Inversion Issues for the SW06 Data

A. Tolstoy
1538 Hampton Hill Circle, McLean VA 22101
phone: (703) 760-0881 email: atolstoy@ieee.org

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LONG TERM GOALS

The primary long term objective of this project is to:

- determine a *fast and accurate* geoacoustic inversion method for use in shallow water.

OBJECTIVES

The objectives of this first year's work included:

- to *apply an iterative geoacoustic inversion method* (Tolstoy, '04; '06a,b) to simulated SW06 scenarios (that data themselves were not available to this researcher during this time);
- to study the *robustness, sensitivity, and uniqueness* of geoacoustic inversions for SW06;

APPROACH

First, a (range-independent) scenario mimicing a SW06 scenario published by Jiang and Chapman (2007) was simulated via a time domain, broadband (BB, 50-800 Hz) PE model (Collins, '93). The parameters for this simulation (assuming a bottom consisting of one sediment layer over a half-space) are shown in Fig. 1 with the simulated PE time domain signal for range 1 km seen on the array phones shown in Fig. 2.

Second, we estimated two geometric parameters from mathematically derived relationships between signal crossings. In particular, we derived relationships between crossings and source depth z_{sou}, and between crossings and water depth D. For the mathematics we assumed a constant ocean sound-speed c_0 and considered up to 8 (eight) boundary reflections for each signal. Different crossings indicate either z_{sou} or D, where such crossings can be seen as a function of time and phone depth in Fig. 2 (see the dotted red lines). We estimated z_{sou} and D from these crossings (even though the data were generated for a depth variable $c(z)$) with error bounds Δ_{ph} based on those expected for the uncertainties in "known" phone depths. After examining Fig. 2 we found that that the estimated source depth was given by $\hat{z}_{sou} \approx z_{ph5} \approx \mathbf{30.6m} \pm \Delta_{ph}$ (versus true $z_{sou} = \mathbf{31.4m}$, Δ_{ph} was the phone depth uncertainty), while the estimated water depth was given by $\hat{D} \approx 0.5 * (z_{ph10} + z_{ph11}) + \hat{z}_{sou} \pm 2\Delta_{ph}$ where $0.5 * (z_{ph10} + z_{ph11}) \approx \mathbf{51.2m}$ gives $\hat{D} \approx \mathbf{81.8m} \pm 2\Delta_{ph}$ (versus true $D = \mathbf{79.7m}$). These are close to the "true" values even though the derivation assumed a constant c_0 rather than the "true" $c(z)$. At the very least these values can be used to bound the search intervals for the parameters z_{sou} and D. But how important is $c(z)$?

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14. ABSTRACT

The primary long term objective of this project is to determine a fast and accurate geoacoustic inversion method for use in shallow water.

