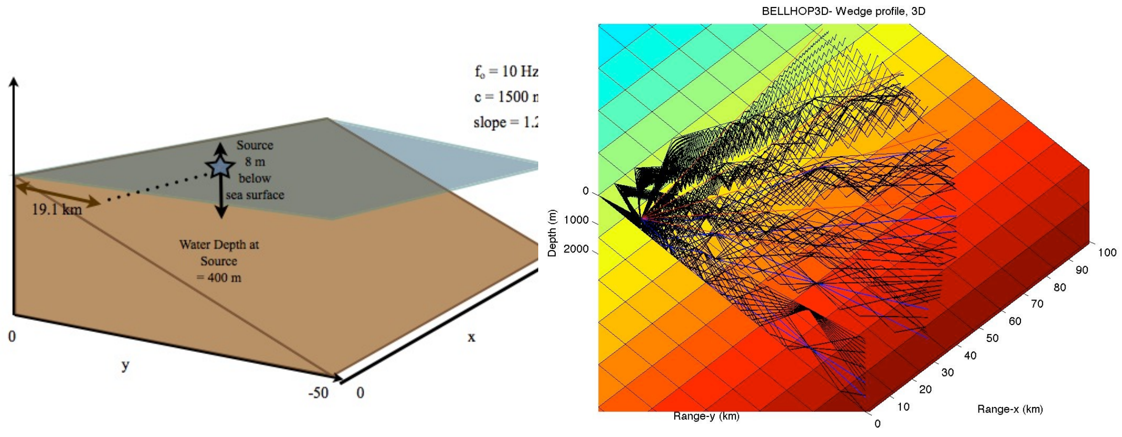

Figure 2: *Schematic of the wedge problem (left) and ray trace (right).*

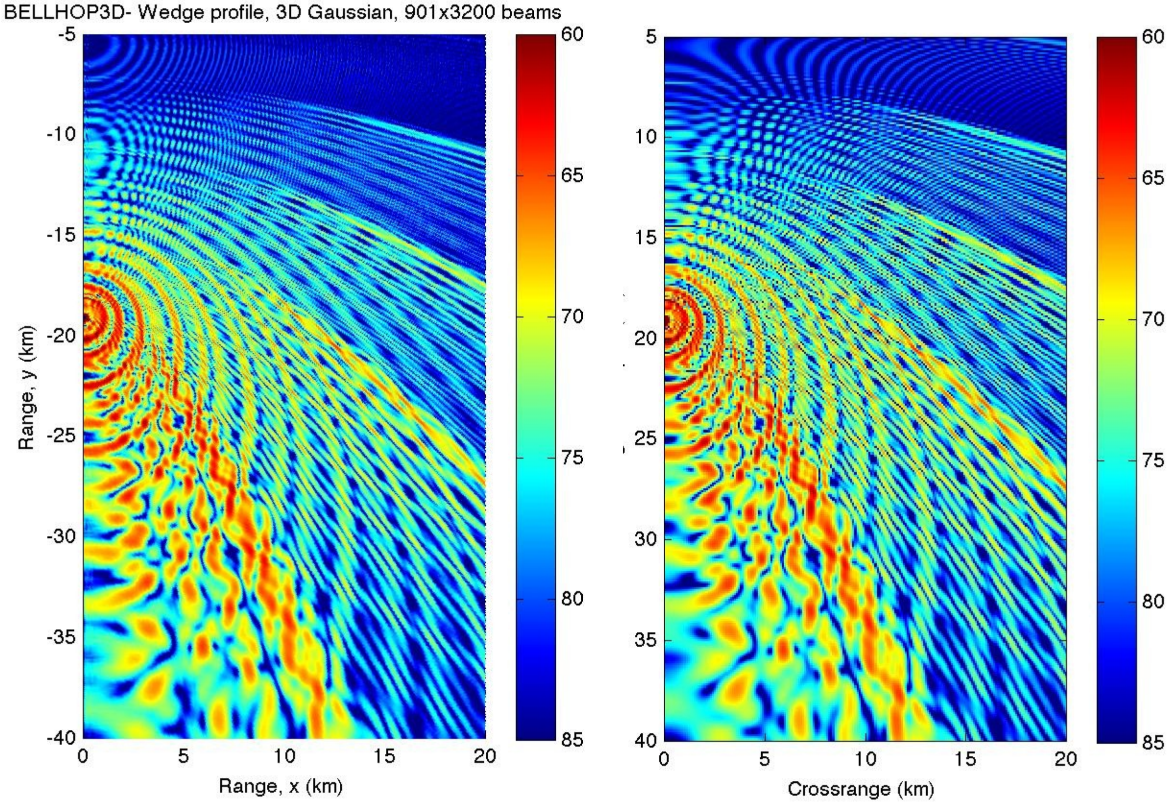

Figure 3: *Comparison of BELLHOP3D (left) to an analytic solution (right).*

