Predicting the Impact of Seabed Uncertainty and Variability on Propagation Uncertainty

Charles W. Holland
The Pennsylvania State University
Applied Research Laboratory
P.O. Box 30
State College, PA 16804-0030
Phone: (814) 865-1724 Fax (814) 863-8783 email : holland-cw@psu.edu

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LONG TERM GOALS

Develop capability for quantifying, predicting and exploiting (QPE) the impact of seabed uncertainty on sonar system performance.

OBJECTIVES

The objective is to develop both measurement and inversion techniques in order to build a 2D geoacoustic uncertainty model (2D-GeUM) over an operationally significant area.

APPROACH

In order to predict the impact of seabed geoacoustic uncertainties and variability on propagation uncertainty along a radial of interest, a 2D geoacoustic uncertainty model (2D-GeUM) is required. Such a model quantifies depth- and range-dependent geoacoustic properties and their uncertainties over the area of interest. For the QPE experiment, the ~50 km x 50 km area of interest was off northeast Taiwan, including part of the Chilung shelf, the East China Sea shelf and upper slope.

The original approach included a combination of direct-path wide-angle seabed reflection measurements and geologic modeling as the basis for generating the 2D-GeUM. The wide-angle reflection data were to be collected at multiple sites in the QPE experiment area northeast of Taiwan in FY09. However, severe weather, equipment problems, and limitations of the research vessel prevented the data from being acquired.

In lieu of this, the approach was to 1) advance theoretical understanding of the impact of seabed variability on propagation uncertainty (see [1]); 2) develop geoacoustic uncertainty methodologies using simulated and experimental data, (see [2-5]) and 3) apply the theory to the experimental geoacoustic uncertainties to examine propagation uncertainty.

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WORK COMPLETED

The FY11 efforts were to:

1. validate the measurement approach, data processing, and theoretical modeling
2. predict propagation uncertainty based on measured 2D geoacoustic uncertainty along a track. The 2D geoacoustic uncertainties were developed in collaboration with Jan Dettmer and Stan Dosso (both at University of Victoria).

RESULTS

The measurements were based on a spatially dense wide-angle reflection data set collected during the Clutter09 experiment from the Malta Plateau (Mediterranean Sea). Data were collected along a 14 km transect with a towed source and hydrophone array close to the seabed. The spatial sampling rate was 3.5m, i.e., every 3.5 m along the track wide-angle reflection was measured. Though the data do not shed light on the geoacoustic variability in the QPE experimental area, the opportunity is that they provide a unique data set for developing high-resolution 2D geoacoustic uncertainty models, a capability the community currently does not have.

For the 14 km track of interest, source and reciever were towed at a constant height, 12 m, above the seabed.and the source was a 10 m offset from the first hydrophone. The measurement quantity is the spherical wave reflection coefficient, R_s, defined here by scaling the reflected pressure from a point source above a planar boundary by the Green's function along the specular reflected path (of length D)

$$R_s(\theta_o, f, z_t) = \frac{ikD}{e^{ikD}} \int_0^{\frac{\pi}{2}-i\infty} J_0(kr\cos\theta)\, R_p(\theta, f)\, \mathrm{e}^{-ikz_t\sin\theta} \cos\theta\, d\theta \tag{1}$$

where θ is grazing angle in the vertical plane, θ_o is the specular reflected angle for a given source receiver horizontal offset r; R_p is the plane wave pressure reflection coefficient; z_t is the sum of the source and receiver height; J_o is the Bessel function of order 0, k is the wavenumber, and f is frequency. Note that unlike the plane wave reflection coefficient, the spherical reflection coefficient depends upon the distance from the boundary z_t. At large distances from the boundary, $kD\rightarrow\infty$ and/or when the plane wave reflection coefficient varies slowly with angle, the plane wave and spherical wave reflection coefficient are similar. Otherwise, the differences between R_p and R_s are generally not negligible.

One of the crucial steps was to validate the measurements, data processing, and theory. This was achieved by comparing the towed array measurements with measurements from a well-established seabed reflection method using a fixed single hydrophone (e.g., [6]) where the uncertainties associated with the latter technique are well-understood [7].