15. SUBJECT TERMS

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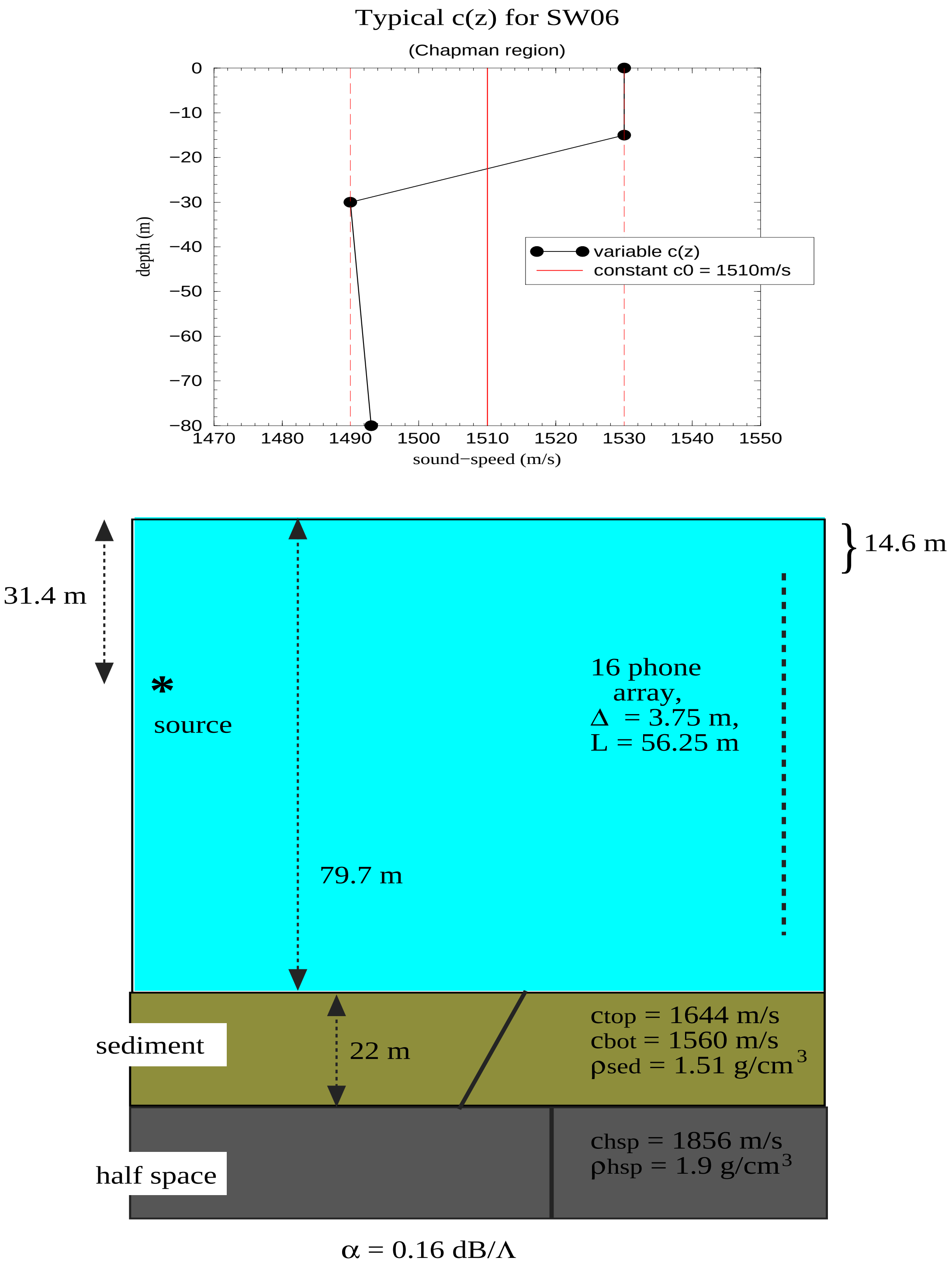

