# Uniqueness Problems in Extracting Environmental Parameters from High-frequency Shallow-water Reverberation Measurements

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## Abstract

*Inversion techniques that extract environmental parameters from measured reverberation often lead to mathematical problems that are not well-posed. Two examples illustrate this possibility. The first shows how a model can produce accurate forward predictions though based on erroneous physical assumptions. The second example involves measured torpedo data, and offers some guidance to resolving ambiguities that are due to abrupt changes in the bottom sediment.*

## 1. Introduction

Inversion techniques are now used to extract environmental parameters, such as bottom-backscattering strengths, from measured reverberation. The simplest scheme requires a forward model to compute reverberation levels at some initial state, and adjusts the unknown quantities using trial and error until the computed and measured levels agree. More sophisticated techniques estimate rates of change of reverberation with respect to the unknown quantities at some initial state, and iterate until convergence occurs.

Typical inversion problems lead to mathematical models that are not well-posed in the sense of Hadamard. In other words, the solution may not exist, may not be stable under data perturbations, or may not be unique. Numerical methods that are concerned with stability are called regularization methods. The recently published book by Engl, Hanke, and Neubauer [1] is devoted to this subject. The material below, on the other hand, is concerned with uniqueness, but not in the mathematical sense. The problems stem from a misrepresentation of the underlying physics.

For example, consider the following simulation for extracting 30-kHz surface-backscattering strength. The inputs are generated by a *primary* model that includes refraction and multipath effects. In contrast, the *inverse* model assumes that the ocean sound speed is constant and neglects multiple boundary interactions. Both models use an Applied Physics Laboratory, University of Washington (APL-UW) surface-backscattering strength algorithm [2] as described below. The results support the conclusion that refraction and multipath effects are insignificant. However, closer scrutiny reveals that this is fortuitous. Refracted, bottom interacting paths often dominate backscattered energy. Since conflicting physical assumptions produce the same reverberation level, the inverse problem is not well-posed.

Reverberation anomalies frequently lead to incorrect conclusions regarding the ocean environment. For example, 20-kHz reverberation measured in shallow waters off the coast of southern California show an unexpected rise in reverberation followed by a gradual decay into the noise background. Similar anomalies have been attributed to caustics created by sound-speed profiles having strong, negative gradients. But in this case, photographs and grab samples of the ocean bottom provide overwhelming evidence that the rise in reverberation was due to the bottom sediment changing from mud to rock along the track. The measurement was eventually simulated using an APL-UW bottom-backscattering strength algorithm [3] and the Gaussian ray bundle eigenray model [4].

## 2. A Wonsan site in the Fall

The three sets of data in figure 1 are computer generated predictions of monostatic reverberation versus elapsed time for a 100-ms pulse. The predictions are based on APL-UW surface and bottom back-scattering models [2] and [3], the APL-UW surface and bottom forward reflection loss models [5] and [6], and Francois-Garrison volume attenuation [7]. In these predictions, surface reverberation dominated bottom reverberation by about 10 dB, and volume reverberation was neglected. A complete list of environmental and system parameters and the sound speed profile are provided in Table 1 and figure 2, respectively