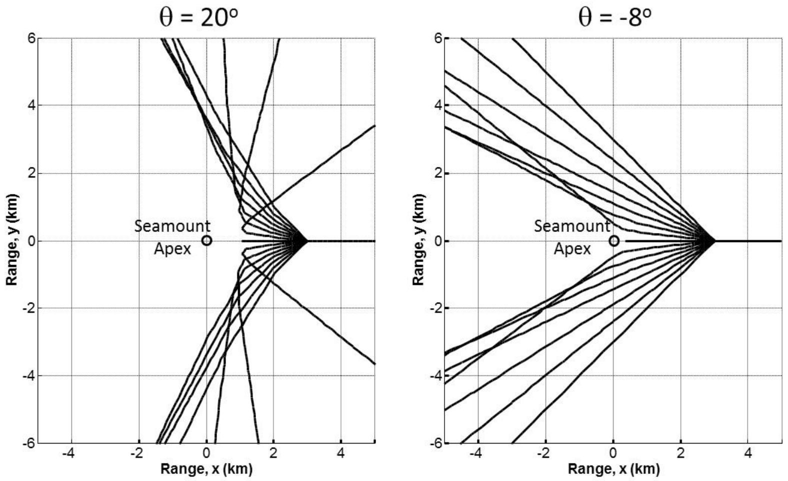

Figure 4: *Rays traveling from the source at the right to the seamount whose apex is in the middle. The rays are refracted by the seamount depending also on the launch declination-angle, theta, of the rays.*