Figure 1: *Simulated SW06 environment and geometry.*

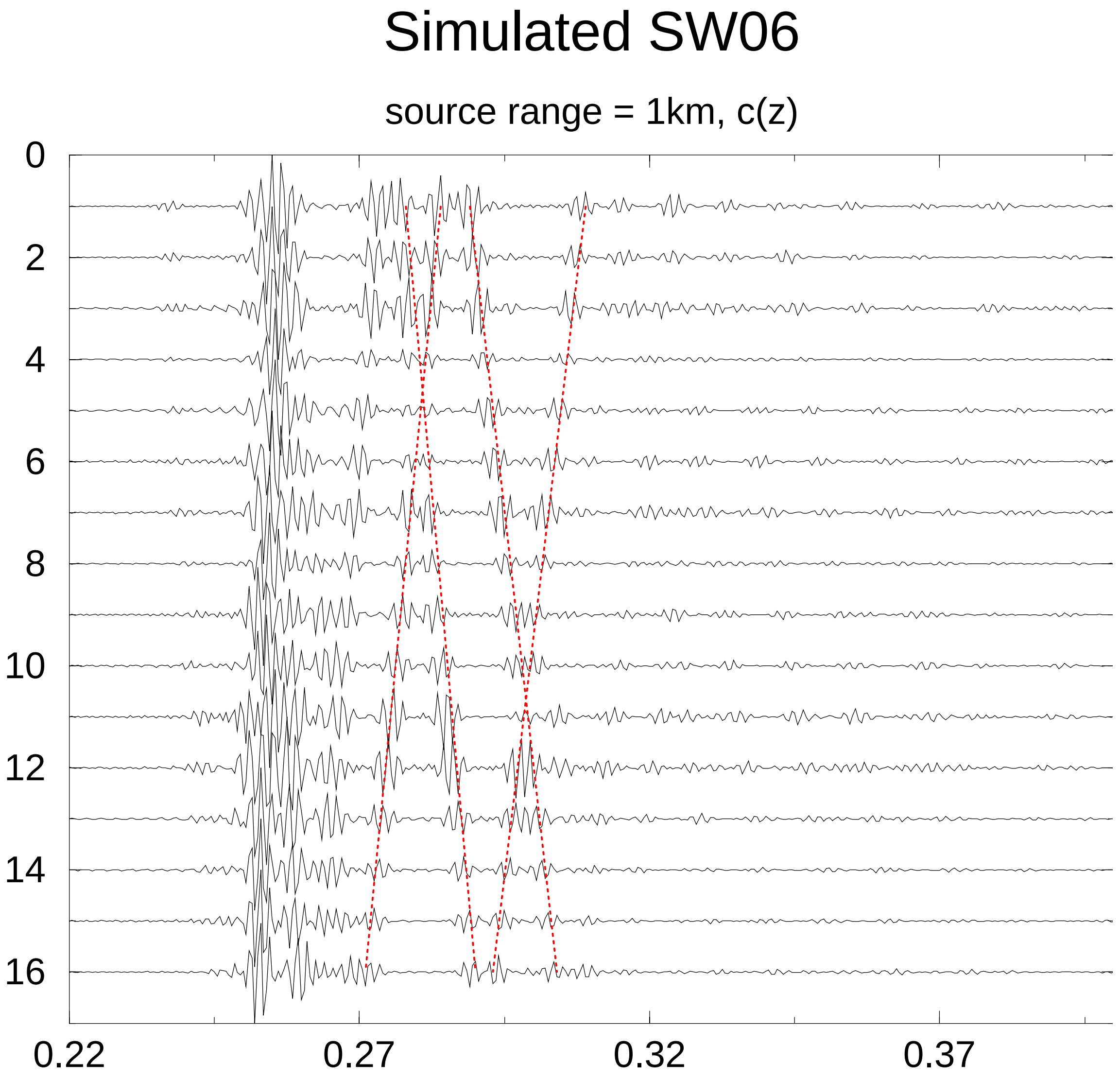

Figure 2: *Simulated SW06 time BB domain data with parameters as seen in Fig. 1. The dotted red lines indicate selected crossings. Time (sec) is the x-axis while phone number is the y-axis (the higher phone number corresponds to the deeper phone).*

Next, we examined a number of source ranges rge from 100m to 1km, and found that ocean sound-speed $c(z)$ only affected the time domain signal at the longer ranges, e.g., for $rge \geq 500$m. Additonally, we observed a few other behavior traits: at the longer ranges the signal appeared to compress as it first arrived with the trailing reflections becoming more distinct and thus, more amenable to distinct crossing estimates (see Fig. 3); and bottom effects (reflections) were also stronger at the longer ranges (Tolstoy, '08). In general, the crossings (based on the later arrivals) were still accurate with regard to estimates of $\hat{z}_{sou}$ and $\hat{D}$ even in the presence of depth variable $c(z)$.

Then, we questioned how well we could resolve the ocean sound-speed profile. In particular, we found that we needed to use the higher frequencies and the longer ranges for better resolution of $c(z)$ and that the more complicated the $c(z)$ the better chance we had of determining the profile. Similarly, *geometric* scenario parameters were best resolved at the *higher* frequencies. Thus, we saw that the best rge resolution occured at the higher frequencies. We note that rge is highly correlated with D and could not be resolved uniquely unless D were known. This VLA correlation exists across frequencies and will not be eliminated by BB (Tolstoy et al., '02).

