Low Frequency Geoacoustic Inversion Method

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LONG TERM GOALS

The primary long term objective of this project is to:

- determine a *fast and accurate* inversion method to estimate bottom properties in shallow water.

OBJECTIVES

The objectives of this year's work (FY11) included:

- to continue study of a *new* low frequency (LF) geoacoustic inversion (G.I.) method (Tolstoy, '10), particularly the investigation of a new broadband method (the minimization method; see Tolstoy, '12);
- to *apply* the LF G.I. method to horizontal arrays in a simulated SW06 environment.

APPROACH

For the simulations to follow we shall consider three single sediment layer scenarios (each defined by a linear sound-speed profile and constant density) over a half-space (constant sound-speed and density) each at multiple (16) frequencies (25 to 100Hz) and multiple (5) ranges (250 to 2075m).

The "true" environments for these simulations (based on SW06 test scenarios) are shown in Fig.1 and Table 1 allowing for thin, medium, and thick sediment layers. Consideration of a variety of scenarios helps to address concerns that our conclusions, particularly with regard to frequency, are very dependent on sediment thickness. For the "exact" inversion processing we shall assume that:

- the bottom consists of a single linear sediment layer (specified by c_{top}, γ, and h_{sed}, over a half-space with sound-speed c_{hsp}) (parameters will vary depending on the layer thickness under consideration; see Table 1);
- all water depths D will be within 78 to 86m (parameter value will vary depending on the layer thickness under consideration; see Table 1);
- the fixed ranges rge will each be less than about 2km;

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- the ocean sound-speed $c(z)$ will vary with depth only (no inversion on $c(z)$; see the solid curve in Fig. 1);
- z_{sou} will be fixed (no inversion done on z_{sou});
- one array will be vertical (VLA) with length 56.25m consisting of 16 phones spaced at 3.75m apart with array element localization and the top phone depth at z_{ph1} =14.6m. Alternately, we may consider a horizontal array (HLA) with length 900m consisting of 19 phones spaced at 50m (optimized) with depth z_{phi} =10m (optimized for all i). The "true" arrays have no tilt (no inversion done on z_{phi}).

	thin	medium	thick
h_{sed}	12m	22m	40m
c_{sed}	1622m/s	1644m/s	1610m/s
γ	2.0/s	-4.0/s	0
c_{hsp}	1806m/s	1856m/s	1900m/s
z_{sou}	29.4m	31.4m	31.2m
D	78.2m	79.7m	80.8m

Table 1: *Table of geometric and environmental values for the three sediment thicknesses (simulated) considered.* h_{sed} *is the sediment thickness,* c_{sed} *is the sound-speed at the top of the sediment,* γ *is the sound-speed gradient in the sediment (sound-speed at the bottom of the sediment is given by* $c_{sed} + \gamma h_{sed}$*),* c_{hsp} *is the sound-speed of the basement half-space,* z_{sou} *is the source depth, and* D *is the water depth.*

As in the earlier simulation work, we will generate the "true" field using the single depth-variable ocean sound-speed profile seen as the solid curve of Fig. 1 (top), and as before we shall continue to generate the synthetic acoustic fields via RAMGEO (Collins, '94).

As seen last year the LF method performs an *exhaustive* search through a *limited* parameter space. However, before performing this search we now look closely at parameter sensitivities. An example is shown in Fig. 2 where we inspect matched field processing MFP (Tolstoy, '93) sensitivity at the frequencies and ranges mentioned earlier. For this case we note excellent sensitivity to c_{hsp} at 25Hz and increasing range, particularly at 1km and beyond. All other parameters are fixed at their exact (true) values. Thus, by studying such behavior we find that for our low frequencies (25-75Hz) and close ranges (250 to about 1000m) we will have some excellent sensitivities.