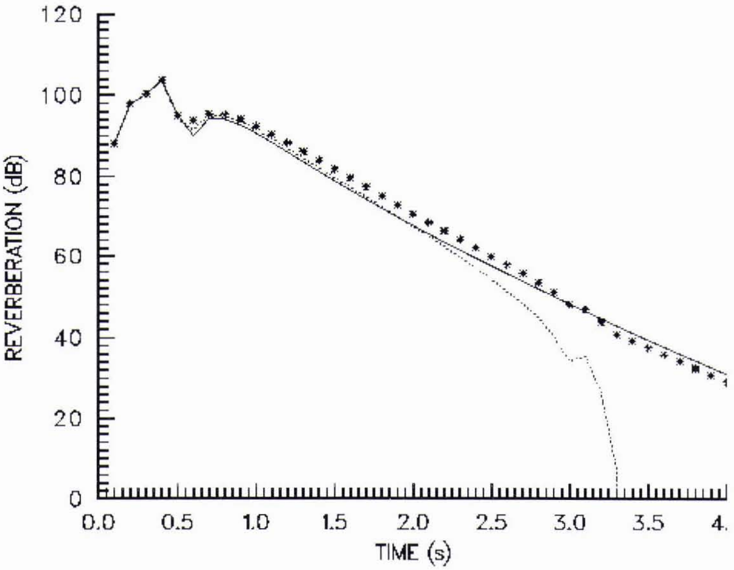

Figure 1: Computer generated predictions of monostatic reverberation versus elapsed time for the Wonson site in the fall. The (*) are assumed to be correct, the (-) is an initial attempt by the inverse model to match the (*), and the (...) denotes the contribution of simple surface backscatter to the (*).

| Parameter | Value |
|---|---|
| site | Wonsan |
| season | Fall |
| bottom depth | 65 m |
| bottom sediment type | coarse silt |
| wind speed | 15 knots |
| surface scattering strength | APL-UW [2] |
| bottom scattering strength | APL-UW [3] |
| surface reflection coefficient | APL-UW [5] |
| bottom reflection coefficient | APL-UW [6] |
| volume attenuation | Francois-Garrison [7] |
| source level | 220 dB |
| pulse length | 100 ms |
| transmitter depth | 26 m |
| transmitter beam pattern | sin(x)/x |
| transmitter vertical beamwidth | 3° |
| receiver depth | 26 m |
| receiver beam pattern | sin(x)/x |
| receiver vertical beamwidth | 10° |
| horizontal beamwidth | 3.2° |

Table 1: Environmental and system parameters for reverberation models.

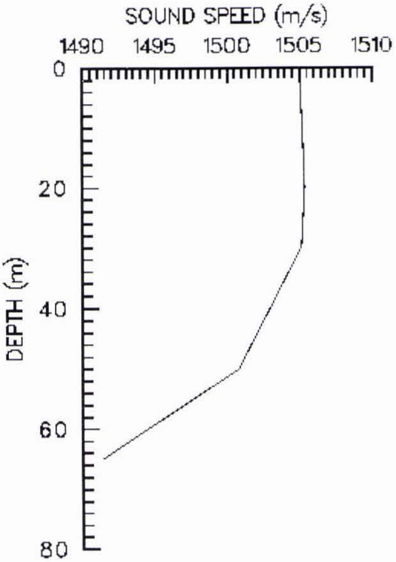

Figure 2: Sound speed profile for the Wonsan site in the Fall.

The (*) in figure 1 were produced by a primary model, which, for the sake of this discussion, are assumed to be correct. This data will be used as inputs for extracting surface-backscattering parameters. The (-) is an initial attempt to match the primary data using an inverse model. Finally, the (...) denote the contribution of direct path surface reverberation to the primary result. In practice, one extracts the surface-backscattering strength by adding the differences between the (*) and (-) in decibels to the initial ARL-UT values. The resulting reverberation levels would match the primary data exactly. Since the primary and initial inverse data agree to within a couple of decibels over the entire time axis, one can argue that the inverse predictions including the estimate of surface-backscattering parameters are accurate.

As noted in the introduction, the primary and inverse models differ by two major assumptions. Because the high value of volume attenuation at 35 kHz limits the ranges of interest to a few kilometers, the inverse model neglects ray diffraction and multipath; The primary model includes both effects. An obvious conclusion is that ray diffraction and multipath are not significant in this example. Many analysts agree that the computer resources required to gain a couple of decibels in accuracy is not warranted in most practical applications.

A more thorough analysis has shown that the conclusions stated above are quite erroneous. It was just fortuitous that the primary and initial inverse results agreed, and the primary contribution to surface reverberation is not the simple surface-backscattered path as claimed by the inverse model. According to the (...) curve in figure 1, the actual contribution to surface reverberation falls off quite rapidly at times beyond 2.5 sec as the direct path enters the shadow zone. The transmitter-surface backscatter-bottom reflection-receiver path (not shown alone) is the dominant source of reverberation. The analysis at shorter times is more complicated. Here the direct path has less propagation loss and shallower surface grazing angles than the bottom interacting paths. Since shallower surface grazing angles are associated with less surface backscattering, the direct path reverberation may be weaker at the shorter times as well. In contrast, the transmitter-bottom reflection-surface backscatter-receiver path is not a significant contributor because the narrow transmitter beam pattern rejects steep downward directed energy.