Finally, we began inversion via low frequencies rather than via the high frequencies of the previous SUB-RIGS approach of Tolstoy (2004) since $c(z)$ is not accurately known. We first considered a low frequency LF (50Hz) such that only 5 parameters should be important:

- rge,
- c_{top} (the sediment sound-speed at the top of the sediment),
- γ (the sediment sound-speed gradient),
- h_{sed} (the sediment thickness), and
- c_{hsp} (the half-space sound-speed).

The other parameters were seen to be "unimportant" at this LF after sensitivity analyses (z_{sou}, densities, attenuation, etc.). That is, sensitivity was essentially flat at the "unimportant" parameters for 10 test sets of various fixed parameters.

Errors at LF with respect to $c(z)$ and z_{phi} showed little sensitivity at LF and were too small to be important, i.e., they are small with respect to a wavelength ($\lambda_{50Hz} \approx 30$m). Consequently, at 50Hz and for approximate $\hat{c}(z)$ ($\hat{c}(0)$=1532m/s, $\hat{c}(20)$=1528m/s, $\hat{c}(32)$=1488m/s, and $\hat{c}(80)$=1490m/s), approximate phone depths $\hat{z}_{phi}$ (1 m deeper), and approximate $\hat{D} = 81$m ("true" $D = 79.7$m) we performed an exhaustive search for the 5 major parameters (approximately 23000 combinations requiring about 20 hrs of CPU on an SGI Octane2 using the RD PE. We found nearly 2200 parameter combinations for which MFP $\geq$ 0.95 at 50Hz (including MFP = 1.00 near the true values). That is, we found a great many potential solutions. We note also that sensitivity analyses indicated sufficiently fine search intervals so that high MFP values would not be missed.

We then examined those 2200 high MFP value parameters (generated given an *approximate* sound-speed profile, approximate water depth, approximate phone depths, and approximate source depth) where the distributions of high value individual parameters are shown in Fig. 4. We note that while