We also find that higher frequencies and longer ranges can be detrimental to G.I. – even without errors anywhere. This has led to the development of a new broadband (BB) signal processing method, $\mathcal{P}_{min}(f)$ defined as selecting the minimum MFP value found over the frequencies f considered at each set of parameter values. To be more explicit, if we consider the usual linear MFP processor behavior at each frequency, and if $\mathcal{P}_{min}(f) = 0.8$, then *all* the linear processor components have values 0.8 or higher. If we compare the usual BB averaging of frequencies versus $\mathcal{P}_{min}(f)$ we find that the new method ignores the lack of sensitivity which may sometimes be found at higher frequencies (HFs) while the simple, standard averaging process incorporates the lack of sensitivity at off true values (see Fig. 3 as well as the 100Hz versus 25Hz components in Fig. 2). Thus, the new minimization method is expected to be more sensitive to parameter values (relative to standard incoherent averaging) while still taking advantage of BB and rge variability.

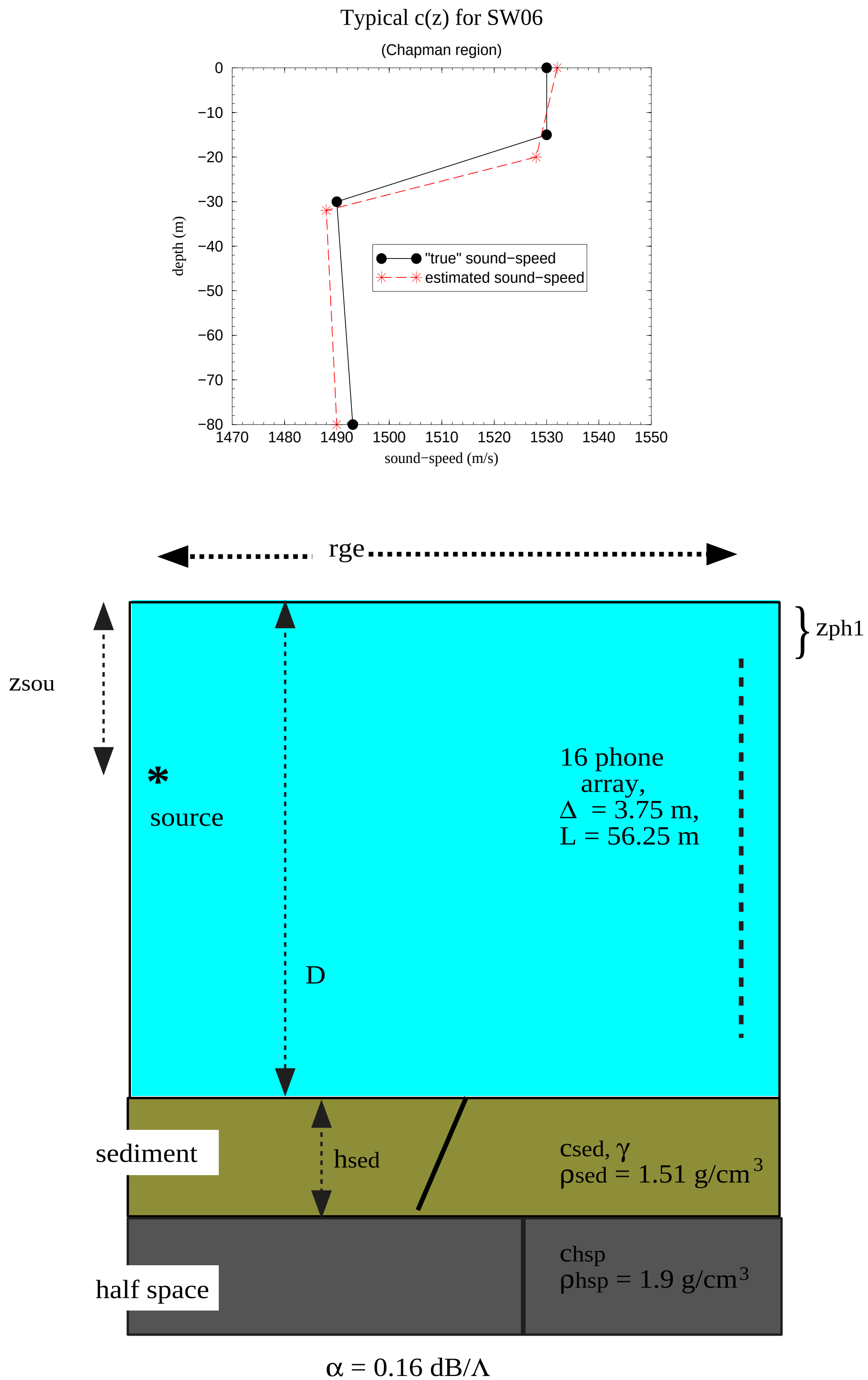


Figure 1: *Plot of simulated SW06 environment where the upper subplot shows the ocean sound-speed* $c(z)$ *used in the simulations (the exact and approximate profiles shown), and the lower subplot shows the ocean waveguide assuming the linear sound-speed profile in a single sediment layer over a half-space basement. Actual bottom parameter values to be found in Table 1. For all exact scenarios we will have true* $z_{ph1} = 14.6$*m and true ranges rge = 265, 480, 780, 980, and 2075m.*