The validation test compares data from a fixed single hydrophone at z_t=167 m with data from the towed array at z_t=24 m. The proximity of the source and receive array to the seabed means that the spatial averaging (i.e., Fresnel zone) will be much smaller for the latter than the former, i.e., order 10 m versus 250 m. The implications for comparison are that we must 1) assume that the seabed layers are completely flat, i.e., the layer thicknesses do not fluctuate between the two locations separated by roughly 100m and 2) use the theory, Eq(1), to compare the two results inasmuch as the z_t differ between the two sites.

In order to make the comparison, geoacoustic properties derived from the fixed receiver reflection data [3] are used to predict R_s for both source heights. That prediction (Figure 1a) shows that at 1000 Hz the R_s are quite different – the oscillations in angle are nearly out of phase. Thus, this should be a good test of whether the experimental methods and theory are adequate. Figures 1b and 1c compare those predictions with measurements. The model-data comparisons in Figure 1b for the fixed receiver data are 'circular' in the sense that those data were used to derive the geoacoustic model, i.e., we expect that the model-data fit should be reasonably good. In Figure 1c, the comparison of the theory and the towed array data is predictive. The reasonably good agreement between theory and the data here indicates that the measurement technique, the data processing and the theory Eq(1) appear to be correct or consistent. Some of the differences between prediction and data may be due to the 100 m spearation between the two locations and the large difference in Fresnel zone size between the two measurements (which would be important if there were any small range depednencies in layer thicknesses).

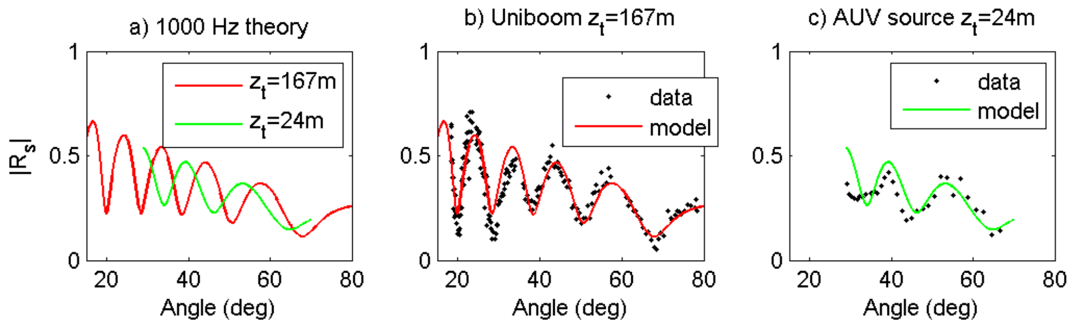

Figure 1 Comparison of 1000 Hz seabed spherical reflection coefficients for z_t=167 m and z_t=24 m at nearly the same location (100 m separation), a) model predictions, Eq.(1) , b) fixed receiver (Uniboom) and model, c) towed array data and model. The agreement between the data and model for the latter helps confirm the experimental method, data processing techniques, and theoretical underpinnings (see [8]).

Concurrent with the development and validation of the measurement technique was the development of a sequential inversion methodology [5] for the reflection data. The inverse problem is computationally intensive and a sequential approach (i.e., relying on information from a previous step) is much more computationally efficient than a brute force independent inversion on each step. Given success of the sequential inversion technique using simulated data [5], we next applied the technique to the measured reflection data in order to obtain the full 2D geoacoustic uncertainty model *(2D-GeUM).* The results are shown in Figure 2. The upper left panel is the sediment velocity vs depth and range along approximately 1 km section of the track. The results show a low-speed sediment layer (i.e., sound speed less than that of the water column) with multiple intercalating higher speed layers. Note that the high speed layer about 3 m sub-bottom shows an increase in velocity along the track., which seems to be real, given the uncertainties. An example of the uncertainties for a single ping (118) are shown in the lower panel. Note that all 3 geoacoustic properties are reasonably well constrained (the red color corresponds to a ~95% confidence bound), with velocity the most tightly constrained with some exceptions. Note that the basement velocities, below ~6 m, are poorly constrained and are multi-modal (as is true on other pings). This means that the apparent variability in the basement properties in the upper left panel is actually driven by the uncertainties. Note in the attenuation that the uncertainties are large when the layer thicknesses are small. Generally, layer boundaries are quite well-constrained (see bottom left marginal plot). The fact that much of the geoacoustic structure is resolved in depth and range means that the experimental method is sufficiently well-designed to produce data that are highly informative about the seabed properties critical for acoustic propagation.