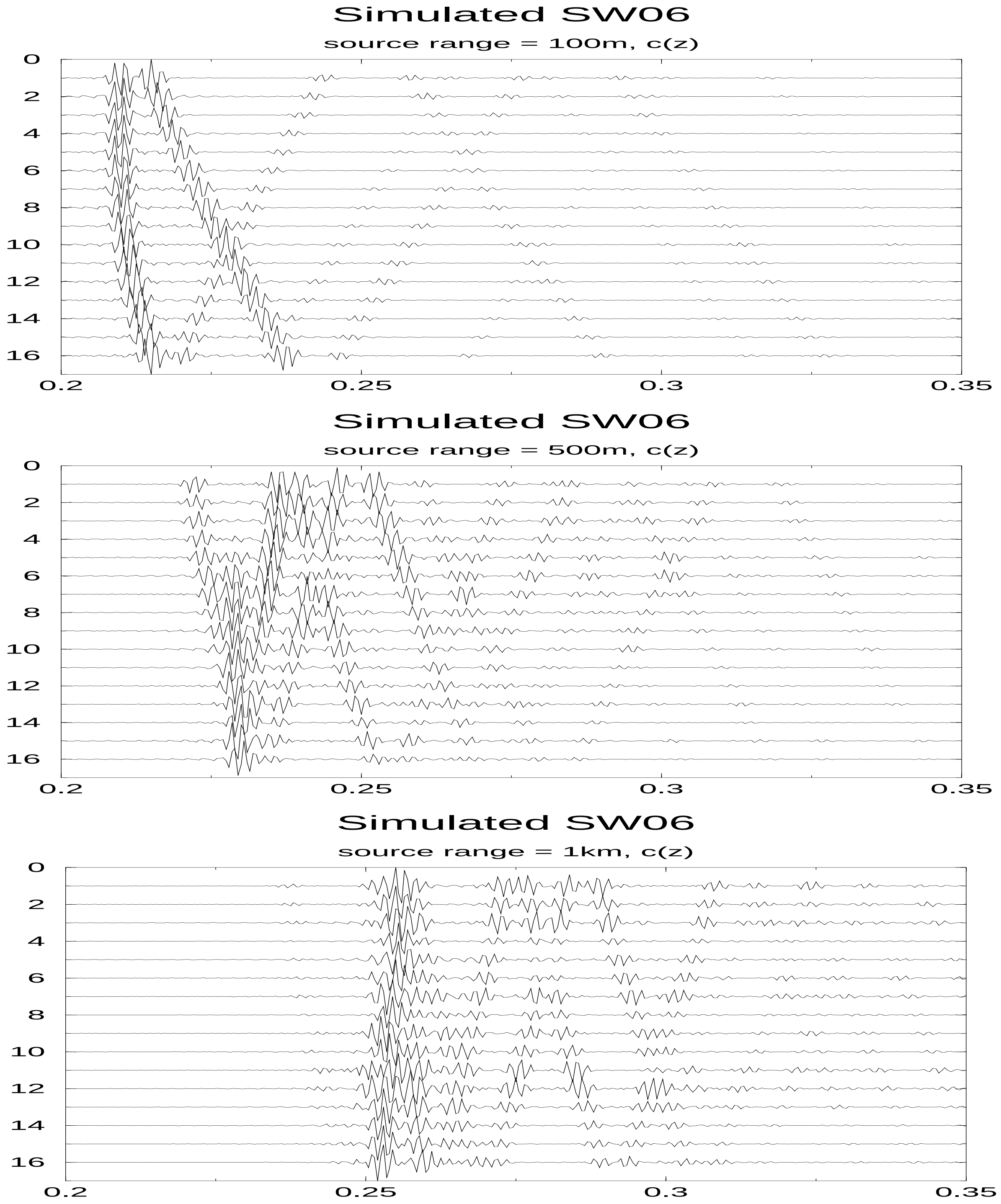

Figure 3: *Simulated time domain signals for a variety of indicated* rge*: 100m, 500m, and 1km. These signals were generated assuming a depth variable* $c(z)$*, i.e., the parameters of Fig. 1. Time (sec) is the x-axis while phone number is the y-axis (the higher phone number corresponds to the deeper phone).*

we cannot tell from Fig. 4, a combination of “true” values is *also* in this set indicating that even in the presence of our many approximations, MFP=1.00 at 50Hz very near the correct values. Next, we need to try to converge to the “true” solution, e.g., use BB. Clearly, we cannot extract the “true” parameter values from the high 2200 values alone. What about 55Hz?

Computing the 5 parameter combinations at 55Hz for all those situations where MFP $\geq$ 0.95 at 50Hz (CPU time is now reduced to less than 15 hrs), we found that there were now far fewer combinations for both frequencies with MFP $\geq$ 0.95 (270 combinations). However, the “true” values are still among the high MFP cases. Unfortunately, sensitivity analyses indicated that the search intervals at 60Hz needed to be smaller for this higher frequency or else high MFP values might be missed. Thus, our exhaustive searches at higher frequencies needed to be refined and constricted in order to run in a reasonable amount of time.

We next assumed a fixed sediment sound-speed gradient of -4 per s (the true value). We are hoping that by including two more frequencies (60 and 65Hz) we will now be able to converge to the “true” parameter set. After only 30 min of CPU we obtain a set of less than 10 parameter combinations for which MFP is 0.95 or higher at 60Hz while also having high MFP vlaues at 50 and 55Hz. Repeating this process at 65Hz we find that only values near a few “true” values show high MFP values. That is, the values 1020m $\leq \hat{\boldsymbol{rge}} \leq$ 1030m, 1620m/s $\leq \hat{\boldsymbol{c}}_{\boldsymbol{top}} \leq$ 1630m/s, $\hat{\boldsymbol{h}}_{\boldsymbol{sed}} =$ 21m, $\hat{\boldsymbol{c}}_{\boldsymbol{hsp}} =$ 1850m/s for $\hat{\boldsymbol{z}}_{\boldsymbol{sou}} =$ 30m, $\hat{\boldsymbol{D}} =$ 81m, and $\hat{\gamma} =$ -4.0per s give MFP values at least 0.95 at 50, 55, 60, and 65Hz. Unfortunately, this may also be true for other values of $\hat{\gamma}$. This needs to be pursued. So far, we have only shown that a restricted search using approximate values of $\boldsymbol{z}_{\boldsymbol{sou}}$ and $\boldsymbol{D}$ (estimated from crossings), approximate $\boldsymbol{c}(\boldsymbol{z})$ and $\boldsymbol{z}_{\boldsymbol{phi}}$, and 4 neighboring LFs can can converge to a solution near “true” for the 5 major geoacoustic parameters.