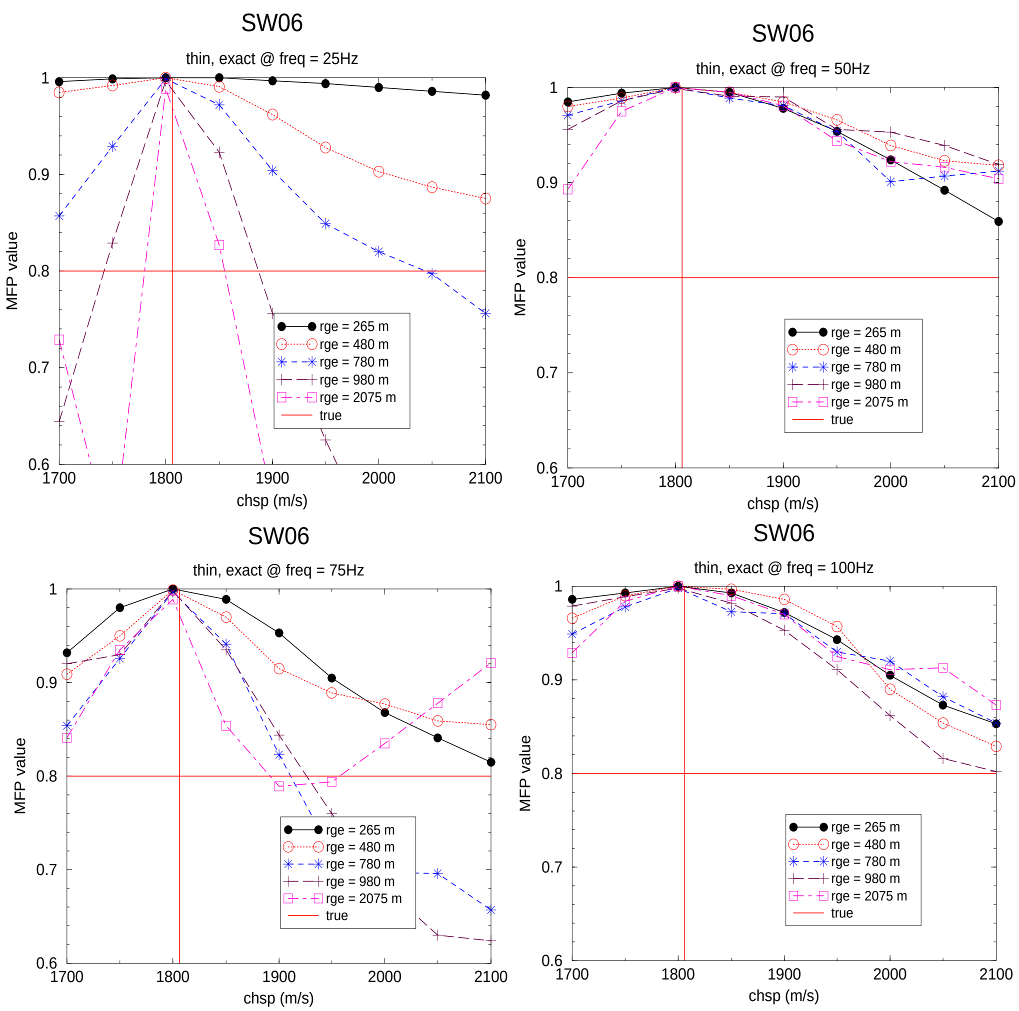


Figure 2: *MFP behavior of* c_{hsp} *as a function of distance (rge) for the thin sediment layer case at four frequencies. Upper left: frequency 25 Hz; upper right: frequency 50 Hz; lower left: frequency 75 Hz; lower right: frequency 100 Hz. The longer ranges and lower frequencies are clearly most sensitive.*