## 3. SOCAL Torpedo data

The reverberation data to be examined next consists of 38 torpedo pings along 14 tracks. The data was measured at the NUWC SOCAL site near southern California. An extensive environmental survey of SOCAL was conducted in two phases by NUWC [8]. The first phase, November 17-23, 1993 measured bottom bathymetry and acoustic backscatter characteristics. The second phase, December 7-15, 1993, collected high-fidelity forward propagation acoustic data and in-situ measurements of water column conductivity, temperature, and depth. The research vessel R/V Glorita performed a bottom survey with precision navigation, precision bathymetry, side-scan sonar, bottom acoustic reverberation characterization and sediment profile and plan-view imagery. Bathymetric data were collected every second from an ODOM Echo Trac dual-frequency precision survey fathometer with a 3° beam and a 208-kHz transducer. Attached to the hull of the R/V Glorita was a bottom acoustic data acquisition system (BADAS) which acquired and digitized signals from a 24-kHz transducer. A towfish with an EG&G Model 260 side-scan sonar system acquired data at 100 kHz, but malfunctioned during the last part of the survey. A small camera attached to the REMOTS frame, a device that can penetrate and image the upper 20 cm of the sediment, took plan-view photographs above the bottom. In addition, a Van Veep grab sampler collected sediment samples.

In spite of the excellent data, the observed reverberation would not be successfully modeled for several years. The main reason was that our experience in explaining blue-ocean acoustics failed when the bottom depth was under 200 m. The first mistake was to try and extract one bottom-backscattering strength for the entire reverberation data set. The data measured from all 38 torpedo pings appears in figure 3. This shows a 20- to 30-dB variability at individual received times. No single bottom-backscattering strength can produce this phenomena. The explanation was literally in front of our eyes. The REMOTS camera and grab samples showed that the SOCAL bottom sediment varied from mud to rock. Some of the torpedo pings were confined to all mud or all rock tracks, while other pings received reverberation from both types of sediments. Once this obvious observation was brought to light, it became clear that any successful inversion technique must allow for range-dependent variations in the ocean environment, and in particular, in the bottom sediment. Although the variation in SOCAL bathymetry was relatively large, the variation in bottom-sediment properties played a much greater acoustic role.

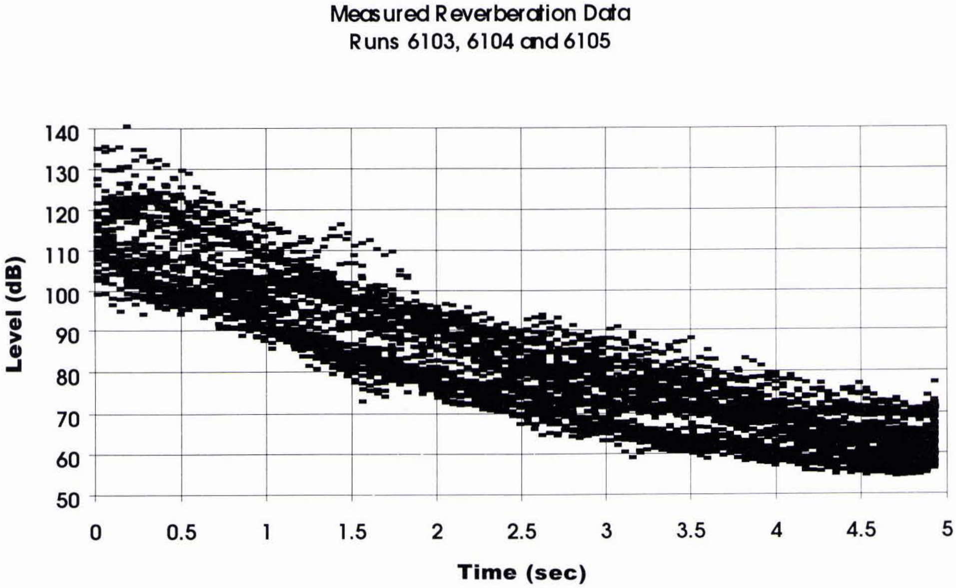

Figure 3: All 38 torpedo pings measured at the NUWC SOCAL site.