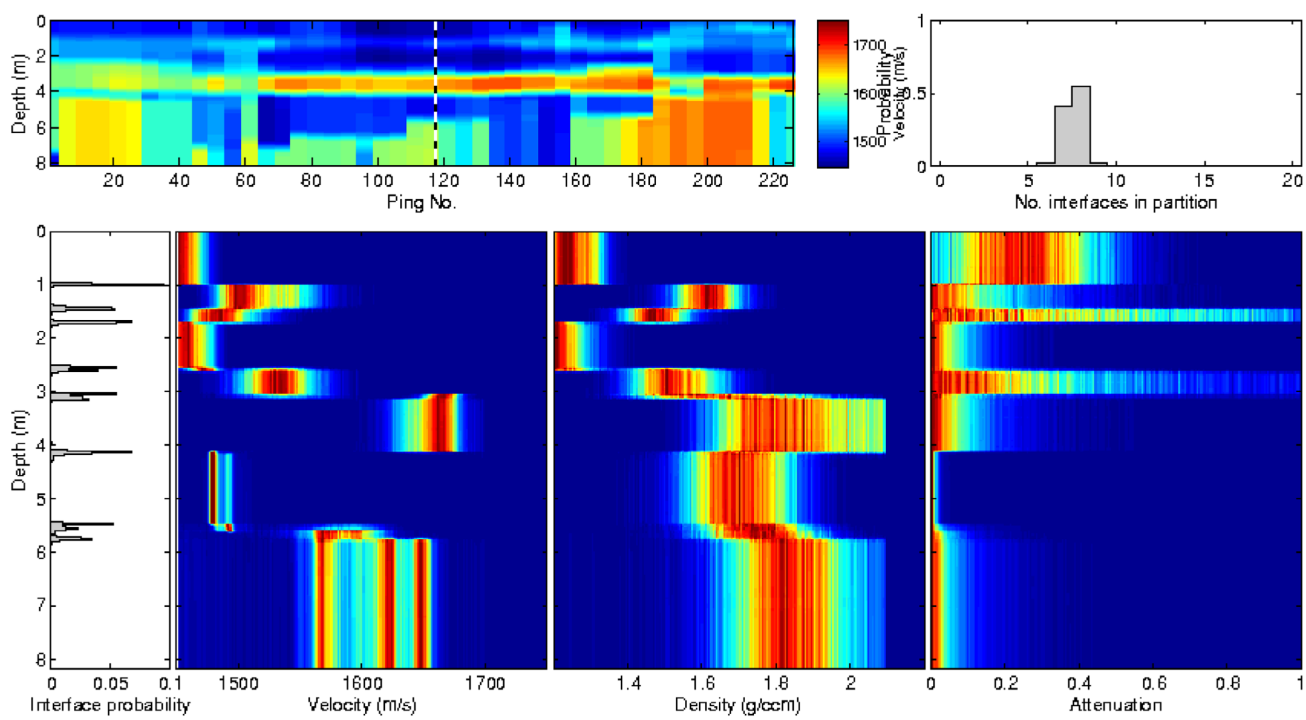

Figure 2. The upper left panel shows the sequential inversion results for sediment velocity vs depth and range along approximately 1 km section of the track. The sequential inversion produces a full 2D geoacoustic uncertainty model (2D-GeUM) for this entire section. An example of the 2D-GeUM is given in the bottom panel for one of the pings (118) which shows that the data are sufficient to constrain the geoacoustic properties reasonably well. The coupling between the uncertainties is an important part of the (2D-GeUM) but is not shown.