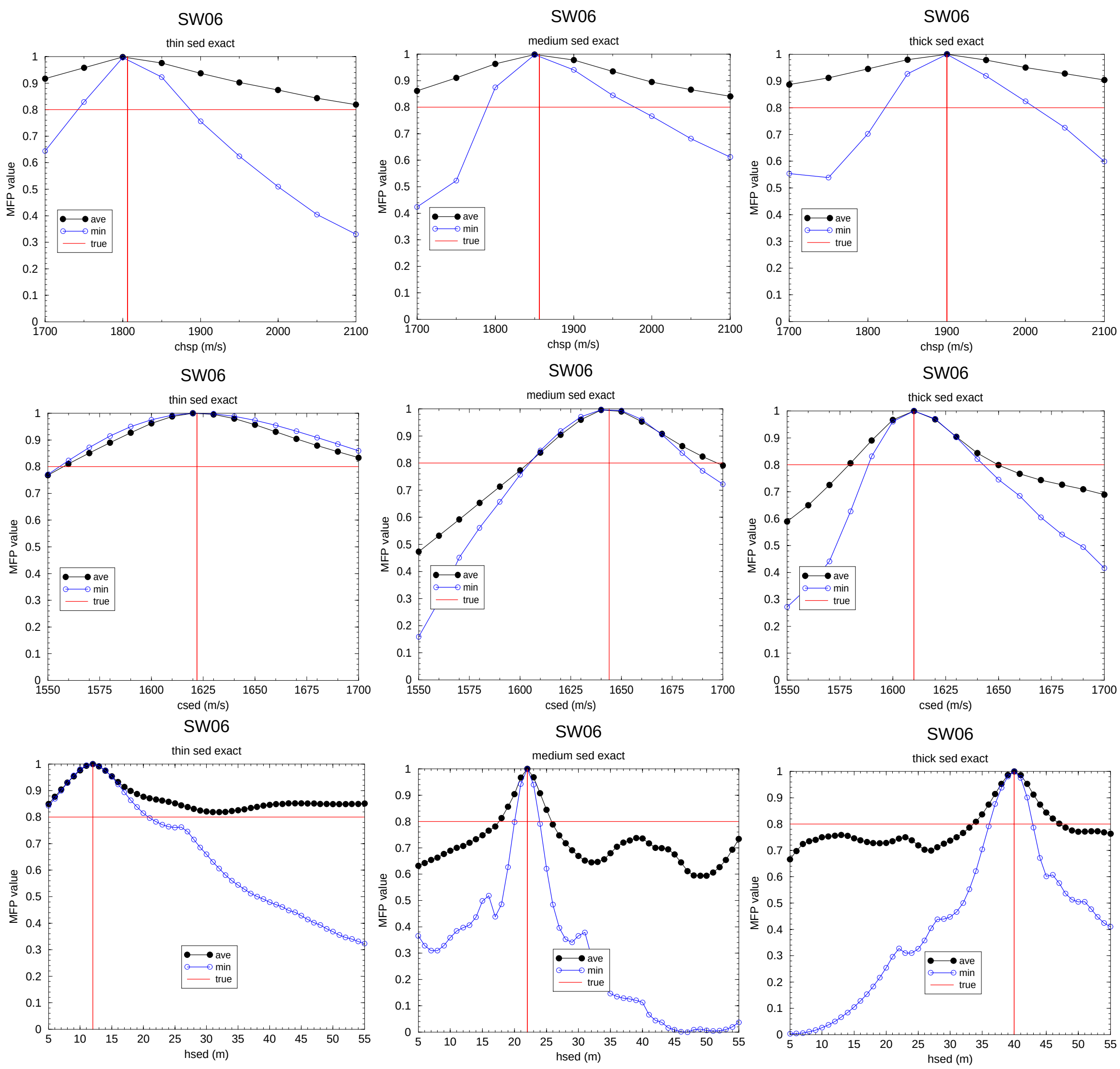


Figure 3: *Plots showing averaged and minimization MFP performance for* $\boldsymbol{c_{hsp}}$, $\boldsymbol{c_{sed}}$, *and* $\boldsymbol{h_{sed}}$ *for three sediment conditions. We have assumed all other parameters are known exactly. We note the significantly better resolution (in nearly all cases) of the min processor (blue curve plus empty circles) vs. the ave processor (black curve plus filled circles).*

We have also considered the effect of expected errors on our sensitivities. In particular, if we assume that:

- $\gamma = 0$, thus inverting for c_{ave} in the sediment layer;
- source range rge is known only to within 100m (rge and water depth D are known to be linearly related – even broadband processing cannot separate out the "true" values of rge and D; see Tolstoy et al., '02). Thus, we will invert only for D assuming a "known" rge;
- the ocean sound-speed $c(z)$ will be assumed by the dashed (incorrect) curve of Fig. 1;
- z_{sou} will be fixed at 30m (rather than its "true" value which will vary as in Table 1);
- for the VLA we will assume top phone depth at z_{ph1} =15.6m (a shift error of 1m depth for all phones).

In the presence of such errors we now find that locating an accurate peak at the true parameter values can sometimes be problematic, especially at the higher frequencies and longer ranges (see recent work by Chapman, Dosso, Gerstoft, and Jiang who wrestle with incorporating error analyses into their work). Very often this difficulty leads to the inclusion of more parameters in the G.I. schemes. However, even this may not be the answer since more parameters make the problem much harder as a result of larger dimensions with even more structure, i.e., difficulties, for peak location. More unknowns may easily mean more trouble finding a solution in a non-monotonic space.

What happens now to our sensitivity curves? It seems that the lowest frequencies (25-50Hz) are not disturbed very much by our errors. However, the higher frequencies 75-100Hz can be quite thrown off by even such small errors, and inaccuracies tend to accumulate at all frequencies as rge increases. In general, if we restrict our G.I. to frequencies less than 75Hz and rge to about 1km or less, then such errors will not severely degrade our LF or the new minimization method while still offering excellent sensitivity to our bottom parameters. We also note that improving $c(z)$ can go a long way toward improving MFP performance (Tolstoy, '12, Jiang and Chapman, '09).