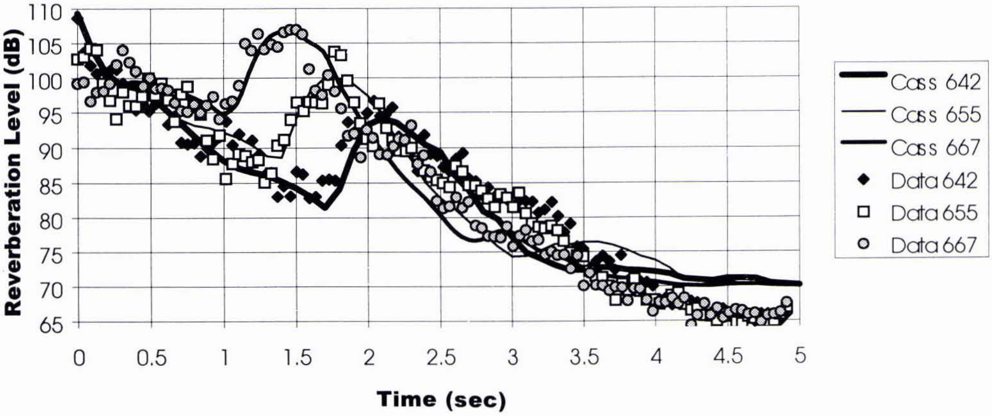

Figure 4: Measured torpedo pings 642, 655, and 667 compared to CASS model predictions.

The numbers 642, 655, and 667 in figure 4 refer to consecutive pings on a mud to rock track. The symbols refer to measured torpedo reverberation, while the lines refer to Comprehensive Acoustic System Simulation (CASS) model predictions [9]. The measured data is a subset of figure 3. Note that the variability in the data is considerably more between one and two seconds than at the earlier and later times. For all three pings, the increase in reverberation levels is due to the increase in bottom backscattering from mud to rock. Ping 667 is furthest away from the transition range, and so its increased reverberation level occurs at a later time. By including the transition range in the environment, CASS was able to extract the bottom-scattering strengths in terms of sediment type.

There was a major difficulty due to an oversight in applying the APL-UW bottom forward reflection loss. This model, basically a plane wave reflection coefficient, showed almost no loss over rock until a critical angle of 60°. The inverse analysis required the loss to be 6 dB per bounce. The APL-UW documentation stated that their model did not include scattering or shear losses. REMOTS camera photographs of the rock areas showed that the rocks were about the size of one's fist, or about a wavelength at 20 kHz, so that scattering due to roughness could not be ignored.

## 4. Conclusions

Environmental parameters that are extracted from measured reverberation data may not be unique unless sufficient constraints are imposed. Fluctuating reverberation levels are particularly difficult to invert. If the fluctuations occur over time periods that are consistent with internal waves, the source is clear. For shorter time periods, the fluctuations may be due to phenomena as diverse as multipath interference and sand ripples. The ambiguity may be resolved by changing system parameters whenever feasible. Fluctuations due to sand ripples should change dramatically with bearing, but not frequency. The opposite should hold for near-surface multipath interference.

In the analysis presented here, the environmental models that were used to perform the inversions were acceptable with one exception. There is currently no generally excepted model for bottom forward reflection loss over rough rock-like sediments. Another shortfall is out ability to model coherent reverberation effects. The examples shown above were all modeled by power summing the various contributions to reverberation at specific times. This approach cannot explain near-surface multipath interference.

## References

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