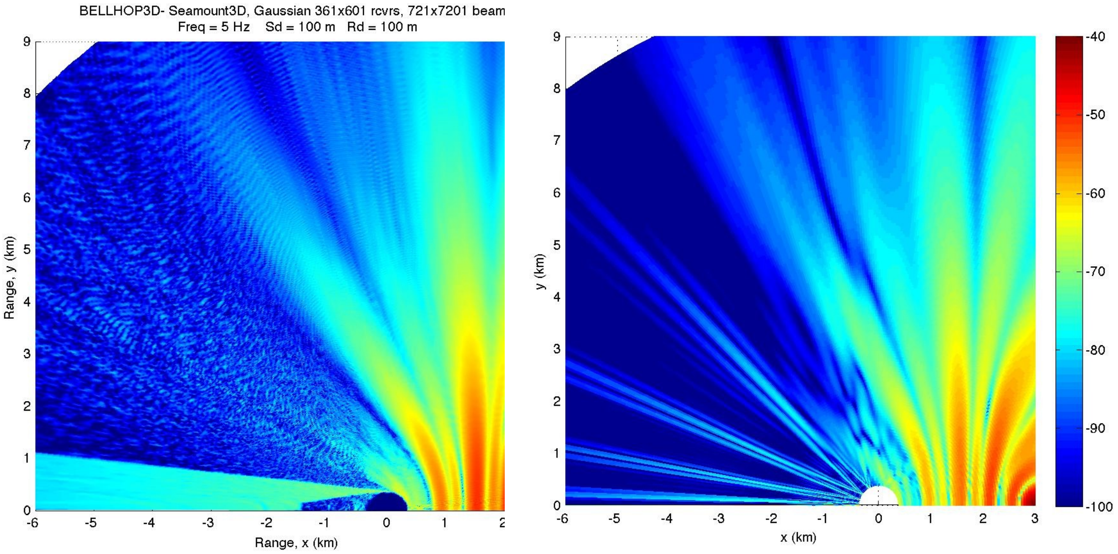

Figure 5: *Comparison of BELLHOP3D (left) to an analytic solution (right).*

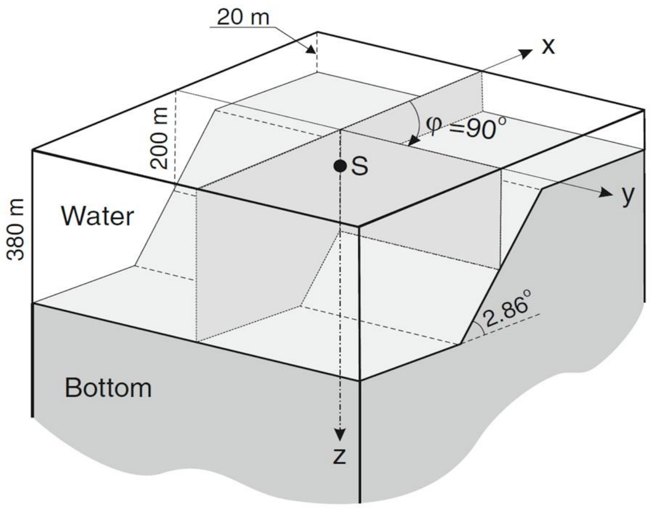

Figure 6: *Schematic of the truncated wedge (shelfbreak) scenario.*

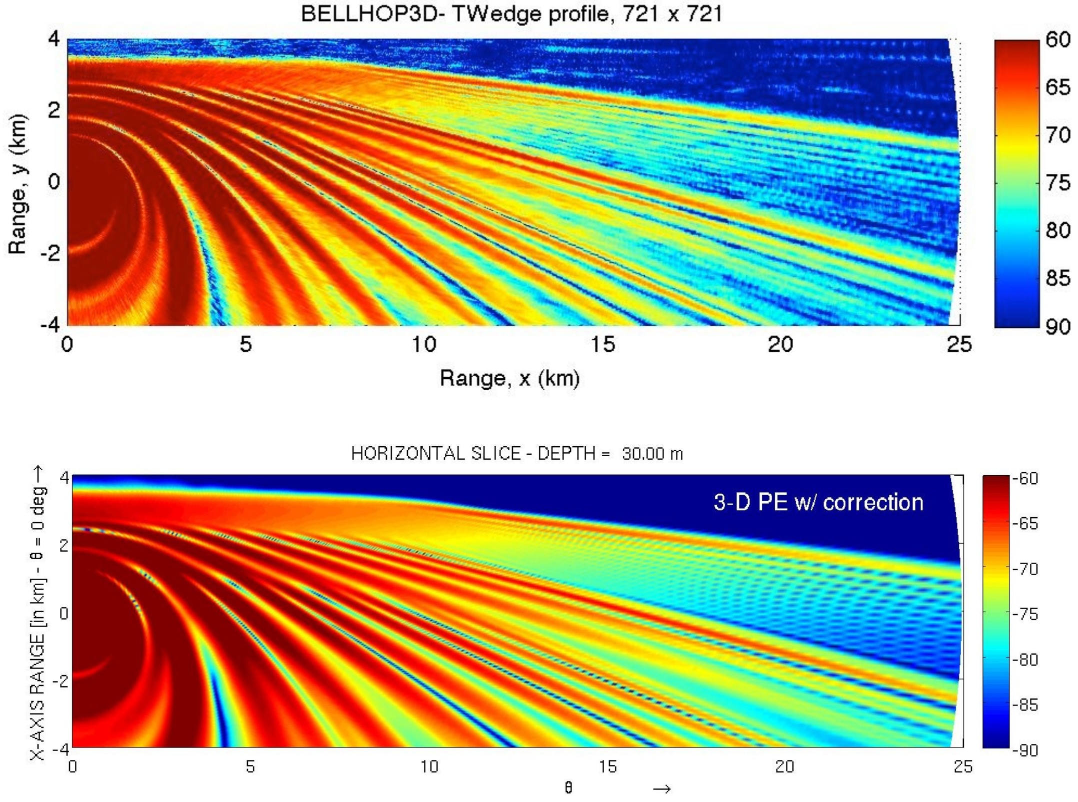

Figure 7: *Comparison of BELLHOP3D (upper) to a 3D PE solution (lower).*