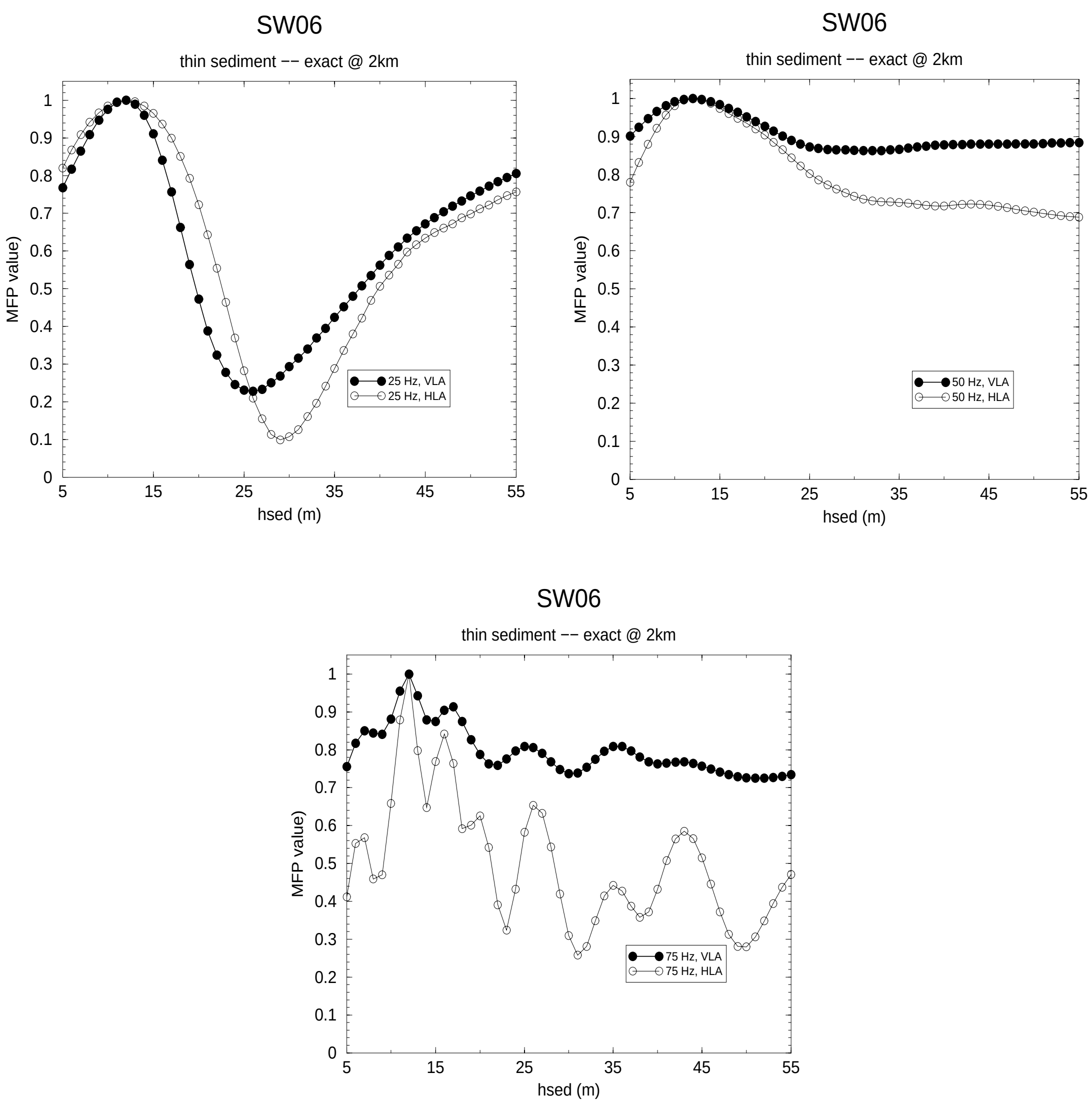
Finally, we have considered HLAs with an interest in eventually performing G.I. with them. In Fig. 4 we see that we have potentially even better resolution and sensitivity with HLAs than with VLAs (other parameters show similar improvements and variety as a function of frequency).

Thus, we conclude from this year's work that (with regard to SW06 scenarios):

- we need to determine either D or rge for G.I. but not both (even in the presence of expected errors);
- we need only determine an average c_{sed} in a sediment layer (we can ignore γ at the lower frequencies);
- sensitivity to c_{hsp} is maximized at the lower frequencies;
- sensitivity to c_{sed} is maximized at the higher frequencies;
- sensitivity to h_{sed} is not monotonic and varies with frequency;

25Hz

50Hz



75Hz

Figure 4: *MFP behavior of* $\boldsymbol{h_{sed}}$ *for 3 frequencies for the HLA versus the VLA with all other parameters known exactly (thin sediment) and rge = 2075m. Upper left: frequency 25 Hz; upper right: frequency 50 Hz; lower: frequency 75 Hz.*

- all bottom parameters become more important with increasing rge;
- small expected errors (such as those in $c(z)$ or in source-receiver geometry) can cause major problems for G.I. at the higher frequencies and longer ranges;
- errors in $c(z)$ accumulate with range and frequency necessitating their inclusion into G.I. methods if frequencies above 100Hz and ranges beyond 1km are to be used;
- HLAs can offer excellent capabilities for G.I. and show wonderful variety as a function of frequency;
- the new minimization method $\mathcal{P}_{min}(f)$ can offer significant improvement over standard incoherent BB averaging for G.I.;
- the new minimization method is most appropriate for LFs (a degraded frequency component such as at a high frequency or long range can severely compromise its results).