WORK COMPLETED

Recent work (FY07) completed includes:

- simulations of a variety of time domain signals for selected SW06 scenarios;
- the derivation of a new method via signal crossings (assuming up to 8 reflections) to find estimates of $\boldsymbol{z}_{\boldsymbol{sou}}$ and $\boldsymbol{D}$. These estimates were valid even in the presence of $\boldsymbol{c}(\boldsymbol{z})$ and at numerous $\boldsymbol{rge}$ tested. This method should be most helpful when phone depths are “known”;
- sensitivity studies for $\boldsymbol{c}(\boldsymbol{z})$. These efforts indicated that $\boldsymbol{c}(\boldsymbol{z})$ should be refined at the higher frequencies only. Additionally, $\boldsymbol{c}(\boldsymbol{z})$ impacts the signal only at the longer $\boldsymbol{rge}$;
- sensitivity studies for selected geometric parameters. These studies suggested that parameters such as $\boldsymbol{rge}$, $\boldsymbol{D}$, $\boldsymbol{zph}_{\boldsymbol{i}}$, and $\boldsymbol{z}_{\boldsymbol{sou}}$ should be refined using only the higher frequencies while the geoacoustic parameters (such as $\boldsymbol{c}_{\boldsymbol{top}}$, $\boldsymbol{h}_{\boldsymbol{sed}}$, γ, and $\boldsymbol{c}_{\boldsymbol{hsp}}$) should be inverted using the lower, more bottom penetrating frequencies;
- initial geoacoustic inversions using some approximate environmental parameters (such as $\hat{\boldsymbol{c}}(\boldsymbol{z})$, $\hat{\boldsymbol{D}}$, $\hat{\boldsymbol{z}}_{\boldsymbol{phi}}$, and $\hat{\boldsymbol{z}}_{\boldsymbol{sou}}$) and low frequencies (50, 55, 60, and 65Hz).

RESULTS

We find a number of results:

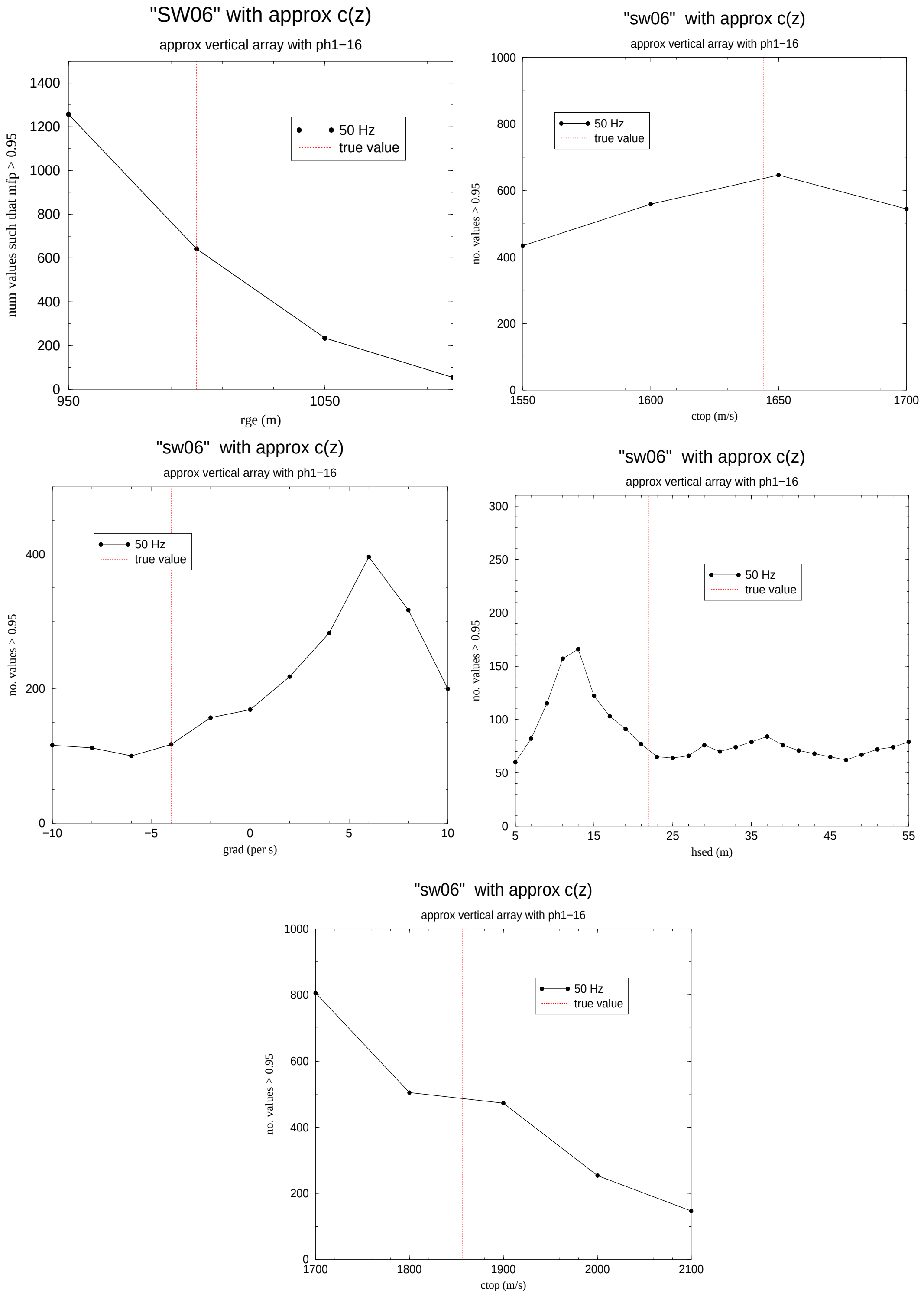

Figure 4: *Single parameter behavior at 50Hz for which MFP $\geq$ 0.95 as indicated. While the actual parameter combinations are not shown (would require 5 dimensional plots), we can see that here there are many combinations for which excellent data fits (MFP $\geq$ 0.95) are possible at 50Hz.*

- First, examining field crossings can give surprisingly accurate estimates of source depth $\hat{z}_{sou}$ and water depth $\hat{D}$ at a variety of ranges (later reflections must be used for the longer ranges). These estimates will significantly reduce the search for geometric source parameters in the presence of phone depth information.
- Second, the time domain field is sensitive to ocean sound-speed $c(z)$ at the longer ranges. Thus, a search for $c(z)$ parameters must be included in inversions at the longer ranges and higher frequencies. However, $c(z)$ can be approximated at the close ranges and LF.
- Third, some parameters should be refined only using the higher frequencies, some only the lower frequencies. Using an all encompassing BB search will degrade some parameter resolutions.
- Fourth, major bottom properties such as c_{top} and γ (linear sediment sound-speed profile), h_{sed}, c_{hsp} may be estimated by means of multiple low frequencies. However, these estimates may or may not be unique – more work needs to be done on this question.

IMPACT/APPLICATION

As a result of the work this past year we have developed and better understand:

- a new method to estimate D and z_{sou} based on signal crossings observed in the time domain;
- a new inversion method (similar to SUB-RIGS but starting with LF and working up in frequency) and its success with simulated SW06 data.

RELATED PROJECTS

The inversion work is related to work by R. Chapman and colleagues (U. Victoria), D. Knobles and colleagues (U. Texas at Austin), W. Hodgkiss and colleagues (Scripps), and other researchers in SW06 and shallow water inversion (such as P. Gerstoft, P. Nielsen, C. Harrison).

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