The geoacoustic uncertainties permit us not only to distinguish between variability and uncertainty but allow us to calculate the impact of the geoacoustic variability on acoustic propagation through the theory developed in Ref [1]. Limits of the computational resources restricted the inversions to date to a 1 km track. In order to study propagation at ranges of interest, the inter-ping range offset scaled by a factor of 10, permitting us to explore propagation uncertainties out to 10 km. This is shown in Figure 3, for the 140 m isovelocity waveguide (the water depth where the reflection data were collected). The blue lines show the maximum a posteriori prediction for transmission loss using the geoacoustic uncertainties from the measured data. The gray lines show the 95% confidence intervals due the geoacoustic uncertainties. Given the information content of the reflection data and the uncertainties in the data and the forward modeling, the total spread in uncertainty at 10 km is about 6 dB. Note that the propagation uncertainties can change significantly over short distances. At about 2 km, 1000 Hz, the uncertainties increase significantly, due to large uncertainties in the geoacoustic properties below about 4 m depth. The 2400 Hz uncertainties also increase at this same range, but to a lesser degree because the acoustic field in the sediment at and below 4m sub-bottom is considerably smaller than at 1000 Hz. In other words, the propagation is less sensitive to geoacoustic uncertainties at a particular sub-bottom depth as frequency increases.

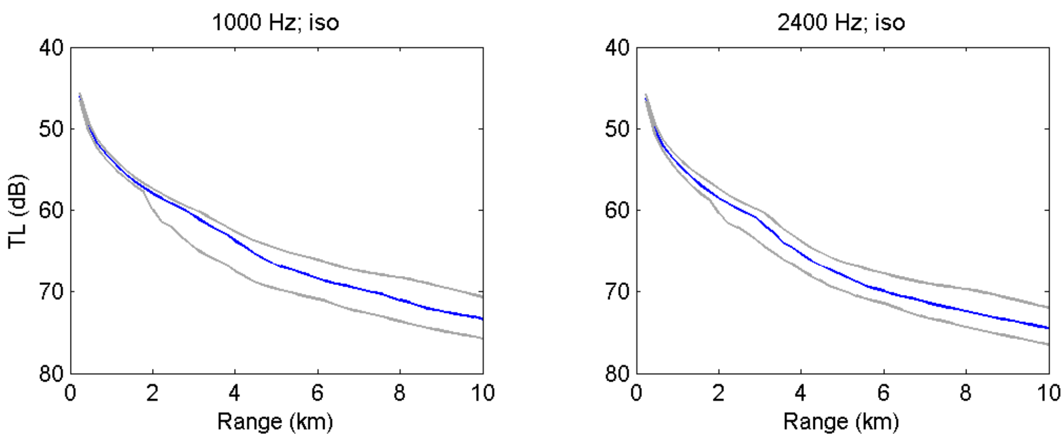

Figure 3. Propagation uncertainty predicted from the measured 2D geoacoustic uncertainty model in a 140m isovelocity waveguide using the theory in Ref [1]. The 2D geoacoustic uncertainties were obtained from analysis of measured reflection data along a track at about 140m water depth. The maximum a posteriori propagation is given in the blue line; the gray lines show the 95% confidence bounds. Rapid increses in the uncertainties, for example at 1000 Hz, 2 km are indicative of sections of the track where the underlying geoacoustic properties are poorly known.

IMPACT/APPLICATIONS

The successful development of 2D geoacoustic uncertainty models has very broad implications for uncertainty estimation in the ocean acoustics community. In some ways, the data from Malta Plateau offer greater potential for understanding uncertainty than the originally planned sparse experiments, inasmuch as the spatial density of the sampling,~10m, provide the data needed to develop/test geoacoustic interpolation methods that will be required for 3D geoacoustic uncertainty models. The measurement and inversion techniques developed here could eventually become a highly useful tool for NAVOCEANO in building next generation seabed databases.

RELATED PROJECTS

ONR Broadband Clutter Joint Research Project: data collected under that project was used to develop the technique for the 2D geoacoustic uncertainty model under the QPE program.

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