WORK COMPLETED

Recent work (FY08) completed includes:

- application of the method to several SW06 scenarios (single sediment layer: thin, medium, or thick);
- examination of the method sensitivity as a function of rge (up to 2km) and frequency (25-100Hz);
- examination of the method sensitivity as a function expected errors (in ocean sound-speed $c(z)$, source depth z_{sou}, and in VLA depth z_{phi});
- development of a new BB signal processing method ($\mathcal{P}_{min}(f)$);
- examination of HLA sensitivity for potential use in G.I.

RESULTS

We have a new BB processor $\mathcal{P}_{min}(f)$ which promises excellent resolution for G.I. at LFs (f within 25-75Hz) and at close ranges (within 250m to about 1km), and even in the presence of expected test errors. This processor will also indicate when it has trouble (it will show low MFP values). Additionally, we see great potential for HLAs in G.I.

IMPACT/APPLICATION

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

- the LF G.I. method as applied to a variety of simulated SW06 data, particularly with regard to sensitivity for bottom parameters as a function of frequency and range;
- the effects of expected errors in a SW06 test environment;

- a new BB inversion method (relative to standard BB incoherent averaging) with demonstrated success on simulated SW06 data;
- the potential success of HLAs for G.I.

RELATED PROJECTS

The G.I. 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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- Tolstoy, A. (2010), "A deterministic (non-stochastic) low frequency method for geoacoustic inversion", *J. Acoustic. Soc. Am.* **127**(6), 3422-3429.
- Tolstoy, A. (2012), "Bottom parameter behavior in shallow water", *J. Acoustic. Soc. Am.* accepted to appear in a special issue scheduled for 2012.

PUBLICATIONS for FY10 & FY11 (this contract to date)

- Tolstoy, A. (2012), "Bottom parameter behavior in shallow water", *J. Acoustic. Soc. Am.* accepted to appear in a special issue scheduled for 2012.
- Tolstoy, A. (2011), "A new broadband matched field processor?", *J. Acoustic. Soc. Am.* submitted to JASA-EL.
- Tolstoy, A. (2011), "A new broadband matched field processor?", abstract for talk to be presented at ASA meeting (San Diego CA Nov).
- Tolstoy, A. (2011), "Broadband geoacoustic inversion on a horizontal line array", abstract for talk to be presented at ASA meeting (San Diego CA Nov).
- Tolstoy, A. (2010), "A deterministic (non-stochastic) low frequency method for geoacoustic inversion", *J. Acoustic. Soc. Am.* **127**(6), 3422-3429.

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- Tolstoy, A. (2010), “Using low frequencies for geoacoustic inversion”, in *Theoretical and Computational Acoustics 2009*, Dresden, ed. S. Marburg.
- Tolstoy, A. (2010), “Geoacoustic Inversion Algorithms when do we stop?”, abstract for talk presented in Cambridge UK April 7-9 2010.
- Tolstoy, A. (2010), “The estimation of geoacoustic parameters via frequencies 25 to 100Hz” abstract for talk presented at ASA meeting (Baltimore MD Apr).
- Tolstoy, A. and M. Jiang (2009), “The estimation of geoacoustic parameters via low frequencies (50 to 75Hz) for simulated SW06 scenarios”, abstract for talk presented ASA meeting (Austin TX Oct).
- A paragraph on using Matched Field Processing for sewer pipe acoustics has appeared in the September ’09 issue of Popular Science.
- Work on using MFP as a monitoring method (described in second article above using sewer pipe data) was discussed on ”The Loh-Down on Science” on over 100 radio stations March 11 (see www.lohdown.org, scripts, Mar 11).

HONORS/AWARDS

- Associate editor for JASA (renewed)
- Associate editor for JCA (renewed)
- member of ASA Committee on Underwater Acoustics (renewed)
- member of ASA Committee on Acoustical Oceanography (renewed)